TRAFFIC ASSIGNMENT IN A ROAD NETWORK WITH DEGRADED LINKS BY NATURAL DISASTERS

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abstract: This paper aims to show an traffic assignment model available for describing traffic flows in a road network with degraded links by natural disasters. The assignment model is then incorporated into evaluating procedure of a network reliability measure. The assignment model and the reliability model is calculated using the actual road network of Shikoku region.

1. INTRODUCTION

Natural disasters such as earthquake and heavy rainfall are possible to cause serious damages on road networks. Improving durability against natural disasters and maintaining reliability are recognized as the objectives of road network infrastructure planning and management. In particular, redundancy became a popular keyword of highway systems planning after the experience of devastated road networks by the Kobe Earthquake. A reliable network is defined as the network which could guarantee an acceptable level of service for road traffic even if the functions of some links of the network are degraded by disasters.

There have been proposed some reliability measures of transport networks. The connectivity between an origin and destination (OD) pair is mainly applied to evaluate topological structure of a network. The time reliability is considered as an appropriate performance measure of travelling an OD pair. However, previous studies on road network reliability have not succeeded in developing traffic assignment models which could be applied to describe network traffic flow for a degraded network. If some links in a network are degraded by disasters, drivers may be obliged to divert to an unfamiliar route with longer distance or there may exist an OD pair which is not topologically connected by a route. Under such conditions, trips will be canceled and consequently travel demand will decrease. Traditional network traffic assignment methods such as User Equilibrium assignment may not be suitable as an assignment method for a partially damaged road network.

This paper aims to show an traffic assignment model available for describing traffic flows in a road network with degraded links by natural disasters. The assignment model is then incorporated into evaluating procedure of a network reliability measure. The assignment model and the reliability model is calculated using the actual road network of Shikoku region.

2. LITERATURE REVIEW

Previous studies are briefly reviewed from two dimensions; transport network reliability models and traffic assignment models. Since a driver is obliged to determine his/her travel choice under uncertain situations, stochastic assignment models are worth discussing.

2.1 Transport Network Reliability Models

There are several studies on reliability of transport networks. Turnquist and Bowman (1980) presented a set of simulation experiences to study the effect of the structure of the urban network into service reliability. Iida and Wakabayashi (1989) developed an approximation method to calculate the connectivity between a node pair in a road network. Assuming the connectivity of each link, they proposed a method using partial minimum path and cut sets. These studies concentrated on the calculation of the connectivity measure of a network and network flows were not explicitly considered.

Asakura and Kashiwadani (1991, 1992) studied road network reliability considering day-to-day fluctuations of traffic flow. They showed a traffic assignment simulation model and a statistic estimation method for describing day-to-day dynamics of network flow. Then, they proposed some reliability measures including a time reliability which is the probability of whether a travel between an origin and destination pair is possible within an acceptable travel time. Time reliability is suitable for evaluating network performance under normal conditions in which a driver may meet traffic congestion caused by heavy travel demand compared with the capacity of a network.

Du and Nicholson (1993) established a theoretical framework to systematically outline the main issues in the analysis and design of Degradable Transportation Systems(DOTS). User Equilibrium model with variable demand was applied to describe network flows for a degraded transport network. They developed an integrated steady-state equilibrium model and efficient methods of reliability analysis. The analytical framework and the approximation algorithm developed for calculating network reliability are powerful tools for reliability analysis of transport networks.

Sanso and Milot (1994) presented a reliability model for urban transportation planning considering traffic accidents. They proposed three-T's model to describe dynamic behaviour of drivers in an accidental state. Applying static equilibrium package EMME2, they calculated travel time during accidental periods and evaluated network plans using the general approach proposed by Sanso and Soumis (1991).

In these studies on the reliability of flow networks, one of the most important components is to describe drivers' behaviour and resulting flows in a transport network. When some links in a network are degraded by disasters, car drivers may not have sufficient information on the situations of the network. Under such conditions, a stochastic route choice assumption seems more appropriate than a deterministic choice assumption. Thus, the following section discusses previous studies on stochastic traffic assignment models.

2.2 Stochastic Traffic Assignment Models

There are some previous studies on the formulation and the solution of stochastic network assignment models. The assignment assumes that a driver's route choice is based on perceived rather than measured link travel times. This emphasizes the variability in drivers' perception of costs and the composite measure they seek to minimize such as distance and travel time. The travel times perceived by motorists are assumed to be random variables, the distribution of which across the population of drivers is known. These models assign a set of OD trips to a transport network in which the link travel times are fixed. This means that the travel time on a link is independent from the flow on that link and traffic congestion effect is not considered.

Several models have been proposed to incorporate these aspects. Ortuzar and Willumsen (1990) categorized them into proportion-based and simulation-based ones. The former methods allocate flows to alternative route from proportions calculated using logit-like expressions. The later methods use ideas from stochastic (Monte Carlo) simulation to introduce variability in perceived costs. This classification is mainly based on the calculation methodologies On the other hand, Sheffi (1984) focused on a driver's route choice behaviour and categorized previous stochastic network loading models into logit-based and probit-based models.

The representative of the logit-based loading models was the one proposed by Dial (1971). The Dial's algorithm is efficiently implements a logit route choice model at the network level. However, this model may exhibit some unreasonable properties of which it tends to allocate more traffic to dense sections of the network with short links, compared with sparser parts of the network with relatively longer links. This is resulted from the IIA (Independence of Irrelevant Alternatives) assumptions of the logit model. There is a need to account for the correlation between the perceived travel times of the various routes.

