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TRANSPORTATION NETWORK SIMULATION FOR DYNAMIC ORIGIN-DESTINATION MATRIX UNDER EARTHQUAKE DAMAGE

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SUMMARY

The ultimate goal of this study is to develop a method with a software package that allows real-time visualization of traffic flows in a transportation network immediately after a disaster event. This will assist first responders to develop optimal and adaptive strategies to minimize human and property losses immediately after the disaster. Disasters include those due to natural hazards (e.g., earthquakes), technological accidents and terrorist attacks. It is envisioned that appropriate sensors will exist for this purpose to monitor and detect not only structural damage but also traffic behavior (speed and volume) at optimal locations. Emerging sensors for this purpose include optical, MEMS (Micro Electro-Mechanical Systems) and traditional electronic-mechanical types with wireless or wireless-internet hybrid capability for transmission of data to traffic control centers where the data are gathered, processed and analyzed for visualization to facilitate rapid decision making. Currently, most transportation network analysis is performed on a fixed origin-destination (OD) matrix under the assumption of the equilibrium of traffic flow. In this study, we demonstrate a model that is applied to Los Angeles area highway network introducing into the analysis dynamical nature of OD matrix, which reflects the effect of urban seismic damage on the societal transportation needs immediately after an earthquake. HAZUS and other urban damage estimation codes are used for this purpose under the assumption that the Los Angeles area is subjected to the scenario earthquake of Malibu Coast (M7.3) in conjunction with the PGA values simulated by EPEDAT for that earthquake. The demonstration shows that the travel pattern (and hence OD matrix) will significantly change and traffic flow visualization identifies location of severe congestion reflecting the need for emergency vehicles converging to and/or leaving from the severely damaged areas utilizing the transportation network which is possibly also damaged.

INTRODUCTION

Newly opened highway routes are designed to accommodate travel demands relating to the growth of regional activity, diverted demand from other routes, and new demand from organizations that have relocated to enjoy the increased accessibility. Travel demands on the new route typically grow gradually

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with time, until the benefits are realized. In contrast to the advantageous situation where new infrastructure is added to the system, an abrupt and unexpected reduction in capacity, due to unexpected events such as earthquakes, may have severe societal repercussions. In the event of a major highway closure, drivers do not usually have access to key information concerning alternative paths and the expected travel times. Their route choice is instead somewhat arbitrary, and consequently, sub optimal. Consequently, closure of a route without advance notice often results in substantially higher travel costs than those incurred under normal conditions.

These negative impacts vary across geographic space. Following an extreme event, additional driving costs are highest where the damage is centered. However, depending on the type of damage incurred, additional costs may or may not propagate throughout the region. The level of disruption will also vary with travel rationale. In general terms, the mandatory delivery of goods between industrial regions will continue regardless of congestion. However, other trips may be changed or postponed if congestion levels are too high.

For example, following the 1994 Northridge earthquake, the demand for travel and resulting congestion on intact public roadways did not significantly increase. The number of factors may explain this pattern of system response. Travel demand is induced from various activities, such as working and shopping. Due to the lack of information on road capacity and condition, increased travel time and cost, people may be reluctant to travel. The benefits of travel may also become less tangible. Where the travel cost exceeds the benefit of performing a given activity, the trip may be cancelled. In addition, structural damage to buildings often reduces or relocates demand. Taking shopping malls as an example, shoppers are unlikely to visit a seismic damaged structure, leading to a fall in demand. For residential buildings, households may seek temporal shelter. Subsequent reallocation of the origin component of home-based trips, such as home-to-work, and home-to-shopping, reduces demand at the original origin.

User equilibrium traffic assignment models are currently being implemented by each of the earthquake research centers (PEER, MAE, and MCEER), to analyze pre- and post-event transportation networks. In general, pre-earthquake travel demand is run through both network scenarios, and the different outputs compared. Taking the recent REDARS validation study (MCEER forthcoming) as an example, user equilibrium assignment models were used to study variations in route choice under diverse network configurations. A recent study by the Multidisciplinary Center for Earthquake Engineering Research (MCEER, [1]) shows that applying pre-earthquake travel demands to user equilibrium network models with a post-earthquake network configuration leads to the significant overestimation of economic losses. The offset between observed and predicted costs emanates from several sources. First, the model assumes that regardless of impedances, travel demands are always computed by traversing the network from an origin to destination. Where alternative routes are not available, the model estimates an almost infinite travel cost on the disconnected (and therefore immeasurable) link. Fortunately, problems associated with network disruption are increasingly well understood and a model to take account of this problem is under development. Second, the model fails to consider the previously mentioned reduction in trip demand following a seismic event, caused by reluctance to travel, reduced benefits and the ramifications of structural damage.

The aim of this study is ‘to improve the accuracy and reliability of economic loss estimates from earthquake induced transportation system disruption’. Improvements center on integrating trip reduction into the transportation network model. Accordingly, the objectives of this study are to:

1) **Establish a method for estimating trip reductions according to earthquake induced regional building damage.**
2) **Integrate this method into a user equilibrium transportation network model.**

METHODOLOGICAL OUTLINE

Estimation of trip reduction from seismic damaged buildings will follow the conceptual framework depicted in Figure 1. The process involves: 1) identifying relationships between earthquake intensity and building damage, and 2) converting building damage (by structural type) to change in activity and travel demand. Once established this methodology will be integrated into an existing transportation network model.

