1927/7/A

SIMULATION AND EVALUATION OF POST-EARTHQUAKE FUNCTIONAL PERFORMANCE OF TRANSPORTATION NETWORK

Nobuoto NOJIMA and Masata SUGITO[1]

SUMMARY

A simple model has been proposed to simulate and evaluate post-earthquake functional performance of a highway transportation network system. The model combines the Monte Carlo simulation method and the modified incremental assignment method (MIAM); the former generates damage states of the transportation network, and the latter simulates traffic behavior in each damage state, producing a set of link flows. On this basis, various performance measures for links, O-D pairs, centroids, cross sections and the total network have been defined to evaluate aggregate and non-aggregate conditions of the network function. Proposed measures reflect mixed effects attributed to decrease in O-D trips due to facility damage and overload, increase in trip length due to detouring actions, and increase in travel time due to detouring and congestion, etc.

1. INTRODUCTION

Highway network system plays a vital role in post-earthquake emergency, recovery, and reconstruction stage, as well as in a normal situation. In recent earthquake disasters, especially in urban region, traffic capability was significantly reduced due to physical damage to transportation facilities and a high demand of emergency traffic, resulting in degradation of urban activities and failure in post-earthquake emergency effort. Being unlike physical flows of utility lifelines such as water and gas delivery systems, post-earthquake performance of highway system is very complex, because it depends not only on degraded capacity of links, but also on various factors such as O-D (origin - destination) requirement, travel time, and trip length. Therefore, earthquake disaster prevention, mitigation and management plans for a highway transportation system require better understanding of traffic behavior in seismic environment. However, the well-known framework of the classic four-stage transport model [Ortúzar et al., 1990] is hardly used for the performance evaluation of transportation networks exposed to seismic risks because of high uncertainty in earthquake disaster and data unavailability; appropriate methodology has not yet been developed to evaluate functional performance of a highway network system subject to intensive and simultaneous occurrence of components failure. As a result, assessment of post-earthquake functional performance of transportation network remains quite a difficult problem in spite of its great importance.

Werner et al. [1997] proposed a method for scenario-based loss estimation due to seismic risks to highway systems. Chang and Nojima [1997, 1998] and Nojima [1999] developed flow-independent measures to evaluate post-earthquake performance of highway transportation network systems. To extend the state-of-the-art, the objective of this study is to propose a flow-dependent performance evaluation method which is applicable to a post-earthquake situation. The method proposed herein is based on a three-step algorithm which includes procedures (1) to generate a large number of damage patterns using the Monte Carlo simulation method, (2) to load the network with O-D trips using the incremental assignment method modified to be suitable for a post-disaster situation (MIAM), and (3) to evaluate the network performance in terms of traffic volumes, trip length, and travel time at various levels of the network. Average values, distributions and correlation of those performance measures provide a wide scope of traffic behavior under seismic risks.

[1] *Department of Civil Engineering, Gifu University, Japan, Email : nojima@cive.gifu-u.ac.jp , sugito@cive.gifu-u.ac.jp*

2. FRAMEWORK OF THE SIMULATION AND EVALUATION MODEL

Figure 1 illustrates the overall concept of the simulation and evaluation model proposed for post-earthquake functional performance of a transportation network.

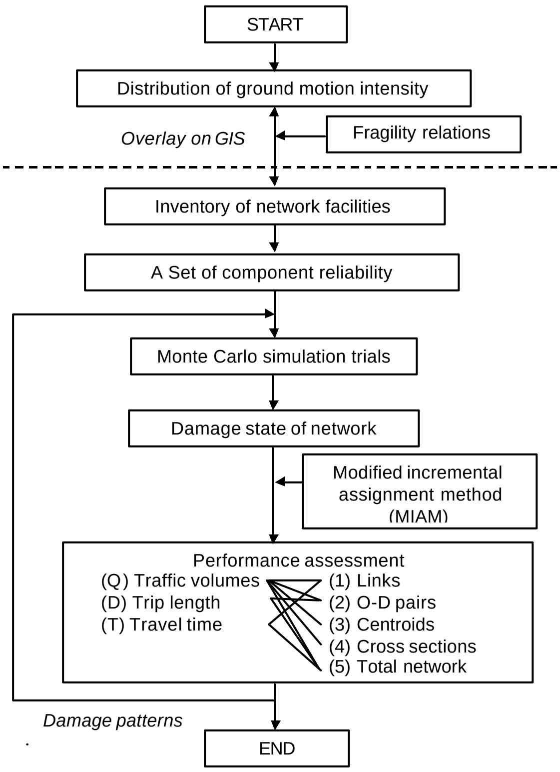


Figure 1: Framework of the simulation and evaluation model.

