DYNAMIC TRAVELER RESPONSE MODEL FOR SEISMIC RISK ANALYSIS OF TRANSPORTATION SYSTEMS

by

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FINAL READING APPROVAL

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ABSTRACT

Earthquakes could significantly impact road network capacity and further change spatial and temporal traffic demand patterns. This paper presents a practically useful dynamic traveler microassignment model to simultaneously capture variable traffic demand and departure time choice dynamic for different trip purposes. These travel choice dimensions are integrated in a stochastic utility maximization framework that considers multiple user decision criteria, such as travel time and schedule delay. For a typical case that assumes the logit-based alternative choice model, this paper develops an equivalent gap function-based optimization formulation and a heuristic iterative solution procedure. A case study using a large-scale transportation network (adapted from the Salt Lake City metropolitan area) is presented to illustrate the capability of the proposed system integration for realistic traffic impact studies. Experimental results from two network damage scenarios show the dramatic changes in postearthquake traffic demand, departure time, and route choice patterns; a small amount of capacity loss in critical links could lead to substantial networkwide travel time increases.

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CHAPTER 1

INTRODUCTION

In an urban transportation system, civilian infrastructure, such as bridges and tunnels, serve as vital links for transporting both passenger and freight through freeway and arterial corridors. Natural disasters, especially earthquakes, can cause capacity damage to these critical components in an interconnected multilayer traffic network and further cause dramatic travel delays and economic losses.

Several studies have been devoted to examining seismic hazards and their impacts in metropolitan regions. Typically, physical damages to the transportation infrastructure first lead to significantly reduced traffic capacity and then further result in degradation of critical urban activities, such as postearthquake emergency response. Unlike physical commodities, flow in utility lifeline systems and postearthquake traffic flow patterns in roadway systems are extremely complex and difficult to estimate. This is because they not only are constrained by degraded capacity of links but also depend on various spatial and temporal factors, such as origin-destination demand, travel time, and trip length, as well as intricate traveler response behavior.

An urban seismic risk assessment method needs to address system performance for both infrastructure components and transportation network layers. Werner et al. (1997) proposed a scenario-based loss assessment method that focuses on seismic hazards to highway systems. Chang and Nojima (1997, 1998) and Nojima (1999) developed flow-dependent measures to estimate the postearthquake performance of highway transportation network systems. Basoz and Kiremidjian (1996) estimated networkwide traffic delays for prioritizing retrofit strategies. In a study by Werner et al. (2000), the risk to the transportation system is computed based on the direct damage to major components (e.g., bridges) and the connectivity between a predefined set of origin-destination pairs.

Describing postearthquake origin-destination (OD) demand patterns has been an essential but thorny issue for transportation-related systems and analyses. As indicated by Table 1 for the 1995 Northridge earthquake study, trip patterns and traveler responses during the reconstruction period demonstrates a diverse spectrum of behaviors (Schiff, 1995):

1. Continue to use freeway then divert to primary detour
2. Continue to use freeway, but divert to parallel freeway (located 8 mile south)
3. Continue to use freeway, but divert to other city or arterials
4. Shift to transit
5. Departure time change
6. Eliminate trip

Cho et al. (2003) developed both fixed and variable demand assignment methods. The variable demand model assumes that trip rates are influenced by the cost of the trip in terms of time or distance. In their model, travelers will decide if they need to cancel or continue to travel, and they further select the mode and route after a seismic event.

Table 1. Changes in Mode and Route Choice Pattern (Schiff, 1995)

	Vehicle	People
Preearthquake	*310,000*	*434,000*
During Reconstruction		
Primary detour	130,000	208,000 (48%)
Parallel freeway	5,000	7,000 (1.6%)
Arterial or other street	128,000	155,000 (35.4%)
Shift to transit	N/A	2,000 (0.5%)
Telecommuting	N/A	2,000 (0.5%)
Trip eliminated	N/A	60,000 (14%)
Reconstruction Total	*263,000*	*434,000*

In a recent study by Kiremidjian et al. (2008), the demand fluctuation was assumed to be the same as what has been observed from two recent earthquake cases in California (i.e., Loma Prieta, 1989 and Northridge, 1995).

Dynamic Traffic Assignment (DTA) modeling methodologies can accurately capture the buildup and dissipation of transportation system congestion by describing route, mode, and departure time choices of individual travelers. Using the Salt Lake City metropolitan network as a case study, this study adopts a multimodal DTA modeling framework developed by Mahmassani (2001) and Zhou et al. (2008) to evaluate the direct and indirect impact of earthquake damage on the transportation network.

This paper is organized into two major parts. The first part seeks to determine link capacity breakdowns due to earthquake damage via a Seismic Risk Analysis (SRA) software package, namely REDARS 2 (Risks from Earthquake Damage to

Roadway System). A wide range of hazards, including ground motion, liquefaction, and surface rupture fault, are systematically evaluated and used to estimate seismic damage in the study area. Two earthquake scenarios (M 7.0 and M 6.0 events) are used to generate realistic damage state estimates on the transportation network.

The second part of this study aims to evaluate network-wide traffic flow patterns by seamlessly integrating a simulation-based DTA modeling system with the seismic risk analysis model. By starting with a preearthquake travel pattern, the DTA model takes postearthquake network capacity as an external input and iteratively simulates day-by-day changes in the postearthquake traffic pattern until long-term traffic flow equilibrium is approached. Based on the Salt Lake City metropolitan area, a case study is used throughout the paper to illustrate the methodology and modeling details.

CHAPTER 2

SEISMIC RISK ANALYSIS

System input

The methodology for integrating Seismic Risk Analysis (REDARS 2) and Dynamic Traffic Assignment (DYNASMART-P) systems is shown in Figure 1. In the REDARS 2 seismic risk analysis, results are developed from a set of input parameters, such as soil, link, node, and bridge data. The evaluated seismic vulnerability of the transportation component results is mapped to the corresponding transportation network as capacity reduction parameters for the dynamic traffic assignment procedure, which provides modified travel demand and traffic time.

The seismic risk analysis methodology in REDARS 2 can be carried out in both deterministic and probabilistic approaches. This software package has been developed and released by the Federal Highway Administration with a number of case studies in the states of California, Tennessee, and Oregon. In these studies, the seismic hazards and the resulting damage states are estimated for each component in the transportation network, and a *static* traffic assignment model (without departure time and traffic flow dynamic representation) is used to perform networkwide traffic delay estimation. Figure 2 shows the study network in the Salt Lake City metropolitan area, which is one of the most rapidly growing urban areas in the United States.