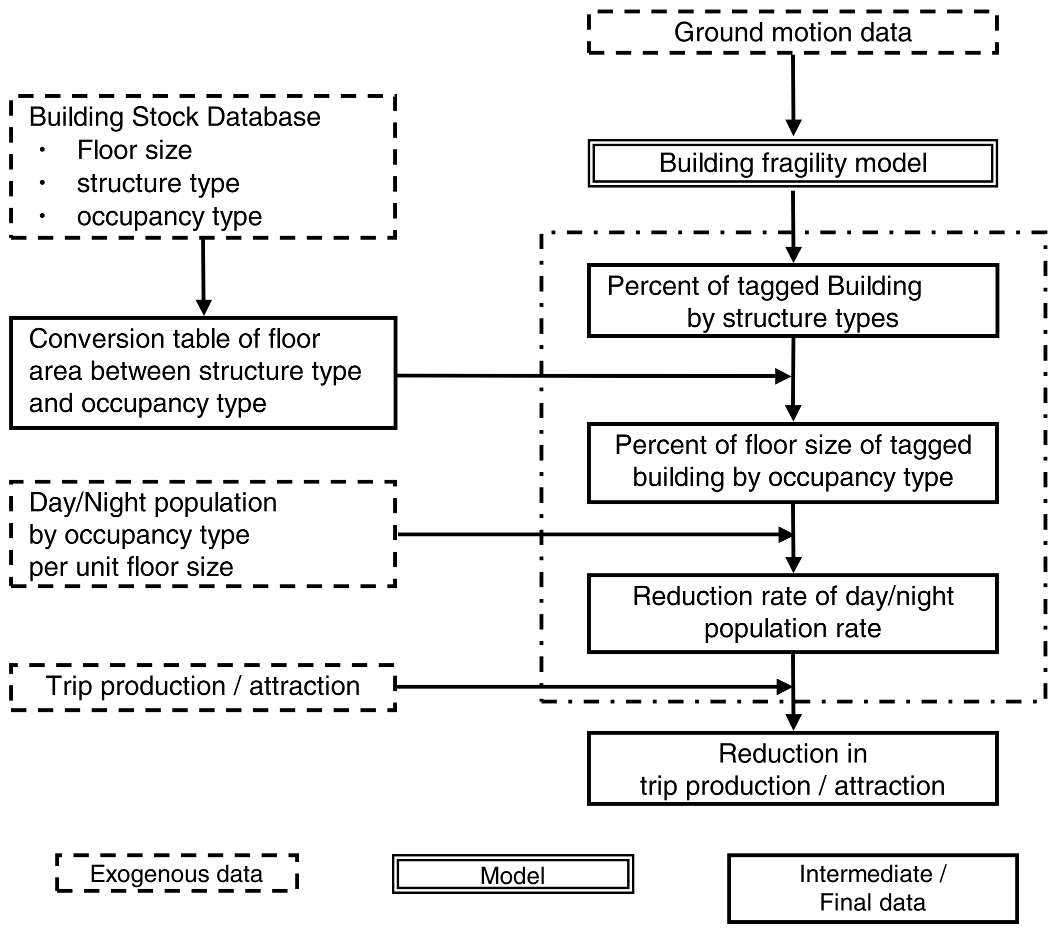


Figure 1. Framework of trip reduction estimation

Building damage due to ground shaking is estimated using fragility models. Of the various publicly available sources, the present study employs the EPEDAT (Early Post Earthquake Damage Estimation Tool) [2] fragility model. This model estimates building damage by structure type and ground motion intensity, as the percentage of floor area that can no longer be used. It was calibrated based on the 1994 Northridge earthquake, in terms of the counted yellow and red tagged buildings per unit of ground motion intensity, for different building structures such as wooden or steel frame buildings.

Estimated fragility is converted to a measure of activity system vulnerability. First, structural fragility is translated into the percent damage ratio by occupancy type (or usage). This assumes inherent consistency between building type and usage. Regional statistics on building occupancy are compiled from FEMA building stock databases released with HAZUS [3]. Although EPEDAT includes a detailed building stock database, it only covers the counties of Los Angeles, and Orange. Selecting the HAZUS database renders the model more widely applicable. This approach may limit application of the model to other locations, because structure-to-occupancy statistics are unique to each region. Furthermore, each of census tracks does not have same structure-to-occupancy ratio. However, where other regions share similar construction practices, the same average ratio may apply.

Once the distribution of fragility by ground motion intensity is associated with the building occupancy type, the damaged floor area is converted into a percent fall in daytime/nighttime population. This is achieved using the average population by occupancy type per unit floor area.

The conversion is based on the assumption that activity is proportional to floor area. However, usability of a building is arguably a stepwise rather than a continuous function. For example, a building with 5% damaged floor area would continue being used, whereas activity would cease within a structure with 60% of damage, due to safety concerns. In addition, with respect to usability, level of activity may not be linearly proportional to the percent of building damage, because, for example, 60% and 100% damage levels are not significantly different. Although this argument is valid for the usability of individual buildings, the percent reduction in usable floor size, and associated activity reduction employed here, are aggregated statistics based on zone boundaries. In a zonal context, these statistics can be presented as a continuous probability distribution for a region which consists of many zones.

The ratio of reduced day/night population to the baseline population will be used to modify trip origins from or destinations to a given zone. The reduction in trips for a given purpose will reflect occupancy levels, and the time of day. For example, the population of a residential area will be obtained from night time occupancy, while the number of daytime trips to work will be adjusted by damage to office buildings. The end product is vectors, representing the number of post earthquake trips generated from and destined to a particular zone.

Estimated trip reduction is then integrated into a transportation modeling framework. Given the post-earthquake network configuration (usually characterized with reduced capacity), and reduced travel demand (from building damage), the model produces post-earthquake traffic volumes (in passenger car unit, PCU), and estimates system-wide travel costs (hours) for economic loss estimation. The model uses an iterative process that: (1) searches for an optimal route between two zones, in terms of given travel time; (2) loads travel demand on the selected route(s) between the two zones; (3) updates congested travel time (or impedance) between zones; and (4) finds the new best route between zones based on updated travel time.

Estimated post-earthquake trip production/attraction vectors should be converted to a demand matrix to ensure compatibility with transportation network model. Travel demand is ideally presented as a 2-dimensional matrix, where a cell in the i-th row and j-th column portrays the number of travelers (or car) generated from zone i, destined for zone j. Unfortunately, the reduction model produces trip production and destination statistics in the form of vectors, since the model only considers zonal damage to buildings and associated activity reduction, without counting where the activity origin or destination. To convert the estimated vectors into an OD matrix, a distribution model, such as the Fratar [4] method or gravity model, will be incorporated. In theory, gravitational force is the interaction between two masses over in space, and is proportional to the multiplication of two masses, and inverse of square of distance. This notion may also be applied to trip interaction between zones. There will be more trips between the activity centers that are close together than demand between centers either located further apart, or with less activity.