2.1 Generation of a Set of Component Reliability:

First, an earthquake motion prediction model EMPR [Sugito et al., 2000] is used to obtain a map of spatial distribution of ground motion in terms of various types of intensity measures such as PGA, PGV, SI, etc. for a given scenario earthquake.

Development of fragility relations representing the relationship between seismic intensity and physical performance of structural components is particularly essential for the whole procedure. To incorporate the effect of various sources of uncertainty, fragility relations inherently take the form of probability-based description. Damage of highway structures of Hanshin Expressway in the 1995 Hyogo-ken Nanbu Earthquake, Japan, is investigated to compile a database of physical damage of highway structures and relevant ground motion. Statistical analysis is then employed to derive a family of fragility relations that provide probability of occurrence of arbitrary levels of damage corresponding to arbitrary levels of ground motion intensity. This part is under development, and its up-to-date result is to be presented in the independent paper [Tanaka et al., 2000].

The first two stages mentioned above exogenously provides the input data for the simulation and evaluation model proposed herein. The inventory of the highway network system is overlaid upon the seismic intensity map on GIS. By combining these two with fragility relations, a set of reliability of network components is obtained for the scenario earthquake under consideration. Since this paper aims to formulate and demonstrate the model itself, great emphasis is placed on the subsequent procedure denoted by the area below the dashed line in Figure 1. In the following subsections, the remaining parts are described. A case study using the whole procedure has been published by Nojima et al. [1999].

2.2 Generation of Random Damage Patterns:

Let binary state variables $\mathbf{x} = \{x_1, x_2, ... , x_n\}$ denote the state of survival (1) and failure (0) of links, where n represents the number of links. A set of reliability index $\mathbf{p} = \{p_1, p_2, ... , p_n\} = \{E[x_k]\}$ (k = 1, 2, ... n) defined as expected values of x_k is evaluated for each link as follows. Assuming random and independent occurrence of damage to links, link reliability is computed as $p_k = e^{-l_k d_k}$, where l_k denotes damage rate representing expected number of failures per unit length, and d_k denotes the link length. Because the actual damage state is inevitably unknown before the occurrence of earthquake disaster, a large number of random damage patterns are generated according to the set of component reliability using the Monte Carlo simulation method.

2.3 Traffic Assignment on Damaged Network:

A modified incremental assignment method (MIAM) is developed to load a damaged network with O-D trips. For simplicity, at the initial step of the assignment procedure, it is assumed that O-D trip matrix does not change even after the earthquake. This assumption may not be appropriate in emergency stage immediately after the earthquake, but significantly simplifies the evaluation process; eventually, the resultant O-D trip matrix turns out to be different from the assumed one, because some part of O-D trips may not be satisfied due to physical isolation of centroids, overload and/or congestion thereby. The algorithm MIAM is described in Table 1.

Since the conventional incremental assignment method [Ortúzar et al., 1990] presumes that all trips are assigned to the network, the original algorithm lacks Step 3 and Step 6. In order to evaluate the maximum network capacity, Iida [1972] added Step 3 and Step 6 to the original algorithm, whereas the termination rule was "if at least one $\Delta b_{ij} = 0$." Iida's algorithm terminates when there appears at least one O-D pair without available route so that trips are satisfied without experiencing any congestion. In disaster situation, however, this algorithm substantially underestimate O-D trips satisfied among the network, because of its strict termination rule. For example, once a centroid is physically isolated, the network carries no flow at all. To solve this problem, in this study, further modification has been made to Step 3; as underlined in the algorithm below, the rule "if at least one" is replaced by "if all." The modified algorithm is designed to terminate when all O-D pairs lose available route or when O-D trip matrix has been completely loaded, while no flow is loaded to links which have reached their capacity. Although the resultant O-D pattern, as well as O-D trips, fail to remain the same as the initially assumed one, it is considered that the difference represents an inherent change of post-disaster O-D pattern.

2.4 Performance Measures of Transportation Network Function:

Notations for input and output data of the simulation and evaluation model are summarized in Table 2. The basic conditions of network flows are defined using the result of link flows h_k and link travel time t_k at the final stage of the incremental assignment procedure. By aggregating these values, various performance measures are calculated at several levels: links, O-D pairs, centroids, cross sections, and the total network. Since these aggregate/non-aggregate performance measures are obtained for each individual damage pattern generated using the Monte Carlo simulation method, average values, distributions and correlation of performance measures can be investigated. This enables one to have a wide view of the traffic behavior in seismic environment under high uncertainty.