The logit based network loading model can, however, be extended so as to incorporate traffic congestion. The perceived travel times are modelled not only as random variables, but also as flow dependent. This dependence is accounted for by assuming that mean travel time for each link is a function of the flow on that link. Sheffi (1984) has introduced the equilibrium dimension into the logit based network loading model and formulated the Stochastic User Equilibrium (SUE) model. The SUE model is possibly involved into the network reliability analysis. However, this requires huge computational costs since large number of iterations is necessary for solving the SUE itself.

Akamatsu (1995) recently investigated the properties of logit type SUE model and improved a drawback of Dial's algorithm. He modified the transition probability so that it would be consistent with the logit model. Then, he developed some efficient algorithms for SUE.

The other category of the stochastic network loading models is the simulation-based approach. Amongst of them, the technique developed by Burrell (1968) has been widely used for many years. It assumes a distribution of perceived costs for each link, which is independently distributed each other. While Burrell originally handled a uniform distribution, other functions such as a normal distribution are possibly used as well. Drivers are assumed to choose the route that minimizes their perceived route costs, which are obtained as the sum of the individual link costs. A general description of these algorithms would be as follows.

Step 0: *Initialization.* Set iteration counter $n=1$.

Step 1: *Sampling.* Compute perceived costs for each link by sampling from the corresponding distribution of costs.

Step 2: *All-or-nothing assignment.* Based on sampled link travel times, assign a segment of OD flows to the shortest path connecting each OD pair. This step yields the set of link flows.

Step 3: *Flow up-date.* Link flows are up-dated using both the link flows in the last iteration and the calculated link flows in the preceding step.

Step 4: *Stopping test.* If the difference of the up-dated link flows and the link flows in the last iteration is close enough or the iteration counter reaches the given number, stop the calculation. Otherwise, set $n=n+1$ and go to step 1.

The original Burrell's algorithm used the idea of the Incremental Assignment, in which total amount of each OD flow are split into N segments beforehand and assigned one after the other in the step 2. The link flow is up-dated as;

$$v_a^{(n)}=v_a^{(n-1)}+V_a^{(n)}, \qquad \text{.................. (1)}$$

where $v_a^{(n)}$ is the up-dated flow on link a in the current iteration, $v_a^{(n-1)}$ is the flow on link a in the last iteration and $V_a^{(n)}$ is the flow on link a calculated in the step 2. The given number of iteration in the step 4 is set to N. If the sequential averaging method is applied, the total amount of each OD flow is assigned as a whole in the step 2. Then the link flows are up-dated as,

$$v_a^{(n)}=[\,(n-1)\,v_a^{(n-1)}+V_a^{(n)}]\,/\,n. \qquad \text{.................. (2)}$$

Daganzo and Sheffi (1977) gave a theoretical interpretation of the simulation-based network loading method assuming a normal distribution of a perceived link travel times. The calculation procedure is insistent to the solution algorithm of a probit-based route choice model which is described as follows.

Let T_a denote the travel time on link a, as perceived by a driver randomly chosen from the population of drivers. T_a is a random variable that is normally distributed with mean equal to the measured (or engineering) travel time on that link t_a and with variance that is proportional to the mean. In other words, $T_a \sim N(t_a, \sigma t_a)$ where σ is a proportionally constant. Since it is assumed that the perceived time of each link is independently distributed each other, the perceived travel time on a route which is given by the sum of link travel times along that route is also normally distributed due to the properties of a normal distribution. The perceived travel time on route k between r and s, C^{rs}_k, is a random variable normally distributed with the following mean and variance.

$$E[C^{rs}_k] = \Sigma\, t_a \delta^{rs}_{ak} = c^{rs}_k \qquad \text{.................. (3)}$$

where δ^{rs}_{ak} denotes the incidence coefficient. If the route k between OD pair r-s includes link a, δ^{rs}_{ak} is equal to 1. Otherwise, that is equal to 0. c^{rs}_k denotes the measured travel time on route k between OD pair r-s. The variance is given by

$$\mathrm{Var}[C^{rs} \; t_a \delta^{rs}_{ak} = \sigma \;\; \Sigma\, t_a \delta^{rs}_{ak} = \sigma c^{rs}_k \qquad \text{.................. (4)}$$

When route k is overlapping with the other route l, the perceived route travel times are not mutually independent. The covariance between the perceived travel times of two routes is thus related to their common portion, that is,

$$\mathrm{Cov}[C^{rs}_k, C^{rs}_l] = \Sigma\, \sigma\, t_a \delta^{rs}_{ak} \delta^{rs}_{al} = \sigma\, c^{rs}_{kl} \qquad \text{.................. (5)}$$

where c^{rs}_{kl} is the measured travel time on the common segments of route k and l between OD pair r-s. When these two routes are not overlapped at all, the value of covariance is equal to zero.

3. TRAFFIC ASSIGNMENT MODEL

Since car drivers may not have complete information on traffic condition under unusual situations, stochastic traffic assignment models seem appropriate as traffic assignment for degraded networks. Simulation-based assignment models like Burrell's algorithm have shown desirable properties which could consider the correlation between routes overlapped each other. On the other hand, it is necessary to describe car drivers' behaviour specific for degraded networks; namely detouring behaviour from a damaged route to an alternative route remained and canceling behaviour due to long distanced diversion expected. Thus, the following sections present the simulation-based assignment model which is modified so that it could consider the detouring and canceling behaviour of a driver.