By performing this redistribution process, travel demand generated from a given zone is assigned to its destination zones. The model repeats this process until all rows in the OD matrix are filled. The sum of destined demand to a zone in the OD matrix should be identical to the trip attraction vector that was estimated by the trip reduction model. The distance measure is then replaced by congested travel time, so that the distribution of demand is now expressed a cost.

The user equilibrium network model assigns the estimated post-earthquake travel demand, represented by the OD matrix, to the most efficient routes between zones. In a network system, there are many alternative routes to accommodate travel demand. The network model adjusts link volume and congested travel time to achieve the equilibrium condition where travel times are identical for all routes. Flow on any unused route, or route recording a lower travel time, will therefore be adjusted to reinstate the equilibrium (Wardrope' first principal for network equilibrium [5]). The total travel time spent by drivers at equilibrium represents the new system-wide travel cost, and its difference from original pre-earthquake baseline costs constitutes the seismically induced economic loss.

Travel times used in the distribution model and estimated by the equilibrium network model are unrelated. If such inconsistency in these datasets is allowed, trip production/attraction vectors and estimated OD matrix will not accurately represent estimated congestion patterns. Iteration between the distribution and network models will alleviate this discrepancy. A distribution model produces the OD matrix according to given travel impedance. This output is input to the network model. In turn, the network model results in congested zone-to-zone travel time, which can be fed back to the distribution model. Repeatedly running the models and adjusting intermediate estimations like auxiliary link volume and trip rate, will reach a converged state with respect to the travel time matrix. For a simple demand (travel demand) - supply (network capacity) system such as this, convergence of price (travel cost) leads the system stability.

Figure 2 presents the framework for an integrated trip reduction model, which iterates between network and distribution models. In this study, the gravity (distribution) model is integrated with user equilibrium network model. The user equilibrium assignment model already requires iterations (inner iteration within the network model) to adjust link volumes so the results meet equilibrium principal. Using the iterative approach, the gravity model involves the inner iteration within user equilibrium model to adjust the OD matrix. With this approach, the distribution model is blended into the network model. This approach is clearly different from sequential, independent deployment of the two models. In this latter case, the two models are waiting until the other model finishes one complete run including all inner iterations. It is beneficial inasmuch that fewer inner iterations are required to achieve consistency.

TRIP REDCTION MODEL

Building damage functions

The fragility model from EPEDAT is known that the model was calibrated for Southern California applications, based on experience from the 1994 Northridge earthquake. However, the available document does not include model parameters (such as a dispersion factor for the lognormal distribution of fragility). Therefore the fragility model was 'inferred' according to the estimation result by EPEDAT, using the 20 MCE (Maximum Credible Earthquake) events [6].

Aggregated EPEDAT results are used to estimate the percent of severely damaged (red and yellow tagged) buildings in terms of floor area. Along with referencing a document on development of the tool, EPEDAT was applied to various combinatorial conditions of building types and levels of ground motion. The application results were averaged for each of ground motion level. MMI and PGA (peak ground acceleration) are both used for ground motion measurement.