Table 1: Algorithm MIAM (Modified Incremental Assignment Method).

Step 1 : Divide the total O-D trip matrix $\mathbf{B}(b_{ij})$ into L fractional matrix $\Delta\mathbf{B} = \mathbf{B}(b_{ij})/L$; select an initial set of free-flow link travel times t_k^0; initialize all flows $h_k^0 = 0$; set $\ell = 0$.

Step 2 : Build the set of shortest distance trees (one for each origin) using the current link travel times; set $\ell = \ell + 1$.

Step 3 : If no available route is found for O-D ij, set $\Delta b_{ij} = 0$; if all $\Delta b_{ij} = 0$, proceed to Step 8.

Step 4 : Load $\Delta\mathbf{B}$ all-or-nothing to the shortest distance trees, obtaining a set of auxiliary flows F_k; accumulate flows on each link : $h_k^\ell = h_k^{\ell-1} + F_k$.

Step 5 : Calculate a new set of current link travel time t_k^ℓ based on the flows h_k^ℓ.

Step 6 : If the flow reaches the link capacity C_k, set $t_k^\ell = \infty$.

Step 7 : If $\ell = L$, proceed to Step 8; otherwise proceed to Step 2.

Step 8 : Terminate the incremental assignment; calculate performance measures.

Table 2: Input and Output Data of the Simulation and Evaluation Model.

Input data		Output data	
subscript for link :	k	[Q-1] link flow assigned to link k :	h_k
subscript for node :	i, j	[T-1] link travel time :	t_k
link flow capacity :	C_k	[Q-2] trips satisfied between O-D pair ij:	q_{ij}
link distance :	d_k	[D-2] trip length between O-D pair ij :	d_{ij}
link damage rate :	λ_k	[Q-3] trips satisfied at centroid C_i :	$Q_i^C = \sum_j (q_{ij} + q_{ji})$
link reliability :	$p_k = e^{-\lambda_k d_k}$	[Q-4] traffic volumes at cross section S_m :	$Q_m^S = \sum_{k \in S_m} h_k$
initial O-D trip matrix :	$B(b_{ij})$	[Q-5] total satisfied O-D trips :	$Q = \sum_i \sum_j q_{ij}$
time-flow relationship :	$t_k(h_k, C_k, \alpha, \beta)$	[D-5] total O-D trip length :	$D = \sum_k h_k d_k$
shape parameters :	α, β	[T-5] total O-D travel time :	$T = \sum_k h_k t_k$

Note: The symbol [M-#] for output data represents "measure M for system range # in Figure 1."

3. NETWORK MODEL AND ASSUMPTIONS FOR A CASE STUDY

A case study was conducted for the highway network which suffered severe damage in the 1995 Hanshin-Awaji earthquake disaster, Japan. The network was modeled as 100 links and 30 nodes including 8 centroids (Figure 2). The network includes Hanshin Expressways Route 3, 5 and 7, Meishin Expressway, Daini-Shinmei Line, National Route 2 and 43, and other major roads; total link length is 492.6km. Peak-hour vehicle O-D matrix was estimated on the basis of daily O-D matrix provided by Hanshin Expressway and actual traffic counts data observed at several cross sections. Time-flow relationship was modeled using BPR function

$$t_k(h_k, C_k, \alpha, \beta) = t_k(0)\left\{1 + \alpha\left(\frac{h_k}{C_k}\right)^{\beta}\right\} \tag{1}$$

with the parameter $\alpha = 0.96$ and $\beta = 1.2$, after several sets of parameters were examined. Pre-quake values of performance measures are : Q = 33,200 (vehicles/hr), D = 803,389 (vehicles*km) and T = 24,637 (vehicles*hr).

As mentioned in the previous section, the damage rate should be determined on the basis of fragility-seismic intensity relationship. However, in this paper, uniform damage rate is assumed for easiness of interpretation of the results. In order to cover various states as wide as possible, 10 kinds of different damage rate λ = 0.005 to 0.4 is uniformly assigned to all links. Corresponding number of average damage occurrence is 2.4 to 197 in the entire network. Monte Carlo simulation trials have been carried out 500 times for each damage rate to include a chance variation inherent in seismic event. Each trial run generates one damage pattern of the network to which O-D matrix is loaded, and traffic behavior is investigated in terms of network flow as a result of traffic assignment. Since 10 kinds of damage rate are considered, totally 5,000 samples of damaged network have been generated.