3.1 Assumptions

Following assumptions are employed for formulating an assignment model. These behavioural assumptions on car drivers are involved in the assignment process explained in the section 3.2.

(1) *Distribution of Link travel times:* For each link in a network, a driver's perceived travel time of link a is a normally distributed random variable, that is T_a~$N(\mu_a, \sigma_a^2)$. The mean μ_a corresponds to the link travel time t_a that is measured or estimated by an observer or a modeller. The standard deviation σ_a is proportional to the mean travel time $\sigma_a = \beta\, t_a$, and the proportional coefficient β is kept constant for all links.

(2) *Travel times of a degraded link:* If a link is physically closed by disasters or the traffic of a link is prohibited due to the precaution against expected disasters, the mean value of the perceived link travel time μ_a becomes t_a plus d_a. Here, d_a denotes the expected duration of traffic closure. However, the variance of the perceived link travel time is assumed the same value as σ_a^2 which corresponds to the variance for a normal traffic conditions.

(3) *Distribution of route travel times:* The distribution of perceived link travel times are assumed to be independent. Due to the properties of the composite variable of independent normal distributions, the perceived travel time on route k of OD pair r-s which is obtained as the sum of the individual link travel times on the route is also a random variable of a normal distribution with the following mean and variance.

$$E[C^{rs}_k] = \Sigma\, E[T_a]\, \delta^{rs}_{ak} = \Sigma\, t_a\, \delta^{rs}_{ak} \qquad \text{(6)}$$

$$Var[C^{rs}_k] = \Sigma\, Var[T_a]\, \delta^{rs}_{ak} = \Sigma\, (\beta t_a)^2\, \delta^{rs}_{ak} = \beta^2\, \Sigma t_a^{\,2}\, \delta^{rs}_{ak} \qquad \text{(7)}$$

where δ^{rs}_{ak} denotes the incidence coefficient shown above.

(4)*Drivers' travel behaviour:* Drivers are assumed to choose the route that minimizes their perceived route travel times. However, drivers will not intend to travel if the ratio of the minimum route travel time in a degraded network to the miminum route travel time in a normal network exceeds the acceptable level. The acceptable ratio is called detour limit m. Since drivers may cancel their trips, the OD travel demand for a deteriorated network will become smaller than the normal level. A driver's travel behaviour is explained using Figure 1.

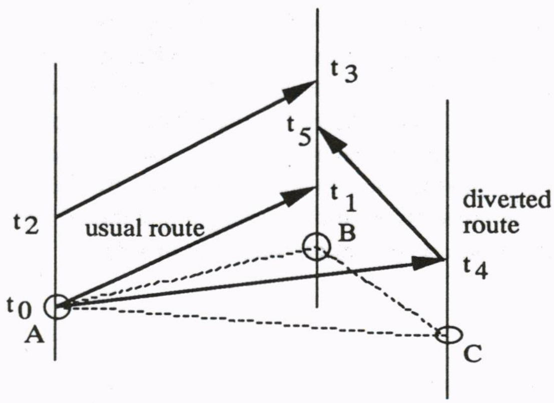


Figure 1 A Driver's Travel Behaviour

A driver travels from origin A to destination B. He/she departs A at time t_0 and arrives B at time t_1 in a normal condition; the travel time is equal to $(t_1 - t_0)$. There is an alternative route via node C. Suppose that the normal route is closed and is expected to be opened at time t_2. The closed duration d is equal to $(t_2 - t_0)$. The driver has three possible travel options; to wait until the normal route is re-opened and use the normal route, to divert to the alternative route or to cancel his/her travel. If the driver waits and then uses the normal route, the arrival time at B will be t_3. If the driver diverts to the alternative route via node C, the arrival time at B will be t_5. The driver will use the diverted route if the travel time of this route $(t_5 - t_0)$ is less than the travel time on the ordinary route $(t_3 - t_0)$ and the ratio $(t_5 - t_0)/(t_1 - t_0)$ is less than the given detour limit m. If travel time of the ordinary route is shorter than the alternative route and the ratio $(t_3 - t_0)/(t_1 - t_0)$ is less than the given detour limit m, the driver will wait until time t_2 and use the ordinary route. If the smaller of these ratios (i.e. the critical ratio) is greater than the detour limit m, the driver will give up travelling.

(5) *Congestion effects:* Travel time of a link is assumed independent from traffic flow on that link, which means that traffic congestion is not considered in the assignment model. This may cause overloading on some links in a network. However, travel demand for a degraded network will be reduced due to the inconvenience of the network as discussed in the assumption (4). Therefore, not so large amount of flows will be loaded onto the network and overloading will not always occur.

When we use the simulation-based stochastic traffic assignment, it is possible to assume any probability density function for link travel time distribution. However, it seems natural to assume the normal distribution as the distribution of perceived link travel times. The same distribution function is also assumed for a degraded link. Although the variance of travel time of a closed link may be different from the one of a link at usual state, we assume the same variance parameter in order to exclude another unknown parameter.