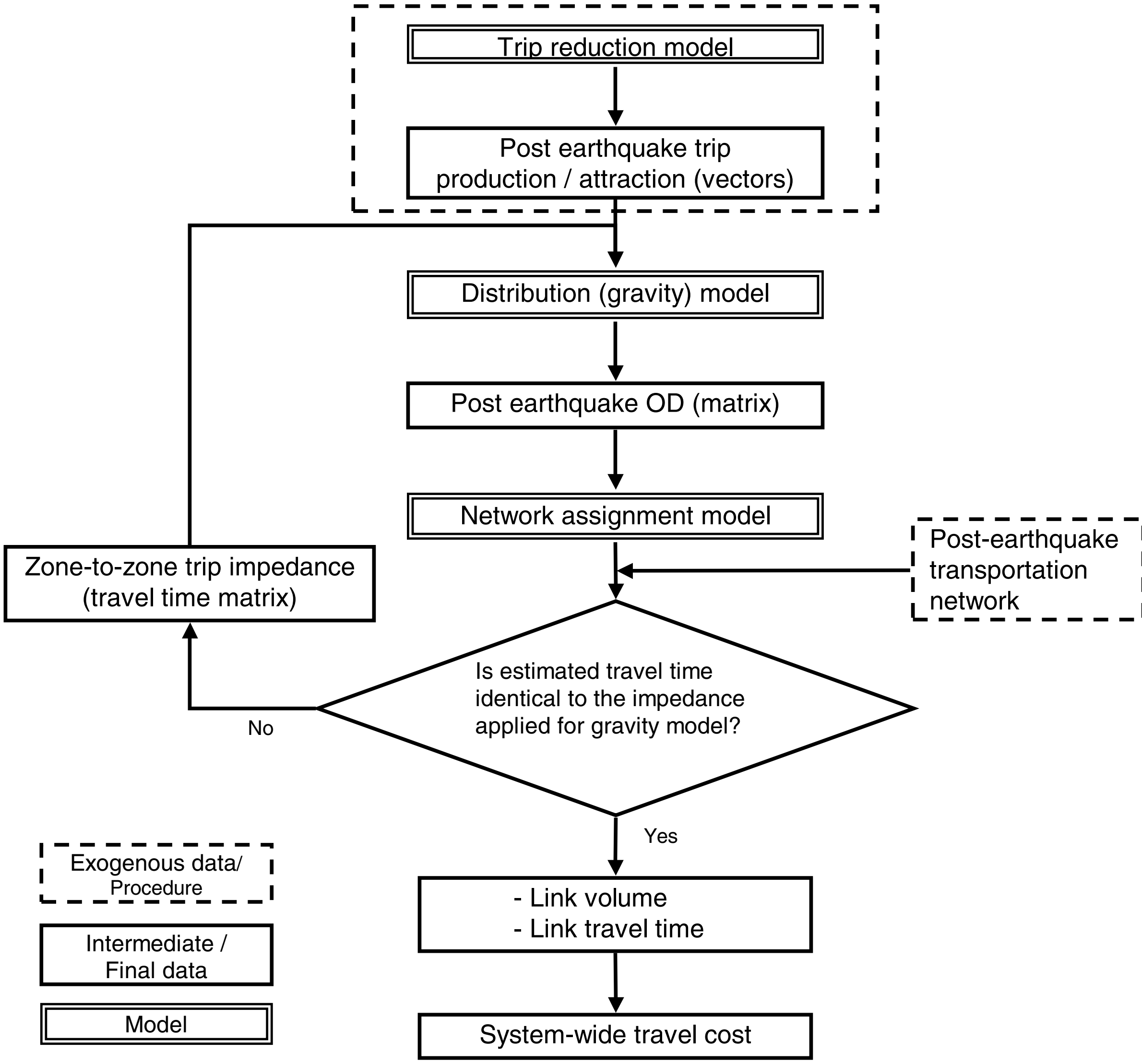


Figure 2. Integrated analysis of trip reduction and network models

Regional Building Stock

According to the HAZUS database, there are 36 specific building structure types and 28 specific building occupancy types. For Southern California (5-county area that consists of Los Angeles, Orange, Riverside, San Bernardino, and Ventura), 15 building structure types and all of the 28 building occupancy types were observed. For this study, the types of structure and occupancy were re-aggregated into 5 structure types and 4 occupancy types.

According to the database, 3.6 million buildings are used in Southern California, with a total floor area of 9.7 billion square foot. Average building size is therefore ~2,700 sq-ft. Almost 90% of buildings are constructed with a wooden structure. However, the total floor area of wooden structures is only ~70%, and the average size relatively small at ~2,000 sq-ft. Based on these statistics, fragility models of wooden buildings, especially light frame structures will dominate the overall building damage estimation. Also, according to the database of buildings in Southern California with respect to occupancy type, more than 96% of buildings, including 6% of counted mobile home, are used for residential purposes. This accounts for ~70% of the total floor area. Besides residential purpose, 2.4 % of buildings, corresponding with 18% of floor area, are used for commercial activity. Industrial buildings are less than 1% in count, but the more than 6% of floor area. Table 1 summarizes further details of the building composition, with respect to floor area. This table reveals the proportion of floor size by structure, for different building occupancies. For example, the 72.7% of floor size used for residential purposes, 64.1% of building floor area is constructed in wooden structure. A minor proportion goes to other structural types, including mobile homes.

Table 1. Summary of Southern California Buildings by Structure and Occupancy Type

(a) Floor Area (1,000 sq-ft)

		Structure Type					
		Wood	Steel	Concrete	Precast	ML & ETC	Sum
Occupancy Type	Residential	6,237,975	125,307	197,649	19,739	491,782	7,072,453
	Commercial	409,541	229,781	292,757	377,155	461,438	1,770,671
	Industrial	60,254	246,985	68,118	188,661	93,728	657,746
	ETC	49,289	56,705	48,178	12,639	62,999	229,810
	Sum	6,757,060	658,777	606,702	598,194	1,109,946	9,730,680

(b) Percent of Floor Area

		Structure Type					
		Wood	Steel	Concrete	Precast	ML & ETC	Sum
Occupancy Type	Residential	64.1	1.3	2.0	0.2	5.1	72.7
	Commercial	4.2	2.4	3.0	3.9	4.7	18.2
	Industrial	0.6	2.5	0.7	1.9	1.0	6.8
	ETC	0.5	0.6	0.5	0.1	0.6	2.4
	Sum	69.4	6.8	6.2	6.1	11.4	100.0

Building composition is assumed to be unique and identical throughout the region. As such, any transportation analysis zone is assumed to have a consistent composition, which can bye represented by a set of fragility curves and their associated "vulnerabilities". However, this composition should be used with caution, because characteristics of buildings might not be transferable to other regions.

The composition of structure type in Table 1(b) is applied as a weight to convert the fragility, which is given by structural type in HAZUS classification, into the "vulnerability" of building occupancy. Table 2 shows detailed vulnerability of building occupancy from ground motion. According to the table, with the exception of mobile homes, buildings used for residential purposes have a lower chance of being damaged by earthquake events. Commercial and industrial buildings have almost identical probability distribution of building damage. The maximum proportion of floor damage from extremely high ground motion is ~ 26% of the total square footage within a transportation analysis zone.

Activity Population

The meaning of percentage of physical damage needs to be converted to a tangible reduction in 'activity', since estimates of trip reduction are activity based. HAZUS building database is utilized to assume the average population per unit floor area for each building occupancy types. The total activity population may not be identical to the up-to-date statistics. However, this study applies activity population to adjust vulnerability of activity based on assumptions that: 1) the change of relative activity population between occupancy would be minor; and 2) average occupancy rate per unit floor area is applicable throughout the region.

Trip Reduction Rate

By incorporating the activity population by building occupancy types, the unit of structural vulnerability of buildings in Table 2 (although it is sorted by occupancy type, the percentage still represents damage to building) is converted to the percent of people no longer doing a particular activity. The resulting table is not shown here, because weighting occupancy rate to the vulnerability is only effective when the percent of damage is aggregated to certain category, rather than to the detailed HAZUS classification.