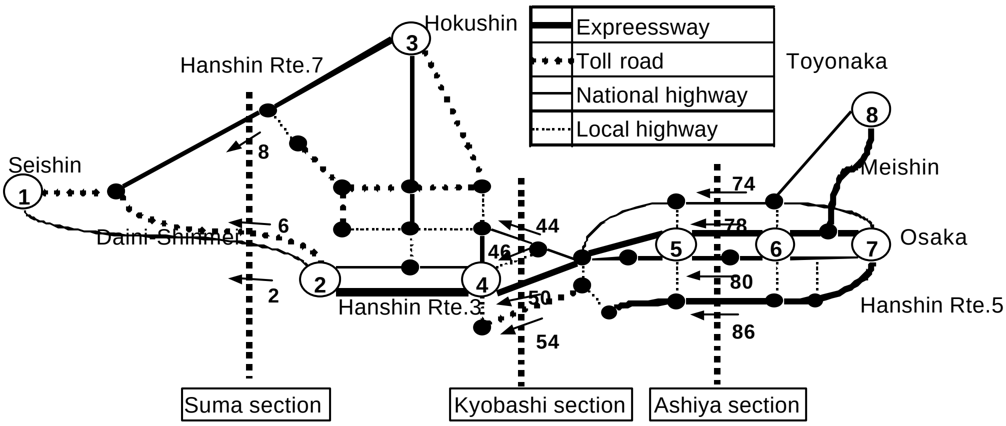


Figure 2: Network model for numerical example (numbers in circles represent centroid ID, numbers attached to links represent link ID).

4. RESULTS AND DISCUSSIONS

4.1 Total Network Attributes (*Q*, *D*, *T*):

The total network performance measures *Q*, *D* and *T*, that are averaged over 500 simulation trials and normalized to each pre-quake value, are plotted in Figure 3 as functions of damage rate λ. It can be observed that those three measures decrease from 1 to 0 as λ increases. In particular, when $\lambda > 0.02$, the network performance is significantlly degraded. It can be said that these curves represent functional fragility relations between magnitude of disaster and performance measures. As an example of distribution of these performance measures, a histogram of the performance measure *T* obtained for λ =0.01, 0.1 and 0.4 is shown in Figure 4. Figure 5 is a scattergram showing correlation between *Q* and *D*. All the results of 5,000 simulation trials are plotted using normalized values. The solid line is a reference line indicating 1:1. In high λ region (lower left corner), *D* is relatively smaller than *Q*, because long trips have less chance to be satisfied. Oppositely, in low λ region (upper right corner), increase in trip length due to detouring is observed. Figure 6 shows correlation between *Q* and *T*. Scatter is more widely seen than in Figure 5. In particular, in low λ region (upper right corner), increase in travel time due to congestion effect and detouring is emphasized.

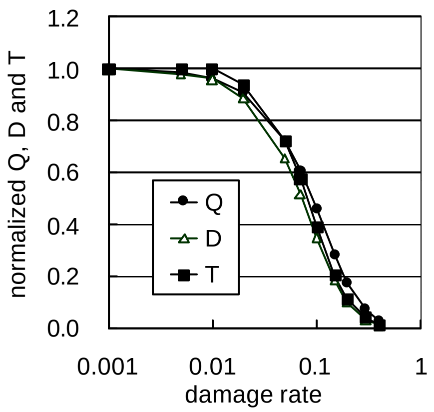


Figure 3: Total network performance measures *Q*, *D* and *T* for various λ (normalized to pre-quake level).

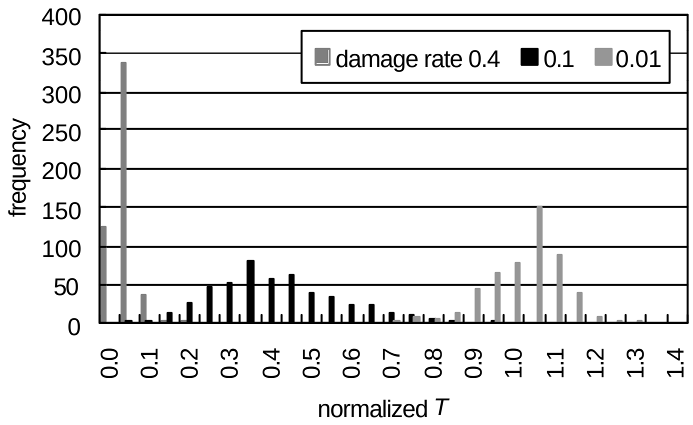


Figure 4: Distribution of the measure *T* for λ = 0.01, 0.1 and 0.4 (500 samples normalized to pre-quake level).