A driver's diverting behaviour has not been studied yet and it is not known how he/she traverses in a degraded network. According to the difference and/or the ratio of route travel times along the ordinary route and the diverted route, a driver will decide waiting, diverting or cancelling the trip. We employ a simple assumption introducing a parameter m called detour limit. However, it is necessary to examine the validity of this parameter in the future studies.

3.2 Assignment Procedure

The simulation-based stochastic traffic assignment is applied to describe network traffic flow in a degraded road network. Here we prepare network configurations of a normal road network without degraded links and a degraded network which includes some deteriorated links. The set of mean link travel times $\{t_a\}$ of the normal network and the set of closed durations $\{d_a\}$ for degraded links are given as well. A normal OD matrix $\{q_{rs}\}$ is assigned onto the network through the Incremental Assignment procedure described as follows.

Step 0: *Initialization.* For a normal network without degraded links, calculate the minimum route travel times between all OD pairs using the mean values of link travel time $\{t_a\}$. This gives the OD travel time $\{U_{rs}\}$ at ordinary conditions. Total amount of each OD flow are split into N segments such as $\{\Delta q_{rs}\}=\{q_{rs}/N\}$. Set iteration counter $n=1$.

Step 1: *Sampling.* Generate a random variable ε_a from the standard normal distribution N(0,1) and compute perceived travel time for a link. The perceived travel time of link a is given by,

$$T_a = \begin{cases} t_a(1+\beta\,\varepsilon_a) & \text{if the link is not degraded.} \\ t_a(1+\beta\,\varepsilon_a)+d_a & \text{if the link is closed for the duration of } d_a. \end{cases}$$

Step 2: *All-or-nothing assignment.* Based on sampled link travel times $\{T_a\}$, calculate the travel time C_{rs} on the shortest path between an OD pair r-s. When the ratio C_{rs}/U_{rs} is smaller than the given detour limit m, assign a segment of OD flows Δq_{rs} to the shortest path connecting the OD pair. Otherwise, go to the next OD pair until all OD pairs are examined. This step yields the set of link flows $\{V_a^{(n)}\}$.

Step 3: *Flow up-date.* Link flows are up-dated using both link flows in the last iteration $\{v_a^{(n-1)}\}$ and calculated flows in the preceding step $\{V_a^{(n)}\}$. The up-dated flow on link a is

$$v_a^{(n)}=v_a^{(n-1)}+V_a^{(n)}.$$

Step 4: *Stopping test.* When the iteration counter n reaches N, stop the calculation. Otherwise, set $n=n+1$ and go to step 1.

The whole assignment procedure is based on the Burrell's simulation-based assignment which is simple and easy to calculate. The original procedure is modified so as to consider some closed links without generating further complexities in computation. It is possible to describe how drivers detour or stop travelling in the degraded network.The total number of OD trips which were not assigned in the step 2 is considered as the canceled OD trips due to the inconvenience of the deteriorated network. The traffic volume consequently assigned on a degraded link is interpreted as the traffic which has watched and waited for a moment.

In order to reduce the number of unknown parameter values, the detour limit m in step 2 is set common for all OD pairs. However, the value of m for OD pairs with longer trip distance may be different from the one with shorter OD distance. In this case, it is possible to apply different value of m for each OD pair such as m_{rs}.

4. EVALUATION OF RELIABILITY MEASURE

Du and Nicholson (1993) developed a general framework for evaluating a reliability measure of a degraded network. In order to identify each degraded network, they introduce the state vector $\boldsymbol{x}=\{x_1,\dots,x_L\}$ whose element x_i denotes whether link i is degraded or not; namely x_i is equal to 1 if it is normal, otherwise x_i is equal to 0. They focus on the ratio of the canceled OD trips to the normal trips, which is defined as $y_{rs}(\boldsymbol{x}) = w_{rs}(\boldsymbol{x}) / q_{rs}$, where $w_{rs}(\boldsymbol{x})$ denotes the number of canceled flows between OD pair r-s for the state $\boldsymbol{x}$. The OD pair r-s is regarded operated for the state $\boldsymbol{x}$ if the decrement rate $y_{rs}(\boldsymbol{x})$ is less than the given criterion θ ($0<\theta<1$). Considering all state vectors, the reliability $R_{rs}(\theta)$ is defined as the probability of whether the OD pair r-s is operated for the given criterion θ. The procedure calculating the reliability measure is explained as the following steps.

Step 0: *Initialization.* For the normal network, in which all components of a state vector are equal to 1, the OD travel time $\{U_{rs}\}$ along the shortest path is calculated, which is used in the step 2.

Step 1: *Identification of State Vector and its Probability.* Enumerate all of the possible component state vectors and estimate the probability $p(\boldsymbol{x})$ for each state vector $\boldsymbol{x} \in X$, where X denotes the state vector space $X=\{\boldsymbol{x}\}$.

Step 2: *Traffic Assignment.* Calculate the stochastic traffic assignment for the state vector $\boldsymbol{x} \in X$. This step generates the canceled travel demand $\{w_{rs}(\boldsymbol{x})\}$.

Step 3: *Operating/Failed Function.* Calculate the decrement rates $\{y_{rs}(x)\}$ using $\{w_{rs}(x)\}$ and $\{q_{rs}\}$. Compute the operating/failed function of each OD pair *r-s* for the given criterion θ, which is

$$Z_{rs}(\theta,\mathbf{x}) = \begin{cases} 1 & \text{if } 0 \leqq y_{rs}(x) \leqq \theta \\ 0 & \text{if } \theta < y_{rs}(x) \leqq 1 \end{cases}$$

Step 4: *Stopping test.* If all state vectors are examined, go to step 5. Otherwise, take another state vector $x \in X$ and go to step 2.