Table 2. Vulnerability of building occupancy

HAZUS Classification			Fragility (to total area of red and yellow tagged building)				
Code		Description	PGA=0.13 (m/s^2) MMI6	PGA=0.27 (m/s^2) MMI7	PGA=0.52 (m/s^2) MMI8	PGA=0.93 (m/s^2) MMI9	PGA=1.55 (m/s^2) MMI10
Residential	RES1	Single Family Dwelling	0.0301	0.2504	0.7386	5.2650	13.1020
	RES2	Mobile Home	0.0450	0.3000	0.6200	7.9000	28.7000
	RES3	Multi Family Dwelling	0.0349	0.2796	0.7699	5.9455	16.1425
	RES4	Temporary Lodging	0.0371	0.2953	0.7485	6.2690	18.5565
	RES5	Institutional Dormitory	0.0340	0.2772	0.6898	5.9762	18.4497
	RES6	Nursing Home	0.0346	0.2668	0.7209	6.1236	17.5700
	Mean		0.0320	0.2608	0.7420	5.5563	14.5891
Commercial	COM1	Retail Trade	0.0458	0.3338	0.8067	8.0210	25.2280
	COM2	Wholesale Trade	0.0502	0.3257	0.8072	9.3042	30.0079
	COM3	Personal and Repair Service	0.0495	0.3407	0.8175	8.7008	27.9671
	COM4	Professional / Technical Service	0.0441	0.3297	0.8263	7.6375	23.4262
	COM5	Banks	0.0441	0.3297	0.8263	7.6375	23.4262
	COM6	Hospital	0.0389	0.3049	0.7631	6.8778	20.9752
	COM7	Medical Office / Clinic	0.0409	0.3338	0.8178	6.8260	20.0405
	COM8	Entertainment & Recreation	0.0447	0.3595	0.7222	7.1615	23.8420
	COM9	Theaters	0.0425	0.3630	0.6762	6.6517	22.3622
	COM10	Parking	-	-	-	-	-
	Mean		0.0462	0.3322	0.8088	8.1345	25.6252
Industrial	IND1	Heavy Industries	0.0416	0.3527	0.6853	6.8173	22.4134
	IND2	Light Industries	0.0481	0.3330	0.7487	8.7633	28.6675
	IND3	Food / Drugs / Chemicals	0.0476	0.3420	0.7433	8.4187	27.7017
	IND4	Metals / Minerals Processing	0.0420	0.3489	0.6686	6.9605	23.2781
	IND5	High Technology	0.0450	0.3047	0.6967	8.4985	28.0725
	IND6	Construction	0.0460	0.3413	0.8022	7.9772	24.9313
	Mean		0.0453	0.3419	0.7309	7.8860	25.7017
Etc	AGR1	Agriculture	0.0415	0.3287	0.7383	6.8694	21.1481
	REL1	Church / Non-Profit	0.0406	0.3223	0.7361	6.8051	21.7071
	GOV1	General Services	0.0404	0.3282	0.7163	6.8071	22.4014
	GOV2	Emergency Response	0.0385	0.3060	0.7864	6.6076	19.0999
	EDU1	Grade Schools	0.0358	0.2918	0.6564	6.1827	19.7773
	EDU2	Colleges / Universities	0.0377	0.3020	0.6323	6.4547	21.6028
	Mean		0.0390	0.3130	0.7021	6.5991	21.1246

The percentage of reduced activity population by occupancy types, can be directly interpreted as reduction rate of trips destined to, or originating from the buildings. This assumes that there is no significant change of occupancy rate after the earthquake hits a region. It is true that people may not want to stay in an individual building, regardless of the damage severity. However, from a regional perspective, the measurement of usability, or willingness to use the building can be described with a probability distribution. Therefore, a certain portion of people still travel to the sub regions where buildings are damaged.

Reduction rates are associated with trip purpose, which in turn have important distinguishing characteristics. For example, the decision making for mandatory trips such as a working trip would be less sensitive even after earthquake. Thus, unless the office building is collapsed, employers and employees would continue to make the trip. However, the same analogy is not applicable to optional shopping trips. In this study, personal trips (travel made by people) are stratified into five purposes: Home-to-Work; Home-to-School; Home-to-Other; Work-to-Other; and Other-to-Other.

Occupancy type of a building, as the origin side of a trip, is different to the usage of a destination building. As an obvious example, a home-to-work trip starts from a residential building and terminates at a building constituting the work place. Therefore, to convert the reduction of activity to trip reduction, building occupancy types need to be associated with the origin/destination of trip purposes. Table 3 depicts the association between building occupancy types and trip purposes. This table was developed based on the assumption that most home-based trips will generate from residential buildings, while majority of commercial / industrial buildings will be destination or origin of work-related trips.

Table 3. Trip Types and Building Occupancy Types

HAZUS Code	Trip Purpose									
	Home-Work		Home-School		Home-Other		Work-Other		Other-Other	
	Origin	Destin	Origin	Destin	Origin	Destin	Origin	Destin	Origin	Destin
RES1	X		X		X					
RES2	X		X		X					
RES3	X		X		X					
RES4									X	X
RES5									X	X
RES6		X				X		X	X	X
COM1		X				X	X	X	X	X
COM2		X				X	X	X	X	X
COM3		X				X	X	X	X	X
COM4		X					X			
COM5		X				X	X	X	X	X
COM6		X				X	X	X	X	X
COM7		X				X	X	X	X	X
COM8						X		X	X	X
COM9						X		X	X	X
COM10						X		X	X	X
IND1		X					X			
IND2		X					X			
IND3		X					X			
IND4		X					X			
IND5		X					X			
IND6		X					X			
AGR1		X					X			
REL1						X		X	X	X
GOV1		X					X			
GOV2									X	X
EDU1				X						
EDU2										

Vulnerability of building occupancy in Table2 is weighted by activity population, and aggregated into each of trip purposes according to the associations in Table 3. The result can be interpreted as the reduction rate of trips due to building damage from ground shaking. Table 4 shows the reduction rate for trips over MMI and PGA scale.

There is no guarantee that the adjusted number of originated and destined trips will be identical to each other after applying the reduction rate. In fact, to be used with network model, the sum of origin, and destination trips should be same. It is because the OD matrix represents travel demand, which is not volatile, and conservation rule is in effect -e.g. all generated trips should be destined. However, the reduction method applies different rates to trip origin and destination, and no OD matrix can be constructed from vectors where sums are inconsistent. To avoid this problem, reduced trip production (origin), and attraction (destination) vectors are compared, and the sum is readjusted to the least sum.