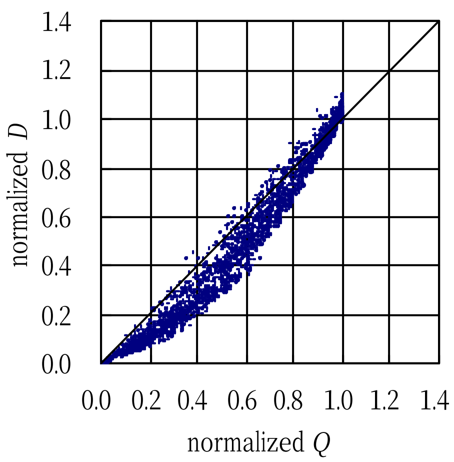


Figure 5: Correlation between *Q* and *D* (5000 samples normalized to pre-quake level).

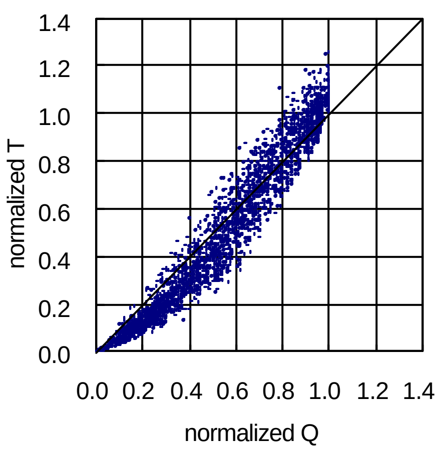


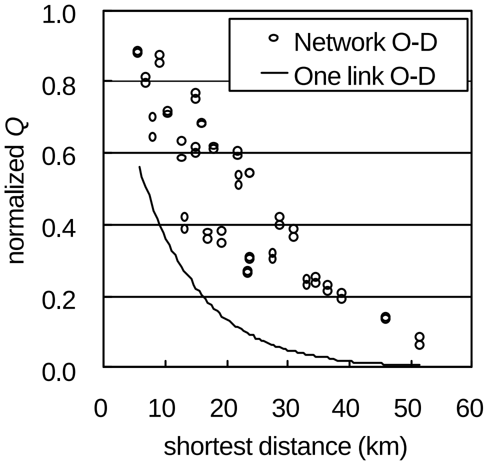
Figure 6: Correlation between *Q* and *T* (5000 samples normalized to pre-quake level).

4.2 O-D and Centroid Attributes (q_{ij}, d_{ij}, and Q^C):

Figure 7 shows the relationship between the average rate of satisfaction of O-D trips q_{ij} and O-D trip length d_{ij} on the shortest route basis (λ = 0.1). In general, long trips are prone to be unsatisfactory more than short trips. The solid line is a reference value indicating $e^{-\lambda d_{ij}}$, which assumes each O-D pair is connected by a single link of length d_{ij} with absolutely no redundancy. Obviously, all plots are no smaller than the single link system, and the difference between the plots and the line comes from the degree of redundancy of each O-D pair. In this case, O-D trips related to node 1 are found to be unreliable because of lack of redundancy (see also Figure 2).

Figure 8 breaks down the result of normalized *Q* (Figure 3) into q_{ij} with respect to O-D pairs. Only four typical pairs with short distance (2-4), intermediate distance (4-7 and 1-4) and long distance (1-7) are shown. It is noted that the O-D pair 4-7 is more reliable than the pair 1-4, whereas the trip lengths of the two are almost equivalent. The difference between the two results from redundancy; more alternative routes are available for the former than the latter (see also Figure 2).

Figure 9 breaks down the result of normalized *Q* (Figure 3) into Q^C with respect to eight centroids. The most reliable centroid is No.6 and the most unreliable one is No.1. The former is connected to surrouding nodes via as many as 12 links (6 in each direction), while the latter is located at the edge of the network and only four links (2 in each direction) are connected. Geographical condition and network configuration resulted in the diffence in redundancy.