Step 5: *Reliability.* The reliability measure of each OD pair *r-s* is given by the expected value of the operating/failed function;

$$R_{rs}(\theta) = \Sigma\, P(\mathbf{x})\, Z_{rs}(\theta,\mathbf{x}).$$

Du and Nicholson (1993) also developed an approximation algorithm[1], which is efficiently calculate the reliability measure without enumerating all of the possible state vectors.

Compared with the connectivity measure of the previous reliability studies, the proposed reliability measure incorporates the decrease of OD travel demand in the network with degraded links. Thus, it is suitable to evaluate the reduced level of activities between an OD pair. The reliability measure is interpreted as the composite variable of the aggregated travel choice behaviour of drivers and the operating/failure criteria θ. The value of θ is exogenously determined according to the level of service of the network. Thus, the decision of the network management authority is reflected in the reliability measure through the criteria θ.

5. MODEL APPLICATION TO SHIKOKU NETWORK

The traffic assignment and reliability models are applied to the road network in the Shikoku Area of Japan. Shikoku is one of four main islands of Japanese Islands and its area is 18,782 km^2 which covers about 5 % of Japan. The population of the region is 4,195 thousands which is amount to 3.4% of Japan. Since Shikoku is located south-west of Japanese Islands and the land is mountainous, it has been sometimes suffered from natural disasters mainly by typhoons. Thus, maintaining reliability is one of the main issues of road network planning and management in the area. Before calculating the assignment and reliability models, the status of the Shikoku road network is presented.

5.1 Analysis of Road Network in Disasters

The national highways in Shikoku has been constructed and managed by the Ministry of

[1] The general idea of approximation algorithm was first proposed by Li and Silvester (1984) and then improved by Lam and Li (1986). The algorithm was developed to analyze communication networks rather than transport networks. The method is efficient since it considers the most probable states instead of enumerating all possible fail states.

Construction (MOC) and four local governments called prefecture. Table 1 summarizes the length of precautioned sections in the Shikoku road network. The total length of national highway networks is 2802.1 km which involves 23% (644.6 km) of road sections that may take precautions against natural disasters. The rate for prefectural roads seems better than the national highways. This does not mean that the secondary roads are safety than the primary roads. Precautions and traffic closures for secondary roads are difficult and this results in the small percentages of the length of precautioned sections to the total administrated length.

Table 1 Length of Precautioned Sections in Shikoku Road Network

	Highways Class-1	Highways Class-2	Sub Total	Prefectural Roads	Total
Total Length (km)	1,207.0	1,595.1	2,802.1	8,492.6	11,294.7
Precautioned Length (km)	156.8	487.8	644.6	1,301.1	1,945.7
Rate (%)	13	31	23	15	17

Length : administrated length in 1992

Class-1 : national highways directly administrated by the Ministry of Construction

Class-2 : national highways administrated by prefectures

Figure 2 shows the location of precautioned sections of the national highways directly administrated by the MOC. A section is physically closed if the occurrence of disaster is expected. The criteria of closure are mainly based on the amount of rainfall; intensity of rainfall per hour or cumulative intensity of continuous rainfall from the beginning. It depends on the geological and structural conditions of a road section concerned.

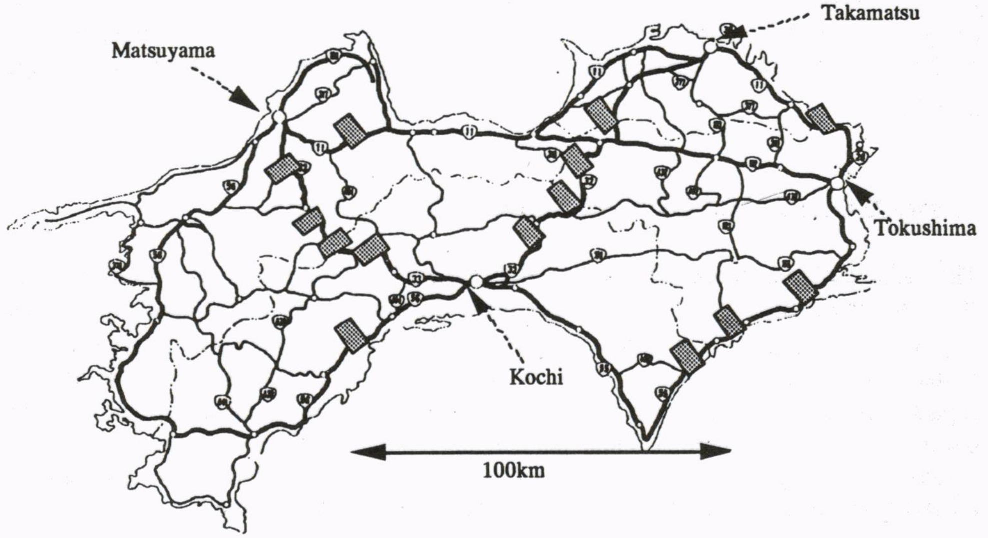


Figure 2 Location of Precautioned Sections of Shikoku Road Network

MOC has put on record of road sections actually closed due to natural disasters or precautions for their occurrence. We obtained the recorded data for 1207 km of road sections of national highways which consist a primary road network in Shikoku and are directly administrated by MOC. A record includes the location, duration and main reason of a closure. The records of last 5 years are used for analysis. There were 128 closures in the national highway network during last 5 years. This means that we must prepare for a sudden deterioration of the primary road network for about 26 times per year. Almost all of closures took place on the southern coast routes and the routes in mountainous areas. About 80% of closures occurred during June and September; rainy seasons and visits of typhoons.