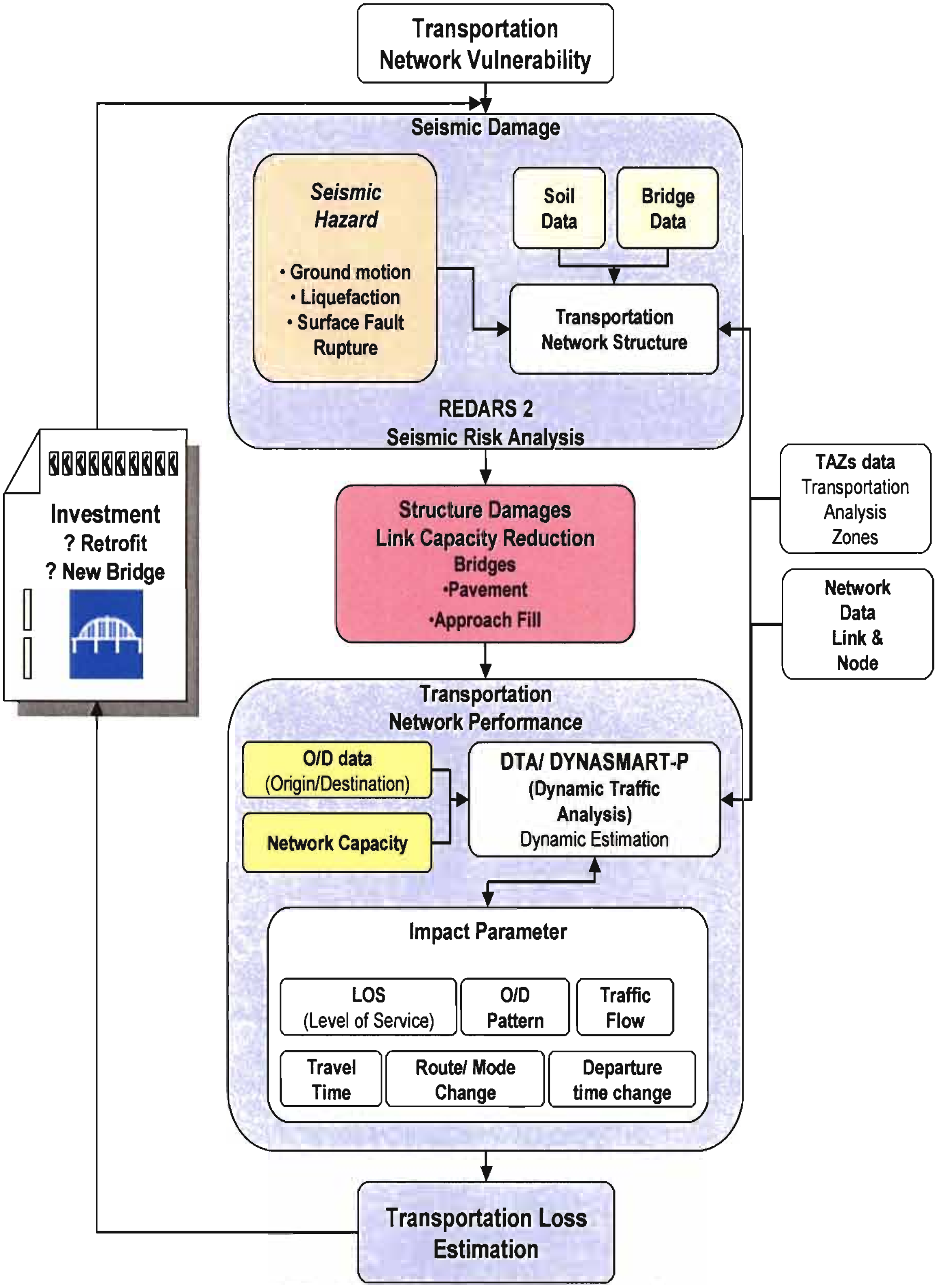

Figure 1. Flow Chart for REDARS/ DYNASMART-P Integration

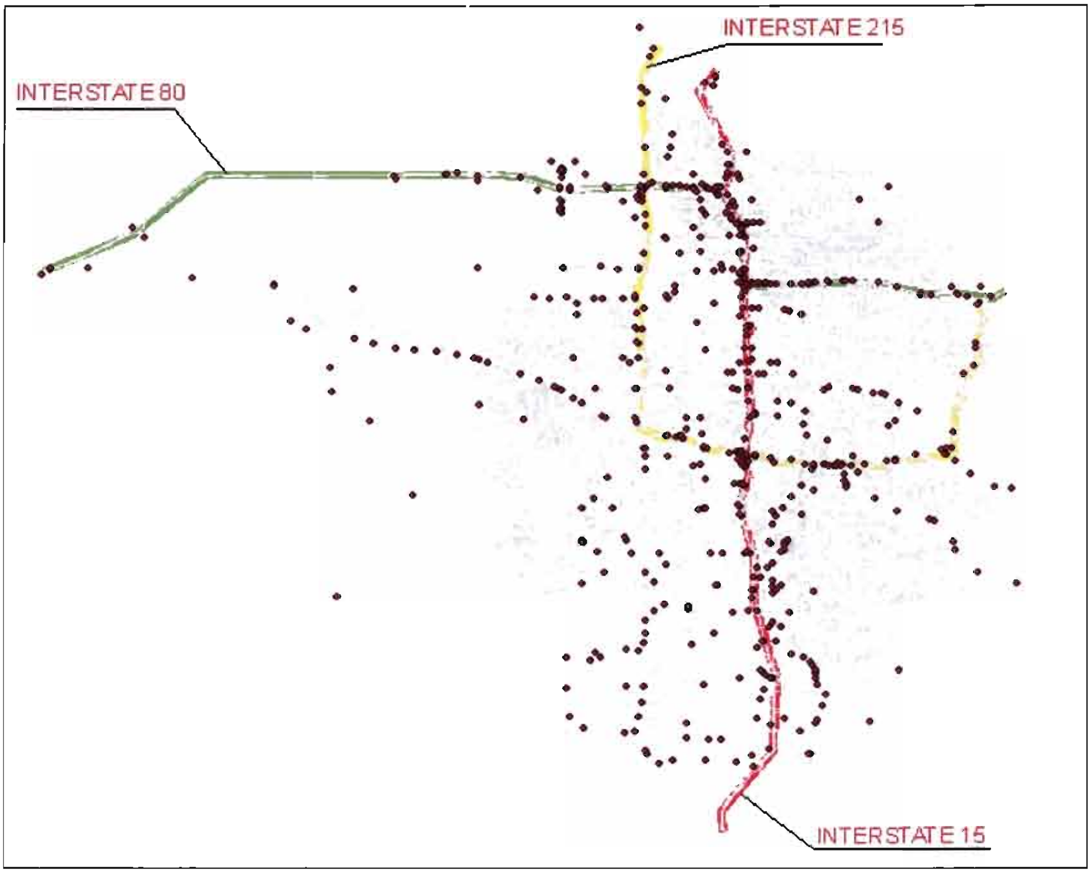

Figure 2. Study Network for Seismic Risk Analysis of the Salt Lake Valley, Utah.

Its population was estimated by the Census Bureau to be 1,468,207 residents as of July 2006. There was an increase of 10.1% since the 2000 Census and 2.5% above the prior year (USCB, 2008). Utah has been widely recognized as having a relatively high seismic hazard. The 240-mile-long Wasatch fault is made up of several segments that are capable of producing up to magnitude 7.5 earthquakes. During the past 6000 years, the Salt Lake City segment has lain under the Salt Lake valley and has ruptured at least four times. The average recurrence interval for surface faulting earthquakes in this segment is 1350 +/-200 years, with the most recent earthquake occurring about 1300 (+/-250) years ago (Black et al., 1996).

The study network includes three major highways, namely I-15, I-80, and a bypass route, I-215, as well as major arterials. The traffic network contains 8524 nodes and 18,601 links, and its link capacity and origin-destination demand data are obtained from the Wasatch Front Regional Council (WFRC), which is the local planning organization for this area.

In 2007, 3813 bridges were recorded in the National Bridge Inventory (NBI) database in the state of Utah. The most up-to-date data from the NBI database and Utah Department of Transportation (UDOT) are used for the 1407 bridges covered in this study area, and a breakdown of bridge locations on different highways can be found in Table 2.

Seismic hazard scenarios

The local soil conditions and fault geometry are key inputs for estimating strong motion hazard. REDARS 2 includes two ground motion models, namely the Abrahamson-Silva (1997) ground motion model, applied to shallow crustal

Table 2. Bridge Locations in Salt Lake City Metro Area (NBI, 2008)

Locations	Bridges
Interstate 15 total	454
Interstate 15 only	214
Interstate 15 & 80	104
Interstate 80 only	160
Interstate 215	139
Salt Lake City Metro Total	844
Study Total	1407

earthquakes in active tectonic regions, and the model by Silva et al. (2002 and 2003), applied to stable tectonic regions. These ground attenuation models typically characterize the effects of local soil conditions by a single term in the ground motion equation. In this study, the soil conditions along the roadway system consist of rock, soft rock, stiff soil, and soft soils, while the last two classes are the most common soil types; some soils are susceptible to liquefaction hazards.

The deterministic seismic hazard scenarios in this analysis used the Walkthrough file, which estimates strong ground motion, fault ruptures, and liquefaction effects. The primary source of seismic hazards is the Salt Lake City Segment of Wasatch fault, which is about 46 km long and parallels the base of the Wasatch Mountain range. According to a study by Wong et al. (2002), this range-bounding normal fault is capable of producing a magnitude 7.0 to 7.5 earthquake. Comparably, the West Valley fault zone is estimated to produce magnitude 6.0 events. Other potential sources of hazards include other mapped faults and smaller unmapped faults (expected magnitude less than 6.5) that are located close to population centers. In this study, we consider two potential seismic effects that may impact or damage the transportation network, as shown in Table 3 and Figure 3.

First, in the Wasatch fault zone, the Salt Lake City segment is located in the east bench of the valley. Second, the West Valley fault zone, the Taylorsville segment, is located on the west side of the valley, which is expected to give considerably less impact than the Wasatch fault in the Salt Lake City section. The scenarios that are used in this study represent realistic seismic events in the Salt Lake Valley.

