EVALUATION MODEL FOR POST-EARTHQUAKE SYSTEM PERFORMANCE OF TRANSPORTATION NETWORK

Nobuoto NOJIMA* and Masata SUGITO

* Gifu University, Associate Professor
Department of Civil Engineering, Faculty of Engineering, Gifu University
1-1 Yanagido, Gifu 501-1193, JAPAN
Tel: +81-58-293-2416 Fax: +81-58-230-1891
E-mail : nojima@cive.gifu-u.ac.jp

SUMMARY

In this study, a simple model has been proposed to evaluate post-earthquake performance of transportation network. The model combines the Monte Carlo simulation method and the incremental assignment method; the former generates damage states of transportation network, and the latter evaluates traffic behavior in each damage state. The result of the proposed method produces a set of link flows. On this basis, various performance measures for the entire network, cross sections, O-D pairs and individual links have been defined to evaluate aggregate and non-aggregate values of network conditions. Those measures reflect mixed effects attributed to decrease in O-D trips due to overload, increase in trip length due to detouring actions, and increase in travel time due to detouring and congestion, etc.

INTRODUCTION

Different from physical flows of utility lifelines, traffic flow depends not only on degraded capacity of traffic links, but also on various factors such as O-D (origin/destination) requirement, travel time, and trip length. However, appropriate methodology has not yet been developed for functional evaluation of transportation network subject to intensive and simultaneous occurrence of components failure. As a result, prediction of post-earthquake performance of transportation network remains a very difficult problem in spite of its great importance. Chang and Nojima (1998) and Nojima (1998) developed flow-independent measures to evaluate post-earthquake performance of highway systems. To extend this state-of-the-art, the objective of this study is to propose a flow-dependent performance evaluation method applicable to the post-earthquake situation for the goal of upgrading seismic reliability of network.

SIMULATION AND EVALUATION METHOD

The proposed method includes three-step procedures. Firstly, using the Monte Carlo method, a large number of random damage patterns of network are generated. Secondly, O-D matrix is loaded to each damage pattern. Finally, system performance is evaluated in terms of aggregate and non-aggregate measures related to traffic volumes, travel time, and trip length of (a) links, (b) cross-sections, (c) O-D pairs, and (d) the total network system.

(1) Generation of 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. 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 given for each link. Because the actual damage state is 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 method.

(2) Traffic assignment on damaged network

For simplicity, 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 estimation process. The incremental assignment method is employed to load a damaged network with O-D trips. Modification has been made as to termination of the flow assignment procedure. In this study, the procedure does not terminate until all O-D pairs lose available route or until O-D trip matrix has been completely loaded, while no flow is loaded to links which have reached to their capacity.

(3) Performance measures of transportation network function

The condition of network flow is defined by link flows at the final state of incremental assignment. On this basis, various performance measures are computed. Notations for input/output data are as follows, where subscript for link is denoted by k, subscripts for node by i, j.

[input data] link flow capacity : c_k, link distance : d_k, damage rate (expected number of damage occurrence per unit length) : l_k, link reliability : p_k, O-D trip matrix : B(b_{ij}), time-flow relationship (BPR-type) : $t_k(c_k, h_k)$

[output data] link flow : h_k, link travel time : t_k, trips satisfied at O-D pair ij : q_{ij}, trip length (shortest distance) between O-D pair ij : d_{ij}, traffic volumes at cross section S_m : $Q_m^S = \sum_{k \in S_m} h_k$, trips satisfied at centroid C_i : $Q_i^C = \sum_j (q_{ij} + q_{ji})$, total satisfied O-D trips : $Q = \sum_i \sum_j q_{ij}$, total O-D trip length : $D = \sum_k h_k d_k$, total O-D travel time : $T = \sum_k h_k t_k$

NETWORK MODEL AND ASSUMPTIONS FOR A CASE STUDY

A case study has been performed for the highway network which suffered severe damage in the 1995 Hanshin-Awaji earthquake disaster, Japan. The network has been modeled as 100 links and 30 nodes including 8 centroids (Fig.1). Peak-hour vehicle O-D matrix is estimated on the basis of daily O-D matrix provided by Hanshin Expressway and actual traffic counts observed at several cross sections. Time-flow relationship has been modeled using BPR function with the parameter $a = 0.96$ and $b = 1.2$. Pre-quake values of performance measures are : Q = 33,200 (vehicles / hr), D = 803,389 (vehicles * km) and T = 24,637 (vehicles * hr). Assuming random and independent occurrence of damage to links, link reliability is computed as $p_k = e^{-l_k d_k}$. In order to cover various states as wide as possible, ten kinds of different damage rate ranging from 0.05 to 0.4 have been uniformly assigned to all links. Monte Carlo simulations have been carried out 500 times for each damage rate, totally 5,000 samples of damaged network being generated. Statistical analysis is then applied to the dataset of performance measures to obtain their average values, distribution characteristics, and correlation among related factors.