Figure 3.a depicts of the frequency distribution of reasons of closures. The figure in the parenthesis after each reason presents the number of cases corresponding to the reason. 70 cases of 128 closures are due to precautions of disasters. About one third of closures are caused by the physical reasons such as structural damages including slope slip, stone fall, submergence and high waves. The rest of them are reconstruction works.

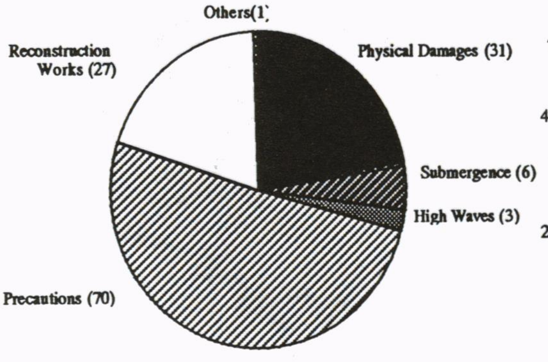


Figure 3.a Reasons of Closures

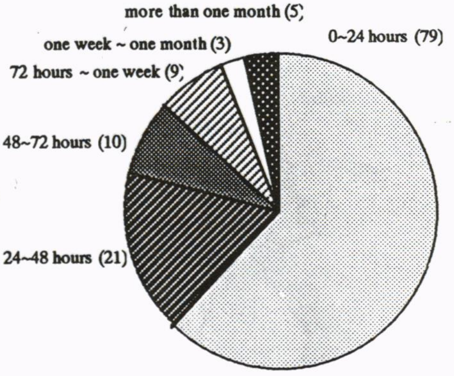


Figure 3.b Duration of Closures

Figure 3.b shows the frequency distribution of closure durations. Two thirds of closures are opened again within 24 hours. This ratio is consistent with the fact that the precaution for disaster usually closes traffic for one day or less. About 20 % of closures continue more than 72 hours and there are 5 cases in which corresponding road sections could not be used for more than one month. The averaged duration of closure is consequently amount to 154 hours (about one week).

The Ministry of Construction monitors road traffic flows by detectors. There are 43 observation stations on primary roads where traffic volumes per hour are automatically recorded. Using the observed traffic counts, we will investigate how much traffic volumes decrease in a degraded network. Taking an example of the traffic closure of road sections due to the visit of the typhoon number 13 in September 1993, when 16 sections including almost all of precaution sections were closed during Friday evening and Saturday morning. The duration of closure was about 8 hours. Figure 4 depicts the closed sections at that time.

Figure 5.a shows the day-to-day fluctuations of observed traffic volumes per day at four stations in the week during Wednesday 1st and Tuesday 7th of September. The traffic volumes on Friday 3rd decreased to about 80~90% of ordinary or usual volumes. The reduction rates of traffic volumes of these stations were not so different since these stations were located on the primary highways. However, the value of the reduction rate at a road section will depend on the location. Trips with longer trip length connecting distant cities are more influenced by the closure of road sections, while shorter trips near city areas are not so affected. If an observation station is located on the road where interregional trips are dominant, the observed traffic volume at the station decreases relatively more than the

stations located near large cities. The other point shown in Figure 5.a is that the traffic volume of Monday seems larger than that of Friday. This may indicate that the trips on the closed day would be postponed to the next weekday.

Figure 5.b illustrates the fluctuations of traffic volumes per hour at an observation station. The general shape of within-day fluctuation is not so different between ordinary and unusual days. However, it is found that traffic volumes begun decreasing in Friday afternoon and recovering in Saturday afternoon. The traffic volumes at peak hours decreased about 80% of the usual volumes.

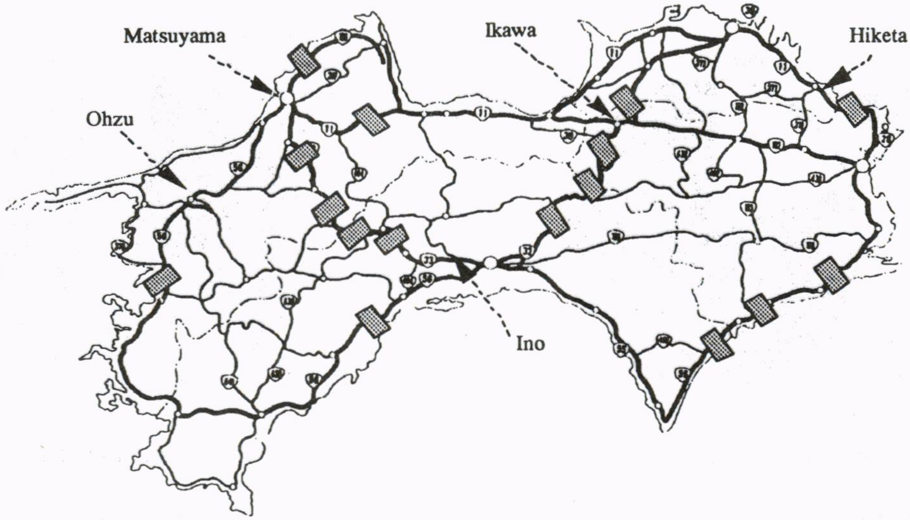
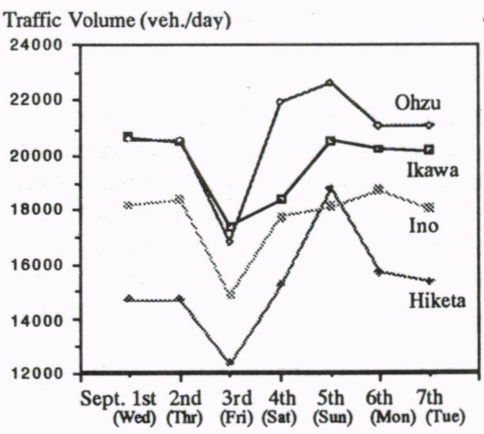