Table 3. Seismic Hazard Scenarios (Bukva et al., 2008)

	Scenario 1	Scenario 2
Scenario name	Salt Lake City segment Wasatch fault zone	Taylorsville segment West Valley fault zone
Fault Rupture Plane Top and Base Endpoint (Latitude/ Longitude)	40.836/ -111.883 40.476/ -111.832 40.821/ -112.122 40.441/ -112.071	40.808/ -111.982 40.661/ -111.945 40.820/ -111.891 40.674/ -111.856
Magnitude	7.0	6.0
Depth	10.0 km	3.855 km

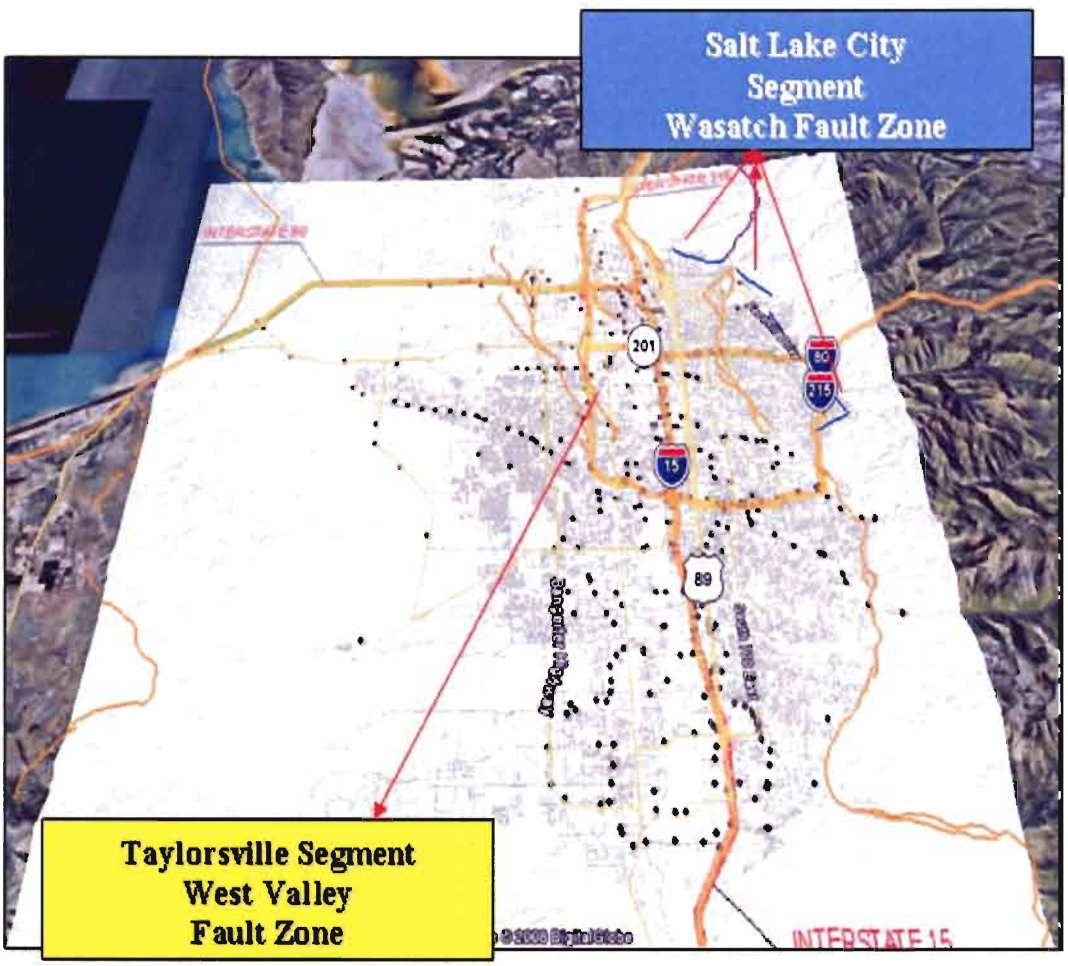

Figure 3. Salt Lake Valley Seismic Hazard Scenarios Map

Postearthquake network capacity analysis

As a result of the seismic hazard evaluations, the network damage states are shown in Figure. 4. Due to the higher level of strong motion, permanent ground displacement (PGD) from liquefaction effects, and surface fault rupture, the Salt Lake City segment component damages are comparably higher than the Taylorsville segment event. By considering major networkwide traffic impacts, congestion that is induced by the seismic event of the Taylorsville segment may not be significant. On the other hand, the rupture of the Salt Lake City segment could impose dramatic damages on the transportation network due to critically damaged locations.

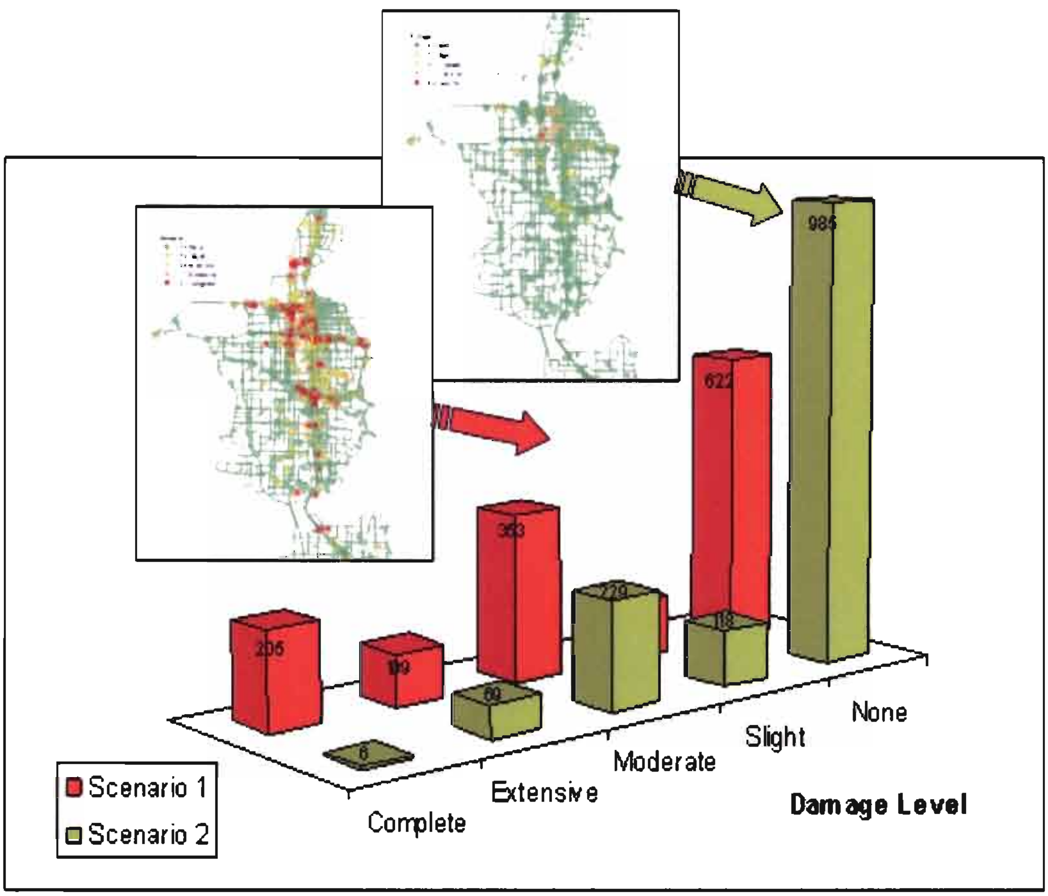

Figure 4. Bridge Damage Status Contour from Seismic Risk Analysis

The network damage contours from these two scenarios are shown on Table 4 and Figure 4. Based on the above considerations, further transportation network analysis will focus on network interruptions due to the activities and damage to the Salt Lake City segment.

The above earthquake damage evaluation gives the component damage status of the transportation network. Table 5 further describes the general repair consequences that are assumed in HAZUS99 (1999). In this study, damage states used as a default repair model from the REDARS2 simulation results. Further in the DYNASMART-P simulation, damaged link capacity is reduced based on Table 5.

Applying damage states to quantitative measures of link capacity can be very subjective (Cho et al., 1999). The most reasonable approach for estimating damaged bridge functionality is to assume that the bridge is to be either fully open or closed after an earthquake. A safety-oriented local policy would close any damaged structures to traffic, regardless of its delay and cost impact on a traffic network.

Table 4. Damage Status from Seismic Risk Analysis from REDARS 2 Simulation

	Scenario 1			Scenario 2		
Scenario Name	Salt Lake City Segment			Taylorsville Segment		
Damage	Bridge	Approach fill	Pavement	Bridge	Approach fill	Pavement
None	622	108	16984	985	1392	18186
Slight	118	2706	2	118	1422	0
Moderate	353	0	200	229	0	0
Extensive	109	0	247	69	0	0
Complete	205	0	1168	6	0	0

Table 5. Repair Consequences and Link Capacity Reduction for Each Bridge Damage State (Modified from HAZUS99 (1999))

Damage State	Link Capacity Reduction (%)	Repair Consequences
1 (None)	0	No damage
2 (Slight)	0	Minor cracking and spalling to the abutment, cracks in shear keys at abutments, minor spalling and cracks at hinges, minor spalling at the column or minor cracking to the deck.
3 (Moderate)	50	any column experiencing moderate (shear cracks) cracking and spalling (column structurally still sound), moderate movement of the abutment (<2"), extensive cracking and spalling of shear keys, any connection having cracked shear keys or bent bolts, keeper bar failure without unseating, rocker bearing failure or moderate settlement of the approach.
4 (Extensive)	100	Any column degrading without collapse – shear failure – (column structurally unsafe), significant residual movement at connections, or major settlement approach, vertical offset of the abutment, differential settlement at connections, shear key failure at abutments.
5 (Complete)	100	Any column collapsing and connection losing all bearing support, which may lead to imminent deck collapse, tilting of substructure due to foundation failure.