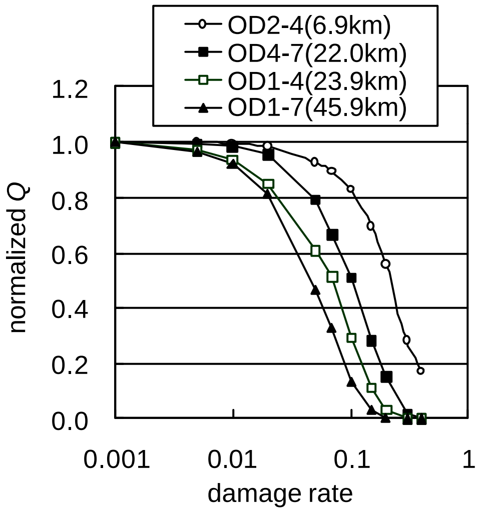
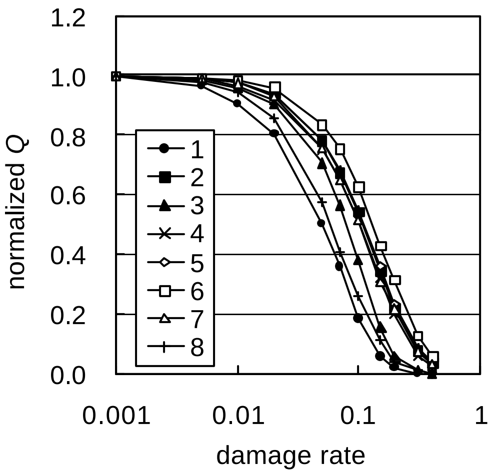


Figure 7: Rate of satisfaction of O-D trips with various trip length (averaged over 500 samples).

Figure 8: Rate of satisfaction of O-D trips with various l (averaged over 500 samples).



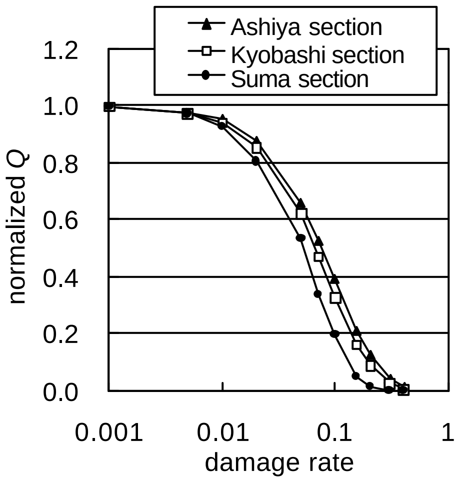
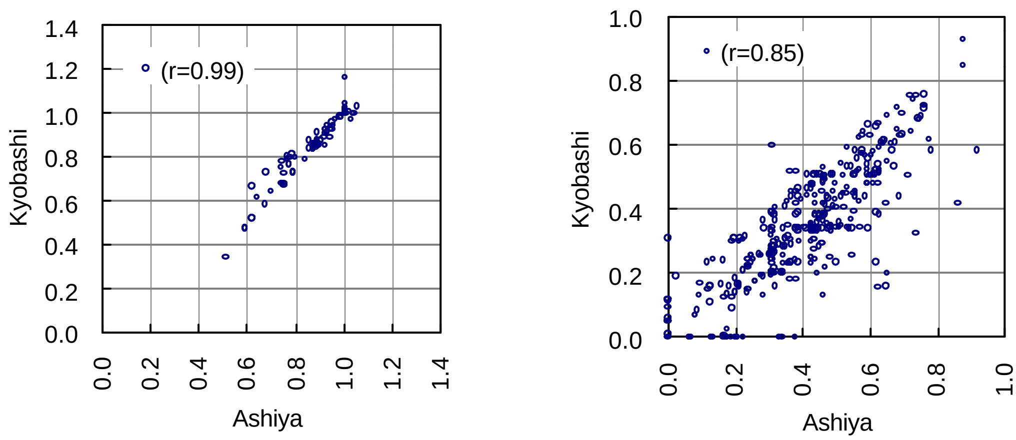


Figure 9: Rate of satisfaction of eight centroids with various l (averaged over 500 samples).

Figure 10: Cross sectional traffic volumes for various l (averaged over 500 samples) .



(a) l =0.01 **(b) l =0.1**

Figure 11: Correlation of traffic volumes at Ashiya and Kyobshi section (normalized to pre-quake level).