Figure 4 Closed Road Sections during Friday 3rd and Saturday 4th of September 1993



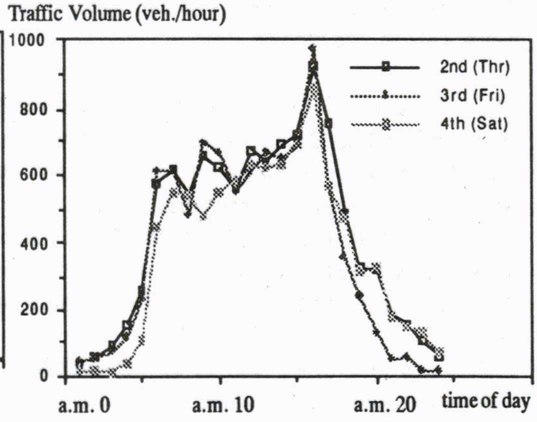


Figure 5.a Day-to-Day Fluctuations of Traffic

Figure 5.b Within-Day Fluctuations of Traffic (Ikawa)

These results are based on the MOC records and observations of primary highways where the level of maintenance is comparatively better than the other roads, of which the possibility of damage will be higher than the primary roads. The primary roads consist of 40% of the highway network, the network as a whole will be less reliable. It is noticed that there are some drivers who must use unreliable routes at any risk.

5.2 Traffic Assignment

We prepare a network for traffic assignment which consists of trunk roads and primary roads in Shikoku area. The network has 2,106 links and 697 nodes including 258 centroids. The MOC administrates the Road Traffic and Transport Census every 5 years, which provides an origin and destination (OD) matrix of vehicles in a normal day through interview survey. We use the OD matrix surveyed 1990, in which about 2.5 million vehicle trips were generated per day in the area.

We calculated traffic assignment for following two networks;

Case A : A normal network in which all links are not closed.
Case B : A degraded network in which some road sections are closed. This corresponds to the precaution taken against the typhoon number 13 in September 1993.

For both cases, we assume following parameter values; the detour limit m is equal to 1.5 and the coefficient of variance of link travel time β is set to 0.2. These values are based on the previous experiences on road network flow analysis. Number of iterations N is set to 20.

The role of *Case A* assignment is to examine the fitness of the simulation-based stochastic assignment model under normal traffic conditions. The calculated values of link traffic volumes were compared with the observed ones. Number of observed links were 101. The value of correlation coefficient between calculated and observed link traffic volumes was 0.871. This indicates the results of the simulation-based stochastic assignment model show relatively good fitness with the observed network flows.

In *Case B* network, 16 sections which correspond to 22 links in the assignment network were set closed for about half day; at least 7 hours at most 12 hours. The calculated value of cancelled trips in the network is amount to 37,909 trips out of 2,567,121 trips in the whole area. There are 116 OD pairs out of 2080 pairs[2] that are obliged to cancel all or a portion of travel demand. More than 50% of travel demand are cancelled for 34 OD pairs of 116 affected OD pairs. 15 OD pairs of them have to completely give up travelling at that time. The percentage of cancelled OD trips to the whole travel demand is less than 2%. However, the amount of total travel demand of affected 116 OD pairs are 739,707 trips. This implies that about 30% of total trips between the 116 affected OD pairs were possibly influenced by the traffic closure of road sections. Thus, the ravellers in the area are potentially faced with the deteriorated level of service of the road network.

The influenced OD pairs spatially distribute along south-east coast, north-west coast, south-west coast and mountainous route connecting Kochi and Matsuyama. The expressway network is not available for those OD pairs and/or the distance between the concerned OD pair is relatively short. Table 2 shows the comparison of the mean travel times from

[2] Traffic assignment was calculated using the 258x258 OD matrix. Then 258 detailed zones were aggregated into 64 representative zones for convenience. This yields to 2,080 OD pairs of the triangle OD matrix with 64 zones.

Matsuyama to other local capitals. The ratio of the mean travel time in the *Case B* network is about 1.1 ~ 1.2 times of that in the *Case A* network. Therefore the amount of cancelled trips were not so large since the value of detour limit was set to 1.5.