However, in this study, it is assumed that except for extensive damaged or collapsed bridges, all other damaged bridges need to be repaired within 6 months and would be restored to be functional at the first stage in the overall reconstruction period.

CHAPTER 3

TRANSPORTATION NETWORK ANALYSIS

Model overview and notations

This study focuses on estimating the network flow transitions from the aftermath, approximately 2 weeks after the incidents, to the stabilized conditions. The multimodal DTA (Dynamic Traffic Assignment) methodology by Mahmassani (2001) and Zhou et al. (2008) is extended to realistically describe postearthquake traffic flow dynamics.

The proposed procedure includes the following three steps:

(1) Convert a large number of transportation network damage states from SRA to DTA simulation,

(2) Load multiclass dynamic OD demand flows to an impacted network, modified to be suitable for modeling postdisaster situations,

(3) Evaluate the overall network performance in terms of traffic volumes, trip length, and travel time in a day-to-day mesoscopic simulation framework.

The following notation is used to represent variables in the problem formulation and solution algorithm:

Notation

i origin zone index, $i \in I$

j destination zone index, $j \in J$

p superscript for trip purposes (e.g., home-based work, home-based shop),

m travel mode index, $m \in M$

T total number of time intervals in the analysis period for modeling departure time choice.

PAT preferred arrival time interval index, PAT=1, 2,…, T

τ departure time interval index, τ =1, 2,…, T

Consider a regional transportation network $G(N, A)$ consisting of $|N|$ nodes, $|A|$ directed arcs, multiple origins $i \in I$, and destinations $j \in J$. The analysis period of interest, taken as the planning horizon, is discretized into small intervals 1,...,T. It is assumed that zone-to-zone static OD demand tables $d_{i,j,p}$ are available (e.g., from regional transportation planning agencies) over the study horizon, representing the number of individual travelers traveling from zone i to zone j with a trip purpose p. One simple way for obtaining dynamic OD demand tables is to convert static OD demand table $d_{i,j,p}$ to

$$d_{i,j,p,\tau} = d_{i,j,p} \times \beta_{p,\tau} \quad (1)$$

where $\beta_{p,\tau}$ is the temporal distribution for trip purpose p that translates static OD demand to dynamic OD demand.

Another commonly used method is to perform dynamic OD estimation using link counts. However, as the demand pattern is expected to have significant changes after a major earthquake, the postearthquake link counts are unavailable before the event; thus, the temporal profile-based method in Equation (1) should be sufficient.

Modeling changes in spatial and temporal demand patterns

As shown in Figure 5, the traffic assignment model with elastic demand can be solved by the standard fixed demand traffic assignment program through network representation. In other words, our current study considers two modes: drive alone and stay-at-home.

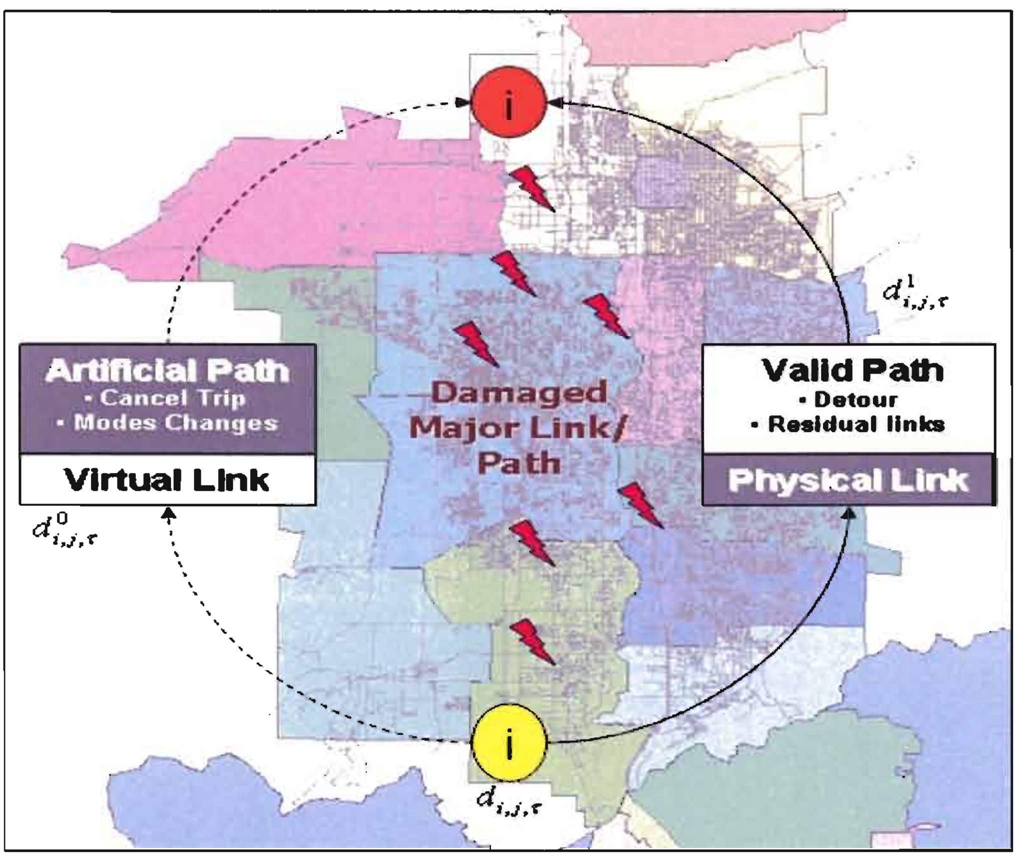

Figure 5. Virtual Link for OD Pair (i, j).

Moreover, an excess demand formulation is adopted to capture the split of OD flows between the physical network and the artificial link that represents the "stay-at-home" mode. A simple flow split function can be illustrated conceptually as the following, while a more elaborate formulation that integrates mode and departure time choice is given in the next session.

$$d_{i,j,\tau} = \sum_m d^m_{i,j,\tau} = d^0_{i,j,\tau} + d^1_{i,j,\tau} \tag{2}$$

$$d^m_{i,j,\tau} = d_{i,j,\tau} \frac{e^{\theta_{i,j} T^m_{i,j,\tau}}}{e^{\theta_{i,j} T^0_{i,j,\tau}} + e^{\theta_{i,j} T^1_{i,j,\tau}}} \tag{3}$$

where m = 0-1 indicator for bypassing or traversing flows

$d^1_{i,j,\tau}$ = demand flows that are accommodated in the physical network

$d^0_{i,j,\tau}$ = demand flows that are carried by the virtual link

$T^1_{i,j,\tau}$ and $T^o_{i,j,\tau}$ are average travel times for paths (i,j,τ) traversing and bypassing in the physical network respectively, and $\theta_{i,j}$ is a dispersion parameter to be estimated. If $T^1_{i,j,\tau}$ is dramatically increased for all of the available paths due to reduced capacity and is higher than a threshold value corresponding to $T^o_{i,j,\tau}$, then part of the travelers will switch to artificial links, i.e., cancel the trip and stay at home.

A damaged transportation network will change both spatial and temporal demand patterns during the reconstruction period. In the Hanshin-Awaji Earthquake case study, the research of Iida et al. (2000) found that an increase in the OD flow of short-distance trips is generated in large part by the need to rely on automobiles due to a lack of availability of other modes of transportation that normally are used for everyday activities.

This indicates the desirability of trip activity to be regulated by physical network accessibility, which affects short-distance trips such as home-based shop trip (HBS) rather than home-based work (HBW) trips. Home-based work trips are usually have fixed destinations and more restricted arrival times, rather home-based shop trips, which have less restricted destination choices. The following discussion considers departure/arrival time adjustment, route change, and destination choice behavior for different trip purposes.

Home-based work trip (departure time and route changes)

This study assumes that the Preferred Arrival Time (PAT) is 8-9AM for the morning peak, and the alternative tree for each OD pair includes:

Spatial dimension:

Path (k=1, m=1)

Path (k=2, m=1)

....

Stay at home (m=0)

Temporal dimension:

Different departure time.