4.3 Cross Section Attributes (Q^S):

Normalized Q^S with respect to westbound traffic are shown in Figure 10 at three cross sections located at Suma, Kyobashi and Ashiya, from the west to the east (see also Figure 2). Suma section is less reliable than Ashiya section, which is coincident with the results previously mentioned. Figure 11 (a)-(b) compares correlation of traffic volumes normalized to pre-quake level at Ashiya section and Kyobashi section for l = 0.01 and 0.1. Each figure plots scatter of 500 simulation trials. It is observed that correlation factor drops from 0.99 to 0.85. This implies that if severly damaged, the transportation network loses its organic unity. The combination of Kyobashi-Suma section and Ashiya-Suma section also exhibit similar tendency.

4.4 Link Attributes (h_k):

Share of link flows at Ashiya section (link 74, 78, 80 and 86) for various l are shown in Figure 12. Link 86 and 78 share more than 80% of the sectional traffic flows in low l region. Clealy, the decreasing share of link 86 moves to the other three links with increasing l. Kyobashi section (link 44, 46, 50 and 54), and Suma section (link 2, 6 and 8) also exhibit shift of share of link flows.

Two typical pairs of links have been selected to investigate correlation among link flow : (a) link 8-44 and (b) link 6-8. Figure 13 (a) and (b) show scattergrams of link flows as results of 500 simulation runs for l = 0.01. Correlation factor is r = 0.77 and -0.59, respectively. Links 8 and 44 compose series connection between Suma and Kyobashi section. When one increases traffic volumes, the other also increases; positive correlation is reasonable. On the other hand, links 6 and 8 are parallel links at Suma section. When one increases traffic volumes, the other decreases, which causes negative correlation. When damage rate is low, this type of interrelationship is alive among flow on links. However, in Figure 14 (a) and (b) which show the cases for l = 0.1, it can be noted that both positive and negative correlation has become significantly weaker. As previously mentioned, the organic connection of transportation network is lost in severe disaster. Consequently, only fragmentary traffic can be carried through the segmented network without close functional ties between links.

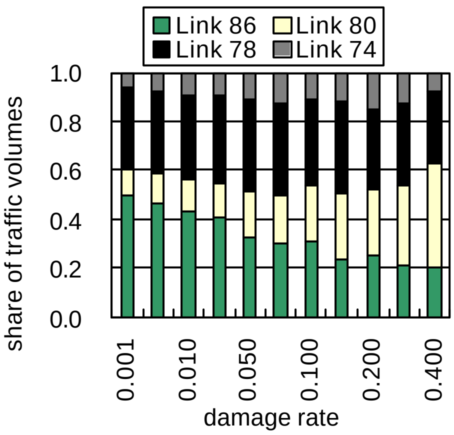
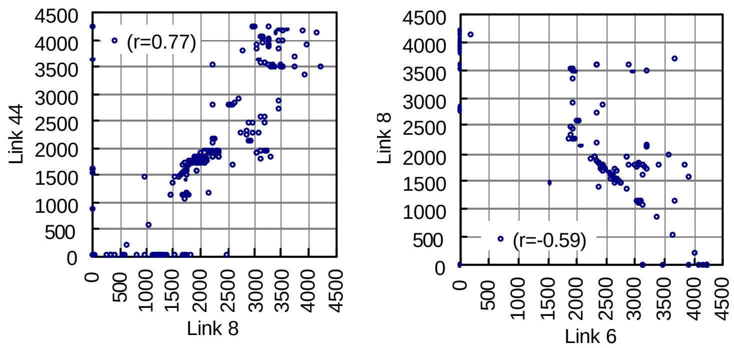
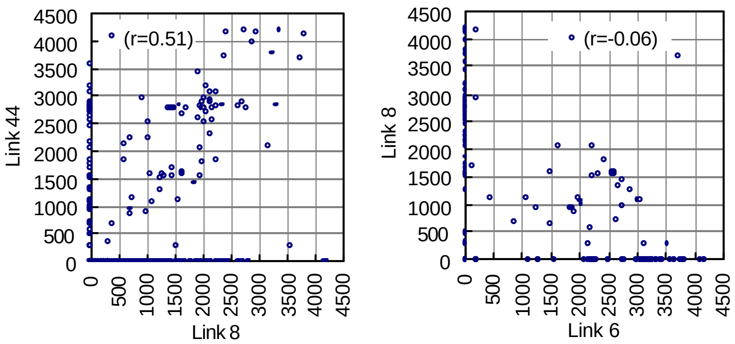


Figure 12: Share of link flows at Ashiya section for various l .