Table 4. Person Trip Reduction Rates

Trip purposes		Level of ground motion				
		MMI6	MMI7	MMI8	MMI9	MMI10
		PGA=0.13 (m/s^2)	PGA=0.27 (m/s^2)	PGA=0.52 (m/s^2)	PGA=0.93 (m/s^2)	PGA=1.55 (m/s^2)
Home-Work	Origin	0.032	0.260	0.743	5.537	14.441
	Destination	0.045	0.334	0.794	7.911	24.938
Home-Schl	Origin	0.032	0.260	0.743	5.537	14.441
	Destination	0.036	0.294	0.651	6.243	20.185
Home-Other	Origin	0.032	0.260	0.743	5.537	14.441
	Destination	0.043	0.329	0.769	7.422	23.548
Work-Other	Origin	0.045	0.334	0.794	7.911	24.938
	Destination	0.043	0.329	0.769	7.422	23.548
Other-Other	Origin	0.043	0.326	0.765	7.339	23.246
	Destination	0.043	0.326	0.765	7.339	23.246

INTEGRATING REDUCTION AND NETWORK MODELS BY USING A DISTRIBUTION MODEL

In this section, the passenger trip reduction models, developed in previous section, are incorporated into an integrated model for post-earthquake transportation system. The reduction models adjust pre-earthquake trip production and attraction according to building damage. A distribution model generates an OD matrix for post-earthquake travel demand based on adjusted trip production and attraction, and travel cost. A network assignment model then loads the travel demand in an OD matrix onto the seismically damaged network, and estimates post-earthquake traffic volume and congested travel time.

The distribution model will make a connection between the reduction model and assignment model. Production/attraction vectors are a type of disaggregated measurement for travel demand. The vectors explain "how many people depart from a zone", or "how many cars enter a zone". With respect to the network model, these two vectors should be combined to generate information about "how many cars depart from zone a to travel to zone b". In other words, travel demand information needs to be disaggregated into associated origin and destination zones. Distribution models estimate travel demand in a matrix form in which rows represent origin zones, and columns destination. In this study, a doubly-constrained gravity model is applied, distributing post-earthquake travel demand based on two criteria:

- Travel demand between an origin-destination pair is proportional to the trips emanating from the origin zone and trips attracted to the destination zone. Estimated post-earthquake trip production – attraction vectors by reduction model, will be used according to this criterion.
- The lesser the travel time (cost) between a zone-pair, the more demand is allocated. This criterion is included in the model by means of a distance-decay function.

Integrating the three component models – reduction, distribution, and network models – involves arranging them in such a way that it yields stable solutions. With endogenous travel demand estimation, the integrated model is expected to generate post-earthquake traffic volume and congested time. As mentioned above, travel demand will be distributed over the zones according to the travel time, while congested travel time is calculated along with the travel time. This means that travel time is generated from the network model and used by gravity model, while OD matrix is generated by the gravity model using travel time. Thus, in the integrated model, trip distribution and network models should be deployed so that the intermediate input and output are consistent.

Gravity Model as the Demand Model

The gravity model is a trip distribution model that estimates trip interchanges between zone i and j, t_{ij}, based on aggregated trip production and attraction from/to each zone. Equation (1) presents the gravity model. The equation shows that, according to the first criterion, travel demand is proportional to the production (O_i) and attraction (D_j). The conservation rule is applied to distributed travel demand, and the sum of the travel demand generated from a zone i over the all of its destination j, where $\sum_j t_{ij}$, should be equal to the O_i. Destined demand to a zone should also be equal to the sum of demand over the origin zones. Application of the conservation rule over the distribution process implies that the distribution model would not alter the (reduced) post-earthquake demand by the reduction model.

$$t_{ij} = O_i \cdot D_j \cdot f(c_{ij}) \quad (1)$$

where t_{ij} : travel demand between zone i and zone j

c_{ij} : travel time between zone i and zone j

$f(c_{ij})$: distance decay function, $f(c_{ij}) = \exp(\alpha + \beta \cdot c_{ij})$

O_i : trip production from origin zone i, $O_i = \sum_j t_{ij}, \forall i, j$

D_j : trip attraction to destination zone j. $D_j = \sum_i t_{ij}, \forall i, j$

α, β : model parameters to be estimated.

Zones are discriminated by the travel time (more generally, cost) from an origin. Demand from the origin zone is distributed according to difficulty in traversing the network to the destination zone. Where a destination zone is closer to the origin, the difficulty associated with traveling between the origin and destination is low. Consequently, more demand would be allocated onto this zone-pair. Demand is thereby distributed according to the difficulty of travel. In the gravity model, a function, $f(c_{ij})$ termed the 'distance decay function', is used to explain this mechanism. In this study, exponential function with a negative coefficient to travel time ($\beta < 0$) is used to represent decreasing rate travel demand over increasing travel time.

Calibration of the Demand Model

The 1996 SCAG [7] transportation data set, which comprises 3,217 traffic analysis zones (TAZ), was used to calibrate the distance decay function. Travel demands are stratified by five purposes of passenger trips (Home-to-Work, Home-to-School, Home-to-Other, Work-to-Other, and Other-to-Other). Table 5 shows calibrated coefficients α, β, and R^2. The exponential function with travel time is able to explain the distance decay of home-based trips (to-work, to-trips, and to-other) with R^2 higher than 0.9. The R^2 for work-related trips and others were no lower than 0.85.