Given a fixed PAT, home-based work trips can change routes or departure times to avoid traffic. Let us further define $AAT_{i,j,PAT}^{\tau,m,k}$, $SD_{i,j,PAT}^{\tau,m,k}$, $SDE_{i,j,PAT}^{\tau,m,k}$, $SDL_{i,j,PAT}^{\tau,m,k}$, actual arrival time, schedule delay, early schedule delay, and late schedule delay, respectively, of an alternative (i, j, PAT, τ, m, k), where

$$SD_{i,j,PAT}^{\tau,m,k} = AAT_{i,j,PAT}^{\tau,m,k} - \text{PAT} \tag{4}$$

$$SDE_{i,j,PAT}^{\tau,m,k} = \max\{0, -SD_{i,j,PAT}^{\tau,m,k}\} \tag{5}$$

and $SDL_{i,j,PAT}^{\tau,m,k} = \max\{0, SD_{i,j,PAT}^{\tau,m,k}\}$ (6)

as illustrated in Figure 6.

For each traveler with (i, j, p, PAT) where p= HBW, the systematic utility equation for an alternative (departure time τ, mode m, and path k) is:

$$V_{i,j,p,PAT}^{\tau,m,k} = \alpha_1 \times T_{i,j,p}^{\tau,m,k} + \alpha_2 \times SDE_{i,j,p,PAT}^{\tau,m,k} + \alpha_3 \times SDL_{i,j,p,PAT}^{\tau,m,k}. \tag{7}$$

The coefficients α_1, α_2, α_3 are utility coefficients for travel time, early schedule delay, and late schedule delay, respectively. Typically, α_3 is greater than α_2, as a late schedule delay has higher penalties than early schedule delays.

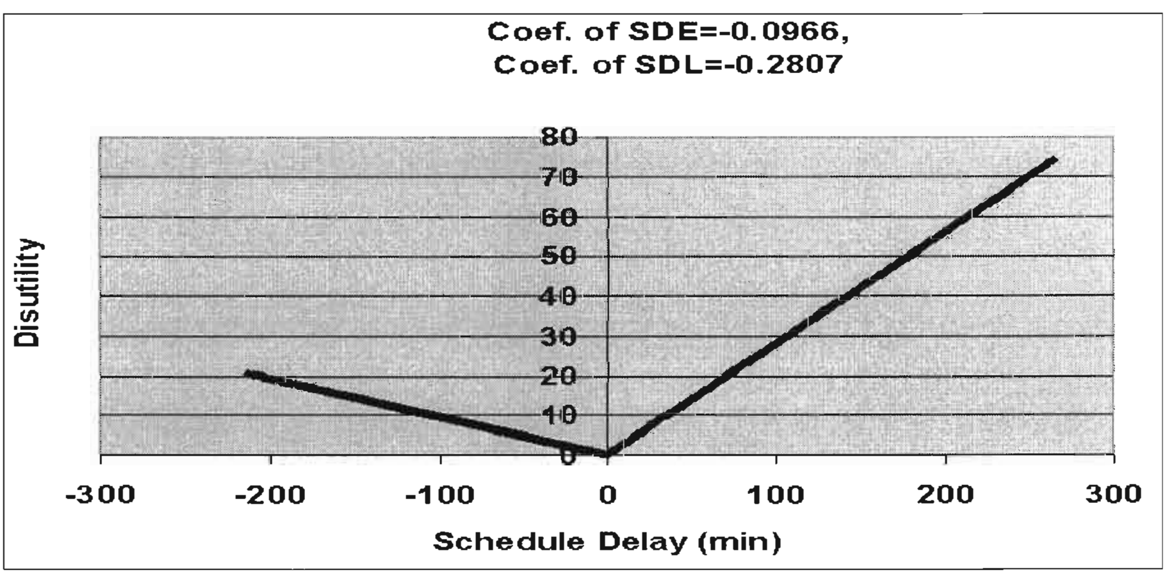

Figure 6. Illustration of Disutility Functions for Schedule Delay (Noland, Small, Koskenoja, and Chu 1998)

By assuming that random error terms are independently identically distributed Gumbel variables, the choice probabilities for each alternative (τ, m, k) correspond to the usual unordered Multinomial Logit (MNL) choice function:

$$\Pr_{i,j,p,PAT}^{\tau,m,k} = \frac{Exp(V_{i,j,p,PAT}^{\tau,m,k})}{\sum_{\tau,m,k} Exp(V_{i,j,p,PAT}^{\tau,m,k})} \quad (8)$$

Other complicated and sophisticated forms, such as path-size logit ordered generalized extreme value models, can be used, because the approach considers details at the individual traveler level. The choice probabilities further link the OD demand to flows that are associated with each alternative:

$$r_{i,j,p,PAT}^{\tau,m,k} = d_{i,j,p,PAT} \times \Pr_{i,j,p,PAT}^{\tau,m,k} = d_{i,j,p,PAT} \times \frac{Exp(V_{i,j,p,PAT}^{\tau,m,k})}{\sum_{\tau,m,k} Exp(V_{i,j,p,PAT}^{\tau,m,k})}, \quad (9)$$

where $r_{i,j,PAT,p}^{\tau,m,k}$ number of travelers for alternative (i, j, PAT, τ, m, k) at iteration n

<u>*Home-based shop trip (destination and route changes)*</u>

For trip purpose p= HBS, the total production from each zone i is

$$d_{i,p,\tau} = \sum_{j} d_{i,j,p,\tau} \quad (10)$$

The alternative tree for each origin i includes

Destination j =1,

Path (j=1, k=1), m=1

Path (1,2), m=1

....

Destination j =2

Path (j=2,,k=1), m=1

Path (2,2), m=1

....

Stay at home, m =0

For each traveler with (i, τ), the systematic utility equation is

$$V_{i,p,\tau}^{j,m,k} = \alpha_1 \times TT_{i,p,\tau}^{j,m,k} , \tag{11}$$

where $V_{(i,j,PAT)}^{(\tau,m,k),n}$ is the systematic utility for alternative (i, j, PAT, τ, m, k) at iteration n.

The choice probabilities further link the OD demand to flows that are associated with each alternative using Eq. (12) for p = HBS.

$$, r_{i,p,\tau}^{j,m,k} = d_{i,p,\tau} \times \Pr_{i,p,\tau}^{j,m,k} = d_{i,p,\tau} \times \frac{Exp(V_{i,p,\tau}^{j,m,k})}{\sum_{j,m,k} Exp(V_{i,p,\tau}^{j,m,k})} . \tag{12}$$

Simulation-based solution framework

To solve the dynamic traveler assignment problem in transportation networks, we essentially want to determine the number of travelers for each alternative and the resulting temporal-spatial loading of vehicles. To this end, we extend the DTA solution methodology to support postearthquake planning and operations decisions. The system features the following three components:

(1) Traffic simulation (or supply) component (with reduced link capacity),

(2) Traveler behavior component, departure time, destination, and route choice

(3) Path processing and traveler assignment component.

A traffic simulator, namely DYNASMART-P (Mahmassani, 2001), is used to capture the traffic flow propagation in the traffic network and evaluate network performance under reduced link capacity and a given mode, departure time, and route decisions that are made by the individual travelers. Given the user behavior parameters, the traveler behavior component aims to describe travelers' mode, departure time, and route selection decisions after an earthquake. The third component is intended to generate realistic alterative route choice sets and perform stochastic network loading for solving the traveler assignment problem under impacted network conditions.

This study presents an iterative procedure for solving the stochastic intermodal dynamic traveler assignment problem with joint mode and departure time choice. In this solution framework, a dynamic step size is used to simultaneously update flow and reference cost vectors (r, π) using the auxiliary solution. The iterative procedure that is adopted here can only be viewed as an approximate (heuristic) algorithm intended for modeling day-to-day traffic changes and learning processes, in which 10% or 25% of travelers (as modeled as different step sizes) every day consider making changes.

Without loss of generality, the following discussion only considers home-based work (HBW) trips, so trip purpose index p is ignored below. The main steps of the solution procedure are described as follows:

Step i: Initialization

Let day n=0. Based on a set of initial link and node travel attributes, find an initial feasible shortest path set for each mode and each departure time in the damaged transportation network. Perform stochastic network loading using the path set. Generate the set of mode-departure time-path flow solution $[r]^{n=0}$.

Step ii: Compute time-dependent intermodal least-cost paths and update choice set

Day index $n = n+1$. Given a time-dependent link travel time, find intermodal time-dependent K-least-cost paths in the multidimensional network for each mode at each departure time for each choice (i, j, PAT).

At iteration n, construct the feasible alternative set $\Omega^{n+1}_{(i,j,PAT)}$ for each (i, j, PAT), which contains all of the alternatives in $\Omega^{n}_{(i,j,PAT)}$ and the new alternatives that are found through the intermodal K-shortest path search process. Given path travel time and travel cost, calculate the schedule delay and travel time reliability that are associated with each path to provide a generalized cost vector $\left[V^{\tau,m,k}_{i,j,PAT}\right]^{n}$.