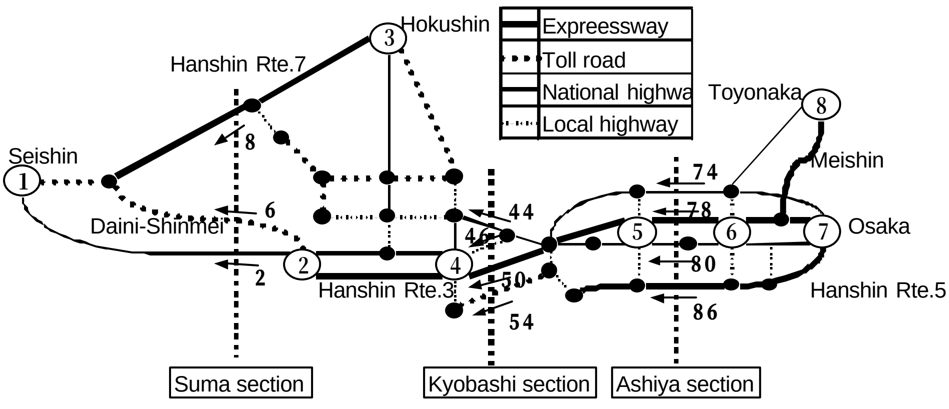


Fig.1 Network model for numerical example (numbers in circles represent centroid ID, numbers attached to links represent link ID)

RESULTS AND DISCUSSIONS

(1) Total network attributes

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 Fig.2 as functions of l . Fig.3(a) are scattergrams 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 l region, *D* is relatively smaller than *Q*, because long trips have less chance to be satisfied. Oppositely, in low l region, increase in trip length due to detouring is exhibited. Fig.3(b) shows correlation of *Q* and *T*. Scatter is more widely seen than in Fig.3(a). In particular, in low l region, increase in travel time due to congestion effect and detouring is emphasized.

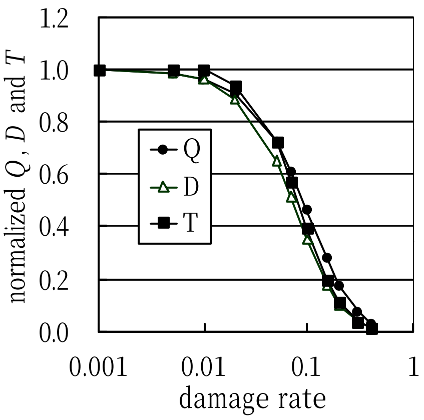
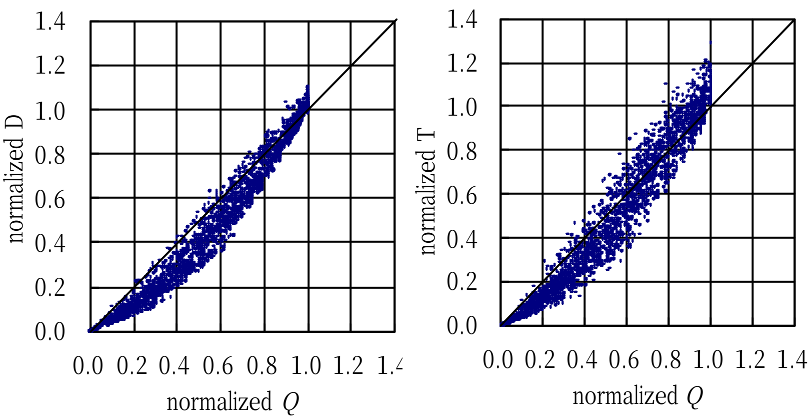


Fig.2 The total network performance measures *Q*, *D* and *T* for various l (averaged over 500 samples , normalized to pre-quake level)



(a) *Q* and *D*

(b) *Q* and *T*

Fig.3 Correlation among total network attibutes (5000 samples normalized to pre-quake level)

(2) O-D attributes

Fig.4 shows the relationship between the average rate of satisfaction of O-D trips (l = 0.1) and O-D trip length on the shortest route basis. In general, long trips are prone to be unsatisfactory more than short trips. The solid line is a reference value indicating $e^{-l d_{ij}}$, which assumes each O-D pair is connected by a single link of length d_{ij} with absolutely no redundancy. Obviously, the difference between the plots and the line comes from the degree of redundancy of each O-D pair. Fig.5 breaks down the result of normalized *Q* (Fig.2) with respect to O-D pairs q_{ij}. 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. More alternative routes are available for the former than the latter (see also Fig.1). Fig.6 breaks down the result of normalized *Q* (Fig.2) with respect to eight centroids. The most reliable centroid is No.6 and the most unreliable one is No.1. Geographical condition and network configuration resulted in the difference in redundancy.