(a) link 8-44 **(b) link 6-8**

Figure 13: Correlation between link flows on two links (500 samples at l =0.01).



(a) link 8-44 **(b) link 6-8**

Figure 14: Correlation between link flows on two links (500 samples at l =0.1).

5. CONCLUSIONS

1. In order to evaluate the post-earthquake functional performance of highway transportation network systems, a simple model which combines the Monte Carlo simulation method and the modified incremental assignment method (MIAM) has been proposed. Various performance measures for links, O-D pairs, centroids, cross-sections and the total network have been defined to evaluate aggregate and non-aggregate conditions of network functions.
2. The functional performance measures reflect (a) physical performance of links, (b) network properties such as capacity and redundancy, (c) decrease in O-D trips due to overload, (d) increase in trip length due to detouring actions, and (e) increase in travel time due to detouring and congestion.
3. Degradation of serviceability in terms of satisfaction of O-D requirement has been shown as a function of damage rate that is assumed to be uniform over the entire network. Correlation among system performance measures such as total satisfied O-D trips, total O-D trip length and total O-D travel time provides visual understanding of traffic conditions and range of values of those measures.
4. Satisfaction ratio of O-D trips related to each centroid and several selected O-D pairs are compared. Topological location of centroids, O-D distance, availability of detour routes, i.e., redundancy of network strongly affect the satisfaction ratio of O-D requirement.
5. Traffic volumes at three cross sections have been compared. As the network performance deteriorates, correlation among traffic volumes at different cross sections becomes weak. This implies that organic connection of network is lost when the network suffer severe damage. Share of traffic flow on links changes in association with significance of damage.
6. The role of each link as a network component has been examined using traffic flows assigned to selected links. Topological configuration of “series” and “parallel” of two links gives positive and correlation of link flow, respectively. Similar to the cross section attribute, correlation among link flows also becomes weak when damage rate is high.
7. The method proposed herein enables one to find vulnerable O-D pairs and isolation-prone centroids, and to understand systematic relations between physical performance of transportation facilities and functional performance of the transportation network.

ACKNOWLEDGMENTS

This study was partly supported by Japan Society for the Promotion of Science, Grant-in-aid for Scientific Research on Priority Areas (A) (grant No.08248112) and Priority Areas (B) (grant No.11895014).

REFERENCES

Chang, S. E., Nojima, N. (1997), “Highway System Performance Measures and Economic Impact,” *Proc. of the 7th U.S.-Japan Workshop on Earthquake Disaster Prevention for Lifeline Systems*, Seattle, Washington, USA.

Chang, S. E., Nojima, N. (1998), “Measuring Lifeline System Performance: Highway Transportation Systems in Recent Earthquakes,” *Proc. of the 6th National Conference on Earthquake Engineering*, Seattle, USA, Paper No.70, 12p.

Iida, Y. (1972), “Studies on Methodology for Maximum Capacity of Road Network,” *Proc. of the Japan Society for Civil Engineers*, Vol.205, pp121-129 (in Japanese).

Nojima, N. (1999), “Performance-Based Prioritization for Upgrading Seismic Reliability of a Transportation Network,” *Journal of Natural Disaster Science*, Vol.20, No.2, pp57-66.

Nojima, N., Sugito, M. and Fukuoka, J. (1999), “Evaluation of Post-disaster Performance of a Highway Transportation System Based on a Scenario Earthquake,” *Proc. of the 4th Symposium on the Mitigation of Urban Disasters by Near-field Earthquakes*, Kobe, Japan (in Japanese, in press).

Ortúzar, J. D. and Williumsen, L. G. (1990), *Modelling Transport, Second Edition*, *Ch.10. Assignment*, John Wiley and Sons, Chichester, England, pp287-321.

Sugito, M., Furumoto, Y. and Sugiyama, T. (2000), “Strong Motion Prediction on Rock Surface by Superposed Evolutionary Power Spectra,” *Proc. of the 12th World Conference on Earthquake Engineering*, New Zealand (in press).

Tanaka, S., Nojima, N. and Kameda, H. (2000), “Evaluation of Seismic Fragility for Highway Transportation Systems,” *Proc. of the 12th World Conference on Earthquake Engineering*, New Zealand (in press).

Werner, S., Craig, E. T. and Moore II, J. E. (1997), Loss Estimation Due to Seismic Risks to Highway Systems, *Earthquake Spectra*, Vol.13, No.4, pp585-604.