Step iii: Update path assignment solution

Use a predetermined size of move to find a new departure time-mode-path flow pattern. In the following example, a Method of Successive Average (MSA) is used.

$$r^{(\tau,m,k),n+1}_{(i,j,PAT)} = r^{(\tau,m,k),n}_{(i,j,PAT)} + \frac{1}{n}\left\{\underline{r}^{(\tau,m,k),n+1}_{(i,j,PAT)} - r^{(\tau,m,k),n}_{(i,j,PAT)}\right\} \quad \forall i, j, PAT, \tau, m, k \tag{13}$$

where the auxiliary departure time-mode-path flow vector is

$$\underline{r}_{(i,j,PAT)}^{(\tau,m,k),n+1} = d_{i,j,PAT} \times \frac{Exp(V_{(i,j,PAT)}^{(\tau,m,k),n})}{\sum_{\tau,m,k} Exp(V_{(i,j,PAT)}^{(\tau,m,k),n})} \quad \forall i,j,PAT,\tau,m,k \tag{14}$$

and an auxiliary reference cost vector

$$\underline{\pi}_{(i,j,PAT)}^{n+1} = \frac{d_{i,j,PAT}}{\sum_{\tau,m,k} Exp(V_{(i,j,PAT)}^{(\tau,m,k),n})} \quad \forall i,j,PAT \tag{15}$$

For home-based shop trips,

and a new reference generalized cost,

$$\pi_{(i,j,PAT)}^{n+1} = \pi_{(i,j,PAT)}^{n} + \frac{1}{n}\left\{\underline{\pi}_{(i,j,PAT)}^{n+1} - \pi_{(i,j,PAT)}^{n}\right\} \quad \forall i,j,PAT \tag{16}$$

Step iv: Stochastic network loading

Under the set of mode, departure time, and path assignment $\left[r_{i,j,PAT}^{\tau,m,k}\right]^{n+1}$, generate the vehicle/traveler attributes and simulate the assigned vehicles between each O-D pair for each departure interval τ and each mode m. Generate $V_{(i,j,PAT)}^{(\tau,m,k),n+1}$ with the latest simulation results.

Step v: Convergence checking (if reaching steady state)

Calculate

$$Gap = \sum_{i,j,PAT}\left\{\sum_{(i,j,PAT,\tau,m,k)\in\Omega_{i,j,PAT}^{n+1}} \frac{1}{2}\left(\ln r_{(i,j,PAT)}^{(\tau,m,k),n+1} - V_{(i,j,PAT)}^{(\tau,m,k),n+1} - \pi_{(i,j,PAT)}^{n+1}\right)^2\right\} \tag{17}$$

If *Gap* < δ, convergence is achieved, where δ is a prespecified parameter.

If convergence is attained, stop. Otherwise, go to Step 2.

In Step 3, as K routes are generated at each iteration and stored in the alternative set of $\Omega^{n}_{(i,j,PAT)}$. Thus, there are at most a total of n*K alternatives for each choice (i, j, PAT) at iteration n. K=5 is used in the experiments of this study.

CHAPTER 4

CASE STUDY ON THE SALT LAKE CITY METRO AREA

The Salt Lake City metro test network is modeled using 1500 traffic analysis zones (TAZs) for a 180-minute simulation horizon. Three different scenarios are tested, including a do-nothing scenario and two damaged network scenarios with network-wide capacity deductions, shown as Table 6. Typically, overpass bridges may impact directly related underlying links. In this study, all of the links that are located under overpass bridges (that have extensive or complete damage) are assumed to be reopened shortly after structural debris is cleaned.

Table 6. Preearthquake/ Postearthquake Network Capacity

	Scenario 1 (Salt Lake City Segment)		Scenario 2 (Taylorsville Segment)	
Damage Type	Link Damage	Bridge Damage	Link Damage	Bridge Damage
Partial Capacity Deduction (Moderately Damaged)(%)	0.5376	12.5444	0.5295	8.1379
Full Capacity Deduction (Extensive/Collapse Damage)(%)	7.6071	22.3169	0.8386	5.3304
Total Capacity Deduction (%)	8.1447	34.86	1.3681	13.4683

The loaded Salt Lake City network includes highway corridors and major and minor arterial streets, as well as connectors, so the total capacity reduction values that are shown in Table 6 are statistically diluted.

The mapping link damages from REDARS 2 to DYNASMART-P are shown in Figure 7. In the following discussion, we sequentially examine the networkwide,

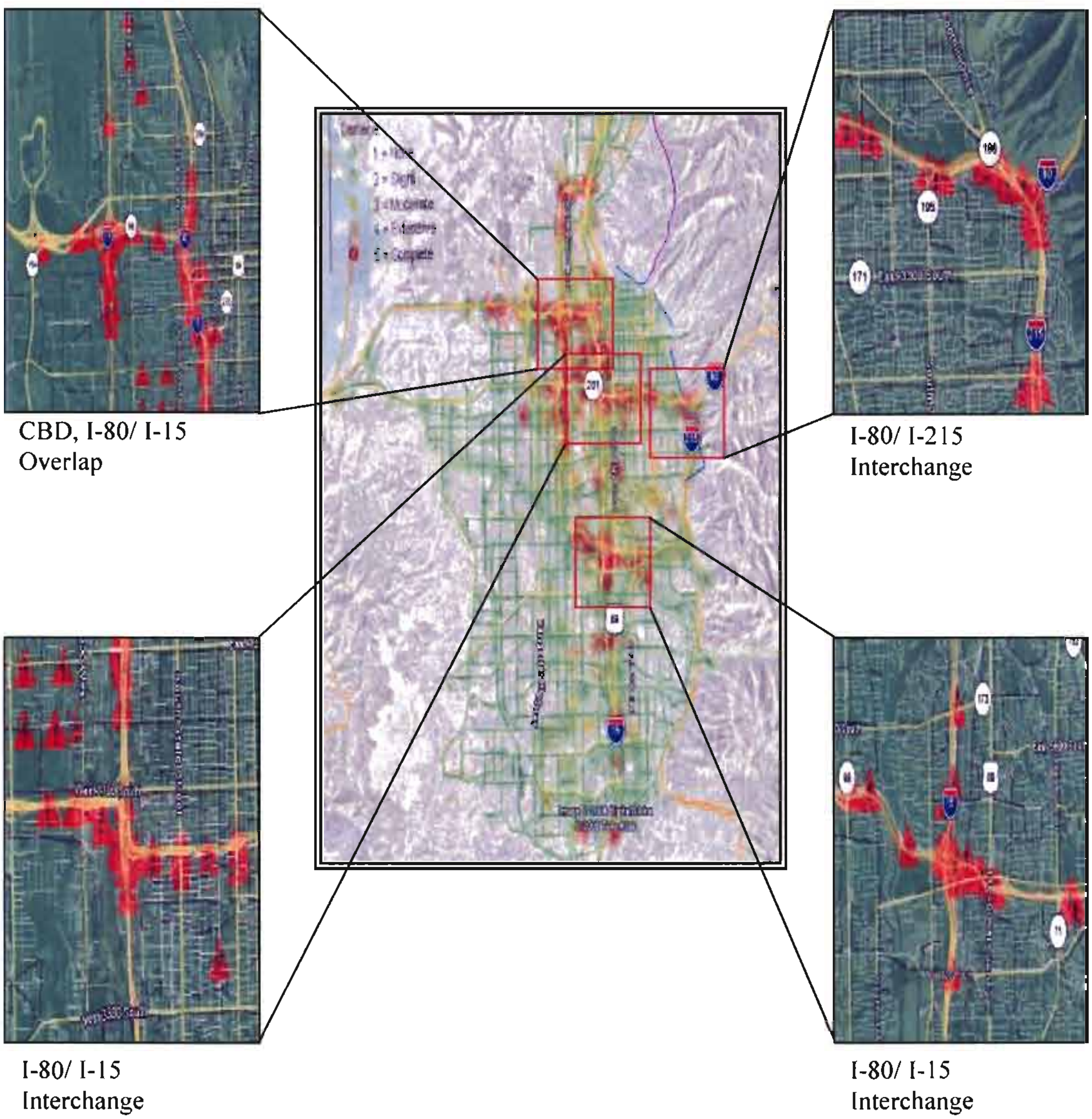

Figure 7. Mapping Link Damage to DYNARSMART-P (Scenario 1)

origin-destination-specific and path-specific travel times, extracted from vehicular simulation results from DYNASMART-P.

Table 7 first gives the network-wide average travel time in the do-nothing case as 21 minutes. Based on the simulation results, scenario 1 (Salt Lake City Segment) and scenario 2 (Taylorsville Segment) produce 123.3% and 31.9% increases, respectively, in terms of average travel time. In the first scenario, many parts of the interstate freeway system are accessible, so most vehicles use limited arterial streets or residual highway segments.