(3) Cross section attributes and link attributes

Normalized Q^S with respect to westbound traffic are shown in Fig.7 at three cross sections located at Suma, Kyobashi and Ashiya, from the west to the east. Suma section is less reliable than Ashiya section. Share of link flow at Ashiya (link 74, 78, 80 and 86) cross section for various l are shown in Fig.8. Link 86 and 78 share more than 80% of sectional traffic flow in low l region. Clealy, the decreasing share of link 86 moves to the other three links with increasing l .

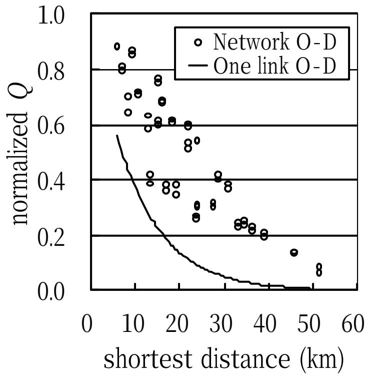


Fig.4 Rate of satisfaction of O-D trips with various trip length (l=0.1, averaged over 500 samples)

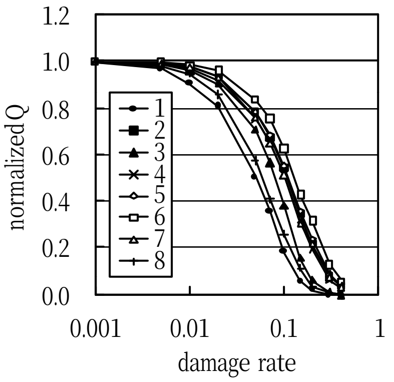


Fig.5 Rate of satisfaction of eight centroids for various l (averaged over 500 samples)

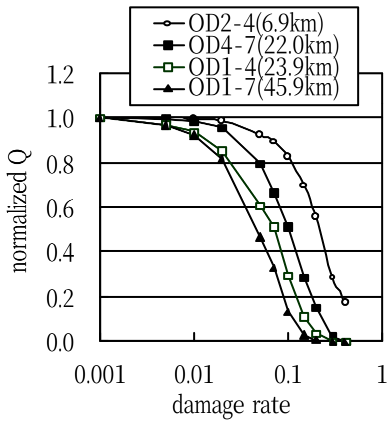


Fig.6 Rate of satisfaction of O-D trips for various l (averaged over 500 samples)

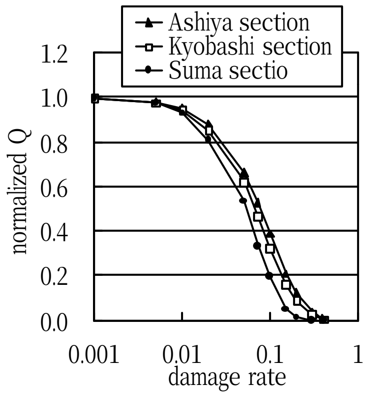


Fig.7 Cross sectional traffic volumes for various l (averaged over 500 samples normalized to pre-quake level)

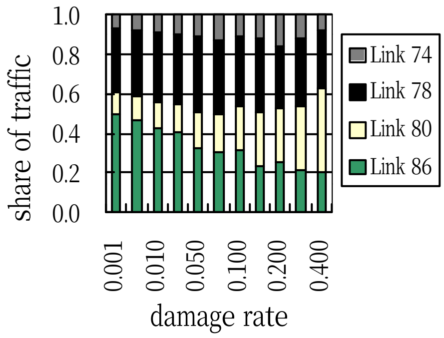


Fig.8 Share of link flow at Ashiya cross section for various l

CONCLUSIONS

Major conclusions derived from this study are summarized below.

(1) The functional performance reflects (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.

(2) Degradation of serviceability has been shown as a function of damage rate. System performance measures such as total satisfied O-D trips, total O-D trip length and total O-D travel time provide visual understanding of traffic conditions and range of values of those measures.

(3) Satisfaction rate 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 rate of O-D requirement.

(4) 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 transportation network.

REFERENCES

Chang, S. E. and Nojima, N. (1998) "Measuring Lifeline System Performance: Highway Transportation Systems in Recent Earthquakes," *Proc.of the 6th National Conf. on Earthq. Eng.*, paper No.70.

Nojima, N. (1998) "Prioritization in Upgrading Seismic Performance of Road Network Based on System Reliability Analysis," *Proc. of 3rd China-Japan-US Trilateral Symp. on Lifeline Earthquqke. Eng.*, pp.323-330.