Table 2 Comparison of the Mean Travel Times from Matsuyama

City Name	Travel Time in *Case A* network (min.)	Travel Time in *Case B* network (min.)	Ratio (B/A)
Tokushima	309	347	1.12
Takamatsu	204	242	1.19
Kochi	195	233	1.19

5.3 Network Reliability

Here we show the results of the case studies of evaluating the reliability measure. The data available for identifying a state vector space X are the MOC records of traffic closure of primary roads, and the situations of secondary roads are not known. Thus, case studies are calculated assuming that traffic closures are taken only for primary roads and all secondary roads are operated at any conditions. Therefore, it is noted that the estimated values of network reliability should be carefully interpreted.

For estimating network reliability measures presented in the section 4, a state vector space $X=\{x\}$ and the occurrence probability $p(x)$ of a state vector $x \in X$ must be identified. All of the 128 closures recorded in the MOC data are classified into 48 patterns such that the combinations of closed links are common. Each pattern corresponds to a state vector. The occurrence probability of a state vector is then estimated as a conditional probability when traffic is closed at any links of the network. Furthermore, the probability is assumed proportional to the duration time of the closure.

The values of parameters m and β, and the number of iteration N used in the simulation-based traffic assignment are the same as the values used in the previous section. The criterion θ for computing the operating/failed function of each OD pair is treated as a parametric variable. This means that the computation of reliability is executed for each different criterion θ.

When the value of θ is set to 0.3, the reliability measures of all OD pairs are calculated and then compared each other. For 83 OD pairs out of 2080 OD pairs, the reliability values are less than 1.0. Table 3 lists the unreliable worst ten OD pairs. The worst value of reliability is obtained for the OD pair connecting mountainous areas in Ehime and Kochi prefectures. The value is equal to 0.917, which implies that 30% of car drivers of this OD pair will give up travelling for 8.3 times if there are 100 times of traffic closure in the network. Due to the assumption that secondary roads are operated at any conditions, almost all of OD pairs might have a diversion route within given detour limit. Therefore, the computed value should be considered as an upper limit of the reliability measure.

Table 3 Unreliable OD Pairs Worst Ten (θ = 0.3)

Origin and Destination Pair (Prefecture)		Reliability Value
Kamiukena(Ehime)	~ Takaoka(Kochi)	0.917
Suzaki (Kochi)	~ Nakamura(Kochi)	0.940
Naruto(Tokushima)	~ Okawa (Kagawa)	0.943
Suzaki (Kochi)	~ Hata (Kochi)	0.962
Miyoshi (Tokushima)	~ Sakaide (Kagawa)	0.965
Miyoshi (Tokushima)	~ Nangoku (Kochi)	0.965
Hojo (Ehime)	~ Ochi (Ehime)	0.965
Kaifu (Tokushima)	~ Muroto (Kochi)	0.978
Anan (Tokushima)	~ Muroto (Kochi)	0.978
Agawa(Kochi)	~ Hata (Kochi)	0.978

When we increase the criterion θ, the computed value of reliability seemingly increases. For example, an OD pair may be regarded operated at $\theta = 0.7$ while the OD pair is not operated at $\theta = 0.3$. This is because a higher value of θ makes an OD pair being operated at lower level of OD flows. For any criteria, unreliable OD pairs distribute along sea coast lines or in mountainous areas. This is consistent with our experience and the estimated reliability values could be used for relative comparisons among OD pairs.

6. CONCLUSION

We presented a simulation-based stochastic traffic assignment model which could be applied to describe traffic flows in a road network with degraded links due to natural disasters. The proposed assignment model is incorporated into an evaluation model of network reliability. Principal findings of this paper are summarized as follows;

(1) Assuming a normal distribution of link travel times, a stochastic traffic assignment model can be calculated using Monte Carlo simulation. A driver's diverting behaviour in a degraded network is explicitly considered in the assignment model. A driver is assumed to travel along the shortest route unless the route travel time spent in the degraded network compared with the travel time in a normal network exceeds the acceptable detour limit. Thus, the reduction of travel demand due to the inconvenience of a degraded network is considered in the assignment model, which is included in a procedure of evaluating network reliability measure.

(2) Traffic closures due to natural disasters in Shikoku area are recorded by the Ministry of Construction. It is found that traffic closures are expected to occur 25 times a year and the averaged duration of a closure is expected more than 150 hours. The observed traffic counts indicate that about 20% of traffic volumes may decrease in a degraded network.

(3) Proposed simulation-based network traffic assignment model is applied to the Shikoku road networks; a normal network and a degraded network. The link traffic volume calculated for the normal network shows a good fitness with the observed one. The calculated

reduction rate of travel demand in the degraded network seems slight. However, one third of travellers are found potentially faced with the deteriorated level of service of the road network.

(4) The value of a network reliability measure is provisionally estimated. The spatial distribution of unreliable OD pairs calculated through the model are consistent with our experience. Since secondary roads are assumed being operated at any conditions, the worst value of reliability between OD pairs seems not so serious. Thus, the estimated value should be interpreted as the upper limit of reliability measure.

Although we have shown that proposed models could be applied to evaluate an actual road network, the models still remain at development stage and further improvements are necessary. In particular, a driver's diversion behaviour should be studied for detailed modelling of traffic assignment. The identification process of a state vector space in reliability modelling must be improved so that the model would be applied to evaluate alternative network plans in the future as well as the analysis of a present network. The trade-off relationships between investment cost and reliability are also investigated. It is useful to examine an optimum investment policy on road networks in order to improve reliability against disasters.

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