In addition, Table 8 provides useful OD-specific MOEs (measures of effectiveness), while OD pair 1480 to 195 is chosen for measuring the major traffic impact in the North-South bound using the I-15 corridor. By examining 26 vehicles that have traveled along this OD pair, in scenario 1, when the I-15 corridor is severely damaged, the impacted vehicles find alternative routes close to the I-15 corridor, further leading to a 29.89% increase in their average travel times.

Table 7. Network-wide travel time changes

Network wide travel time	Pre Eq	Scenario 1 Salt Lake City	Scenario 2 Taylorsville
Link capacity decreased by PreEq.		2.433%	0.6909%
Simulated Travel time (minutes)	21.0	46.9	27.7
Travel time increased by PreEq.		123.3%	31.9%

Table 8. Travel Time Impact for OD Pair 1480 to 195

Tested Trip OD 1480 to 195 (26 Vehicles)	PreEq.	Scenario 1 Salt Lake City	Scenario 2 Taylorsville
Travel Time (minutes)	55.0	71.44	57.0
Travel Time Increased (%)		29.89%	3.51%

Comparably, the I-15 corridor has minor damage in scenario 2, and the average travel time is increased by 3.51% because additional trip length due to detours does not significantly impact the travel time along the whole trip.

Based on the dynamic OD demand matrix in this network, 6 critical OD pairs are selected to be compared under both preearthquake and postearthquake conditions. Selected critical OD pairs are shown in Figure 8.

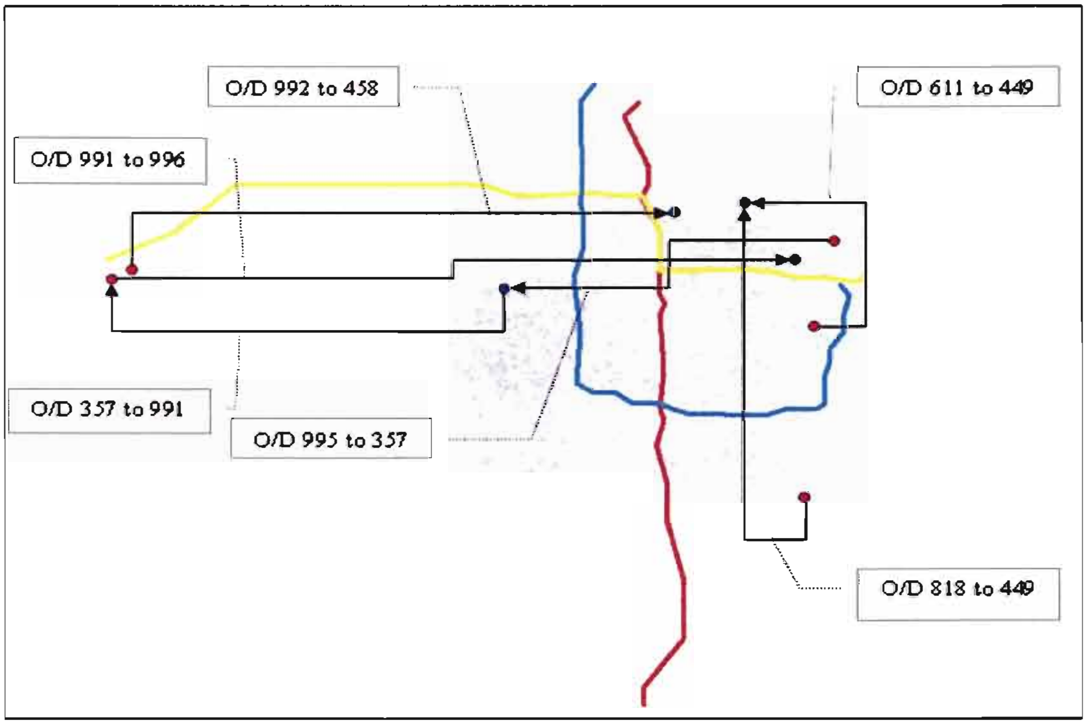

Figure 8. Tested Sample OD Pair

The OD pair 991 to 996 represents incoming traffic flow from the west side of Salt Lake City to the CBD area through the I-80 corridor. Those OD pairs that originally need to cross the I-15 or I-80 corridor in the preearthquake case either need to find detour routes or experience severe traffic congestion on available underpasses in the postearthquake case.

Overall, the average travel time is increased by 25% to 35%, and the additional delay for each OD pair depends on the related severity on its passing routes. Specifically, the heavy delays from OD pair 357 to 991 are mainly due to the lack of detour routes available in this impacted area. As only AM peak demand in considered, traffic flow OD pair 357 to 991 (in the counterflow direction) shows slightly reduced travel times. Figure 9 shows the difference in terms of average travel time between preearthquake and postearthquake cases for each critical OD pair.

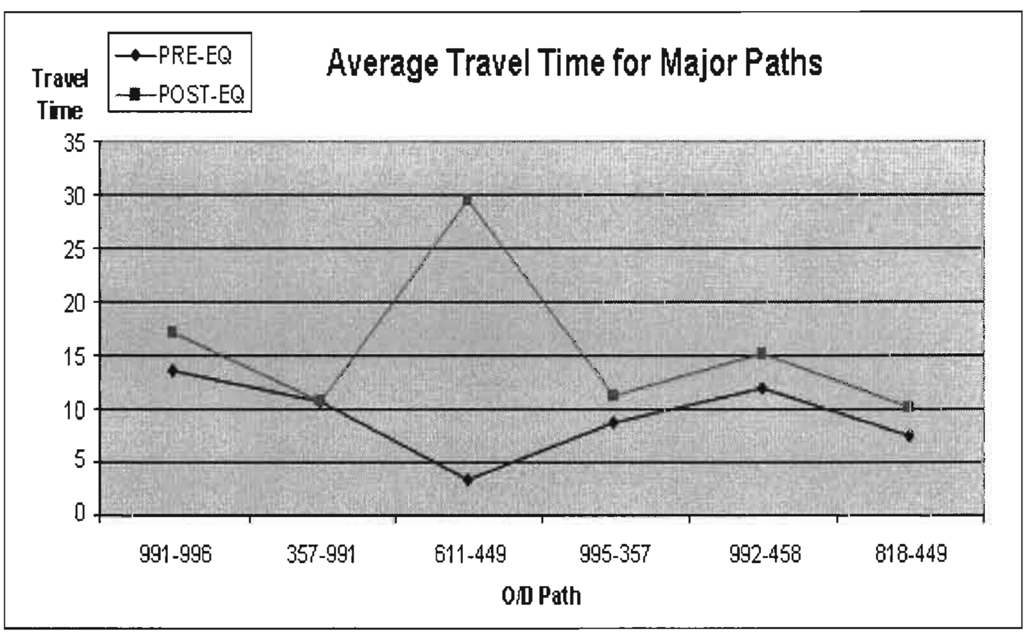

Figure 9. Average Path Travel Time for Major O/D Pair

Table 9 further details vehicle-specific statistics as a result of route, mode, and departure time changes, while OD pair 995 to 357 is selected with 6 vehicles in the preearthquake case and 10 vehicles in the postearthquake case.

As illustrated in Figure 10, in the postearthquake conditions, the departure times for 10 vehicles are almost evenly spread due to the congestion level on the projected paths.

Table 9. Adjusted Departure Time Pattern for OD Pair 995 to 357

Preearthquake			Postearthquake		
# of vehicle traveled: 6			# of vehicle traveled: 10		
Average Travel Time: 8.71			Average Travel Time:11.29		
Vehicle ID	Departure Time	Travel Time	Vehicle ID	Departure Time	Travel Time
4866	5.8	8.77	4777	5.8	11.36
11223	13.5	8.77	19903	24.3	11.19
67227	82.6	8.56	33125	40.6	11.23
81201	99.7	8.58	58686	72	11.25
81527	100.1	8.78	70812	86.9	11.53
83822	102.9	8.82	71200	87.4	11.31
			84708	104.1	11.11
			84871	104.1	11.2
			90006	110.8	11.58
			138993	170.9	11.17