Table 5. Calibration of Decay Function Parameter

Trip Purpose	Time of Day*	α	β	R^2
Home to Work	AM	3.151973	-0.06616	0.9903
	PM	3.170573	-0.06693	0.9917
	MD	3.469839	-0.10274	0.9822
	NT	3.539828	-0.13011	0.9771
Home to School	AM	4.288389	-0.12286	0.9311
	PM	4.544710	-0.14933	0.9513
	MD	5.568479	-0.27000	0.9775
	NT	5.856893	-0.33459	0.9853
Home to Other	AM	3.607120	-0.08362	0.9121
	PM	4.279050	-0.12497	0.9034
	MD	4.564984	-0.17333	0.9004
	NT	4.966864	-0.23647	0.9211
Work to Other	AM	4.580842	-0.14985	0.9547
	PM	3.620443	-0.08406	0.9143
	MD	3.970968	-0.12998	0.8586
	NT	4.446589	-0.18854	0.8999
Other to Other	AM	4.186721	-0.11903	0.9017
	PM	4.322647	-0.12511	0.9324
	MD	4.545936	-0.16752	0.9358
	NT	4.846849	-0.22063	0.9520

*AM: Morning Peak; PM: Evening Peak; MD: Mid-day; NT: Night

APPLICATION FOR LOS ANGELES NETWORK

In this section, the trip reduction rate and gravity model as the demand model, developed in previous sections, are applied to the freeway and state highway network in Los Angeles and Orange County shown in Figure 3. The network model consists of 148 nodes and 231 links. The evaluation model for the seismic performance of transportation system follows Shinozuka et al. (2003, [8]), which developed empirical fragility curves and evaluation methodology of comprehensive seismic performance of transportation systems. The Fragility curves, developed as a function of the ground motion intensity such as PGA, are utilized to generate, in Monte Carlo simulation, the state of damage for each bridge in Los Angeles and Orange County under postulated scenario earthquakes, and hence, the following analysis applies only to the bridge prior to the post-Northridge retrofit. The reader is referred to Shinozuka et al. (2003) for the detail of evaluation methodology.

As a case study, Malibu Coast (M7.3, MCE (Maximum Credible Earthquake), [6]) is selected for the scenario earthquake. EPEDAT is utilized to estimate PGA distribution for the selected scenario earthquake. Figure 3 shows PGA distribution and the average damage states of bridges simulated under the Malibu Coast scenario earthquake.

The origin-destination (OD) data used in this case study consists of the 1996 southern California origin-destination survey results for 3,217 traffic analysis zones. This large matrix is reduced to a manageable size following Shiraki (2000, [9]) in this study. The method relies upon the Thiessen function (an ArcGIS software [10]) where the number of OD locations are reduced to the number of nodes of the freeway network, each representing OD information within the Thiessen polygon developed around the node. The person trip reduction rates (Table 4) are applied to make a post-earthquake OD matrix. Figure 4 displays the number of trip reduction for the both of origination and destination.

To perform the traffic equilibrium analysis numerically, the method of user optimizing deterministic is used with the aid of the incremental assignment technique. For the sake of convenience, we used fixed demand model for the network analysis in this case study. Figure 5 shows the result of V/C ratio (loaded Volume/Capacity ratio) of each links for pre- and post-earthquake. For network model under the post-earthquake, the load capacity and free flow speed of each links are changed depending on bridge damage states (see Shinozuka et al. (2003) for the detail). After the earthquake, there are a lot of links with the V/C ratio higher than 300%, but some links has a lower V/C ratio than the pre-earthquake.