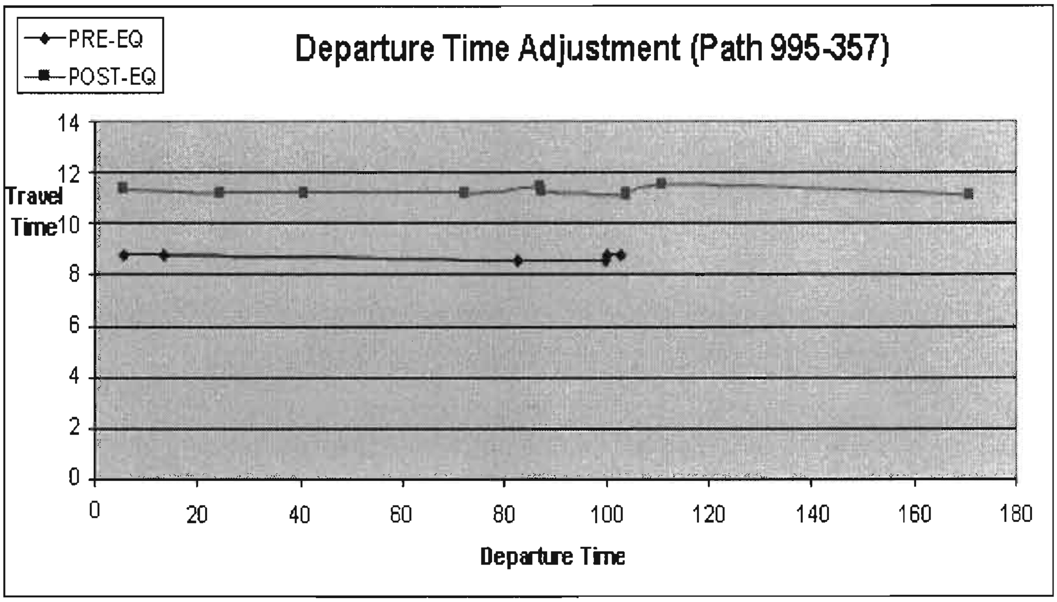

Figure 10. Departure Time Adjustment for Path 995-357

Indirect loss estimation on postearthquake transportation network

The risk assessment problem on capacity-reduced transportation networks could be more complex under this approach, since the indirect loss has two strongly correlated components: (1) the cost of the traffic delays and (2) the cost of the lost trips. Recently, Nilsson (2008) tested incremental seismic scenarios in the Charleston, SC urban area. The intensity of an Mw 7.0 earthquake used in this study leads to an estimated loss of $83 million and $1.1 billion for the direct and indirect damages, respectively. In Nilsson's study, the cost of indirect loss, such as expenditures associated with traffic diversion, was calculated approximately by using a multiplication factor of 13 based on the study by ATC(1991), in which indirect cost was estimated as 7~20 times the calculated direct costs.

As indicated by Moore et al. (2006), REDARS validation studies showed that the loss estimation model substantially overestimated travel volumes and delays in the Los Angeles network relative to the observations following the 1994 Northridge earthquake. In some cases, the overestimated travel volumes was about 2.5 times greater than what were observed on the day following the earthquake, and the modeled delays was around 12 times greater than what were observed (Cho et al. 2003a; Werner et al. 2004).

Moore et al. (2006) further conducted a study with an Mw 7.1 earthquake event along the Hayward fault in the San Francisco Bay Area. For this intense earthquake, the REDARS 2.0 model estimates 92 collapsed bridge, 466 damaged bridges as well as 36 links failures due to liquefaction. The total cost of transportation delays and the value of trips forgone (due to reductions in service) were estimated to be $656.81 Million. The REDARS recovery model suggests that all the collapsed and damaged bridges would be repaired or reconstructed within 231 days. It should be remarked that, this total loss does not include the cost of repairing transportation structures or the cost of freight flows forgone.

Estimated the indirect loss in the Salt Lake Valley study in this paper was based on the following assumptions: a value of time at $15 per person-hour, and average vehicle occupancy of 1.2 persons per passenger car unit, and a factor 4.0 for converting traffic demands from the 4 hour peak to a daily pattern. The travel impacts of daily delay loss are estimated $1~3, million varied by reconstruction time frames.

The total indirect loss subject to delayed travel time is estimated to be \$1.8~2 billion for a reconstruction period of 18 months. Figure 11 shows the difference between upper bound network capacity recovery (UB) and lower bound network capacity recovery (LB).

The daily total delay cost due to the reduction of transportation capacity was strongly related with network recovery capabilities provided by the transportation authority and returning volume of foregone travel demand in the network. The calculated cost was based on the number of trips on year of 2030 forecasted by Mountainland Association of Governments (MAG, 2002). Table 10 further summarized the delay cost following the earthquake and during the course of recovery.

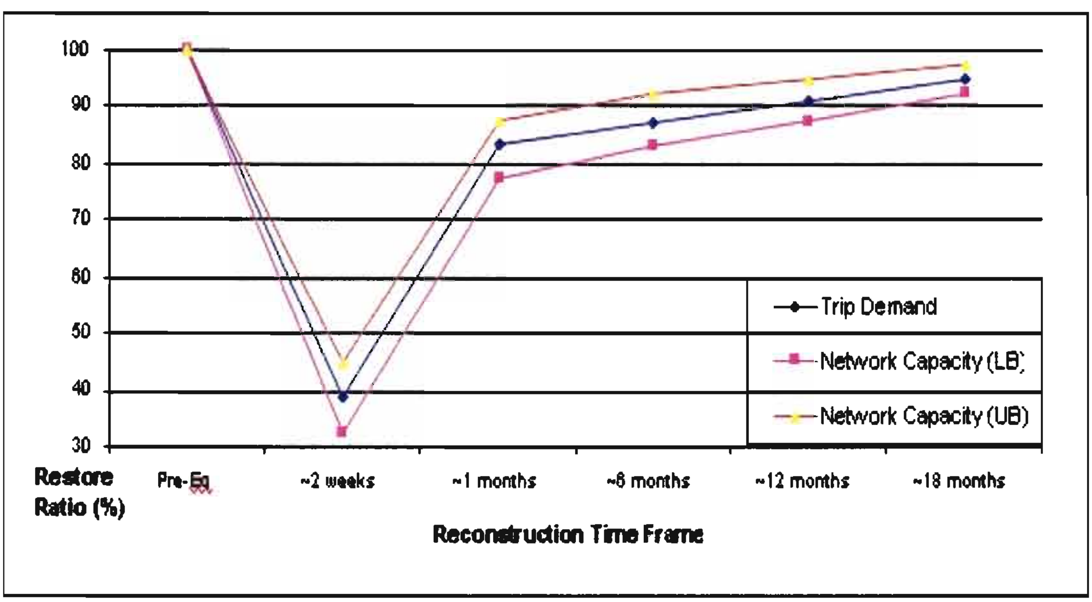

Figure 11. Trip Demand/ Network Capacity Restoration

Table 10. Estimated Travel Delay Cost by Level of Traffic Severity

Time	# of Trips	Daily Cost by Traffic Delay Severity (1,000$)				
	(4hr peak)	35%	25%	15%	10%	5%
Post Eq ~2 weeks	415,980	3,668	2,621	1,572		
~3 months	892,835	7,875	5,625	3,375	2,250	
~6 months	933,419		5,881	3,528	2,352	1,176
~12 months	974,002			3,682	2,455	1,227
~18 months	1,014,586					1,278

CHAPTER 5

CONCLUSION

Satisfactory evaluation of transportation network performance after a major earthquake depends on careful planning and an integrated system level perspective, which calls for the adoption and deployment of emerging earthquake hazard evaluation and traffic network analysis tools. In this context, this research proposes a desirable transportation analysis framework that can (1) consider realistic link damage scenarios based on scientific and systematic earthquake engineering considerations; and (2) analyze traffic network performance based on dynamic traveler assignment approaches.

This paper presents a practical dynamic traveler microassignment model to simultaneously capture variable traffic demand and departure time choice dynamics. One particular focus is on how to represent different trip-making options and characteristics for different trip purposes. A case study using a large scale transportation network is presented to illustrate the capability of the proposed system integration. The OD-, path-, and vehicle-specific information is systematically examined to provide a better understanding of traffic flow evolution after a major earthquake event in an urban region. The proposed methodology can uniquely meets the needs of metropolitan planning organization (MPO) and state department of transportation (DOT) agencies for sophisticated decision-making tools that involve large-scale dynamic traffic simulation.

One of the main contributions of the present paper is to describe the implementation details of a platform for integrating a rich set of traveler choice models, applied at the individual traveler level within a realistic representation of the dynamics of traffic flow in networks with dramatic capacity changes due to earthquakes. Furthermore, integrating REDARS 2 and DYNASMART-P to perform earthquake hazard evaluation and traffic impact studies through dynamic network simulation at a mesoscopic level will provide transportation planners with a realistic estimation of seismic risk-related road capacity damage and provide earthquake engineers with detailed evaluation of large-scale network-wide traffic impact. While many elements of the representation can be further improved, especially on the behavioral side for postearthquake, day-to-day traffic evolution, we believe that the platform provides a robust framework for the delivery of the kind of integrated capabilities that are required to address emerging demand management measures of interest at the network level.

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