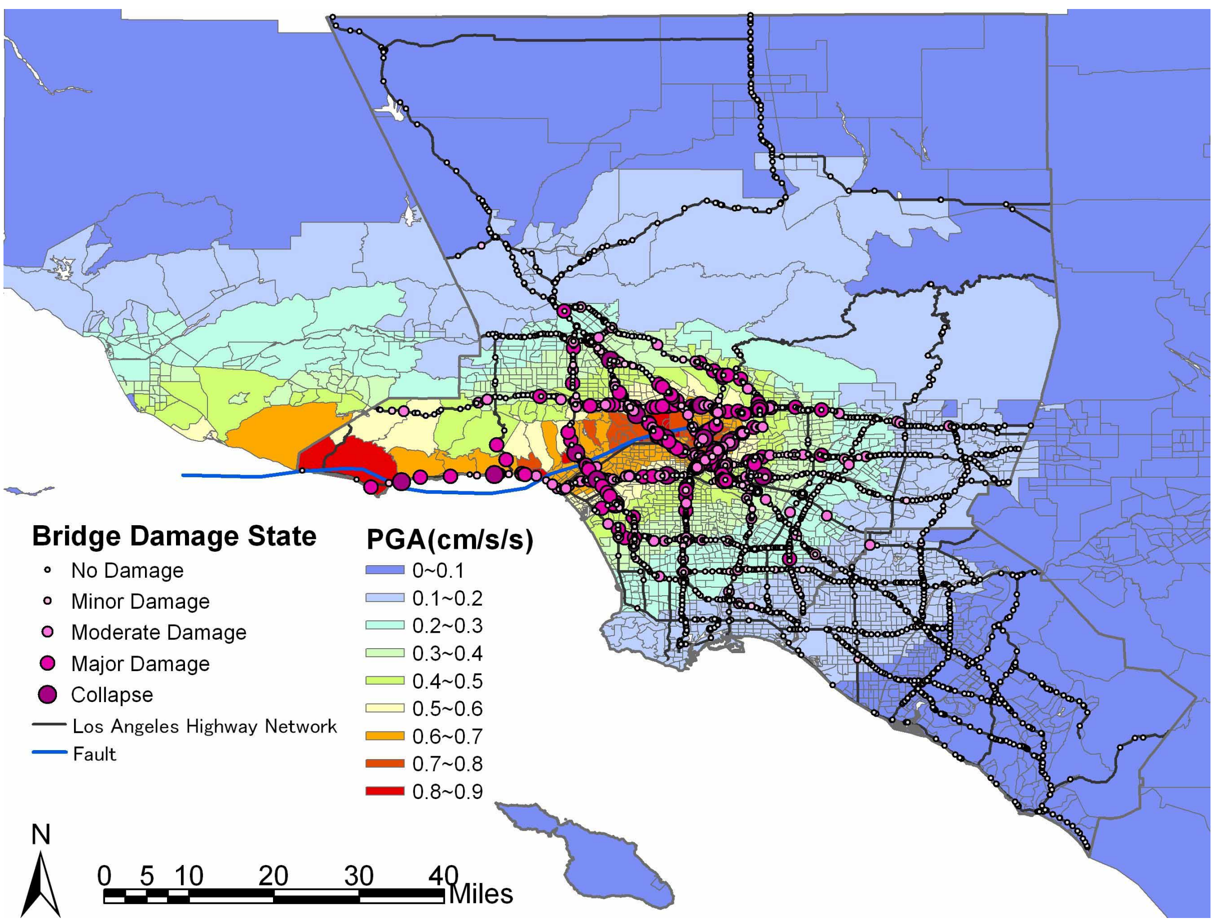
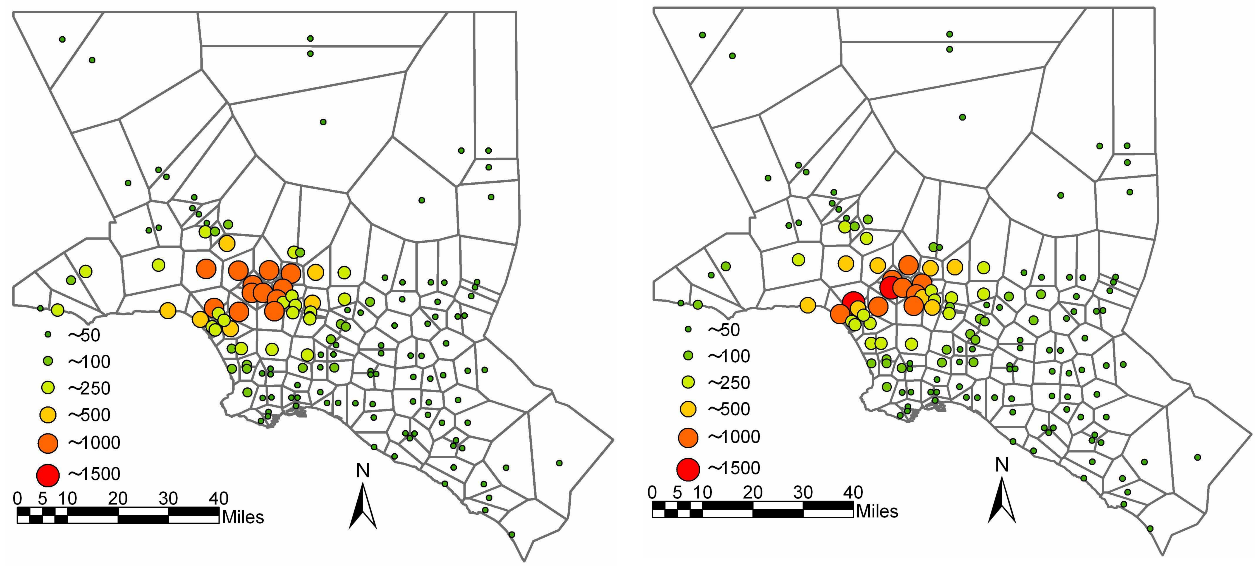
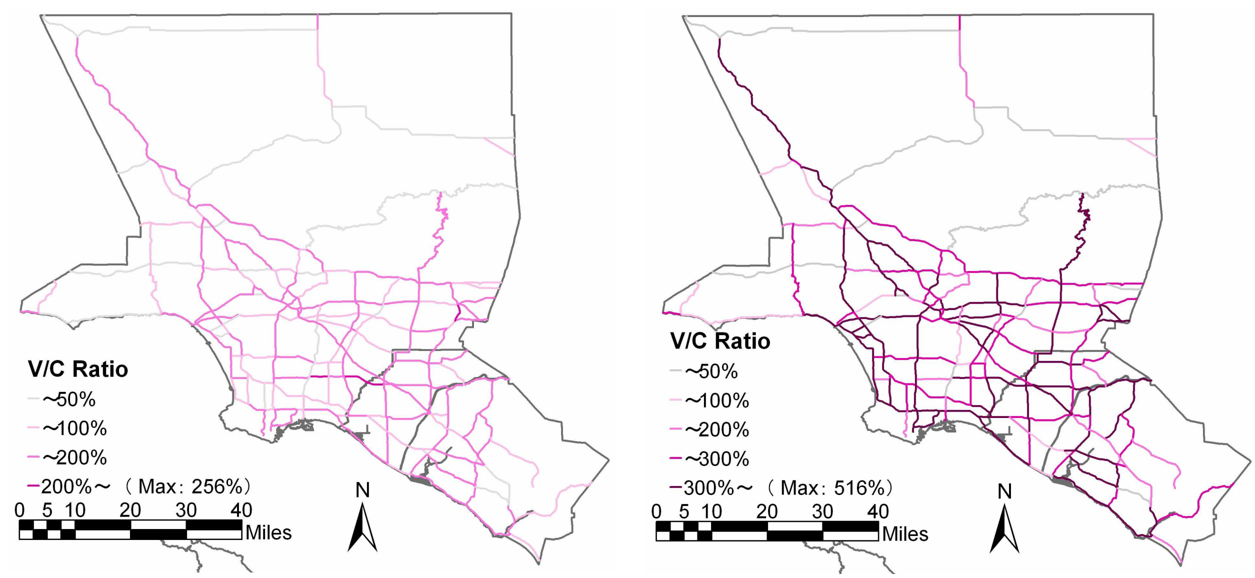


Figure 3. PGA Distribution of Malibu Coast Scenario Earthquake, Average Damage States of Bridges



(a) Origination Trip Reductions **(b) Destination Trip Reductions**

Figure 4. Trip Reduction due to Seismic Damage (PCU/3 hours) (PCU: Passenger Car Unit)



(a) Pre-Earthquake **(b) Post-Earthquake (Malibu Coast, M7.3)**

Figure 5. Loaded Volume/Capacity Ratio (V/C) for Each Links

CONCLUSIONS

This study developed the person trip reduction rate for each trip purposes over the level of ground motion intensity scale such as MMI or PGA. Integrating reduction and network model by using a distribution model, gravity model as the demand model is calibrated, and distance decay function are developed. Those person trip reduction rate and distance decay function are applied to the freeway and state highway network in Los Angeles and Orange County, and the simulation results shows that the travel pattern and the aspect of the congestion will significantly change immediately after an earthquake.

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