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RISK MANAGEMENT BASED ON AN INTEGRATED TRANSPORTATION NETWORK AND INPUT-OUTPUT MODEL

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ABSTRACT

When a large-scale disaster occurs, a road network system can be severely damaged. This damage causes economic loss due to the failure of trading goods inside and outside the physically damaged areas. Hence, the disaster influences not only the damaged companies, but also the non-damaged companies. It is important from the viewpoint of management to determine which route should be reinforced or quickly recovered by specifying the route to which damage can bring the greatest economic losses.

Economic loss by a disaster has been analyzed using the input-output model. However, because the trading pattern could be changed due to the traffic network damage during a disaster, the structure of the input-output model must be arranged for the disaster mode. The trading pattern after the disaster must be determined considering the increase in the transport time and cost by detours and congestions.

In this way, an economic model that considers the road network model is necessary. Based on previous studies, this paper extends the models, which integrate the input-output model and road network models. As a case study, the Mid-Niigata Earthquake, which occurred on October 23, 2004, is then focused on, and the economic loss caused by the traffic damages is calculated.

KEY WORDS

risk management, transportation network model, input-output model, economic loss, Mid-Niigata Earthquake

INTRODUCTION

As the population and economic activities grow in urban areas, our lives and economy depend more on the transportation network system for shopping, commuting and trading.

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Basically, the transportation network system tends to be optimized or planned for our daily lives.

However, what we have learned from past disastersis that the system can be easily paralyzed and people and firms are obliged to use the partially available road network after a severe disaster. The Mid-Niigata Earthquake that occurred in Niigata Prefecture, Japan, in 2003 is the typical case, which demonstrates the vulnerability of the transportation networks. In this disaster, trunk road networks were severely damaged and several villages and towns were isolated. Many firms has to use detour routes and the increased transportation costs became one of the reasons to stop the business activities.

The loss estimation caused by the transportation network damage is of great concern to determine the strategy for the reinforcement and recovery of a road network against large-scale disasters. Using the OD (origin-destination) flow data and traffic assignment model for each link (i.e., transportation network model) would be one of the traditional approaches to determine the impact of transportation damage. However, the affected area is usually very local, and usually only a limited amount of OD flow data is available. In addition, in the disaster case, the trading pattern itself could be temporarily or permanently changed.

The combination of the input-output model and transportation model, such as shown by Kim et. al has the possibility to provide the "rules" to determine both the OD pairs and link flows "inside" the damaged areas. This paper aims to extend the models focusing on the inbound and outbound traffics inside the damaged areas, and apply the model to the actual Mid-Niigata earthquake case. The applicability of the model is thoroughly tested and the case study and the recommended recovery strategy based on the model calculations are compared with the actual recovery patterns of the road network.

FRAMEWORK OF THE ANALYSIS

PREVIOUS RESEARCH

There have been many studies which aimed to estimate the economic loss caused by the transportation disruption. Basically, once the OD flow data are obtained, a traditional traffic flow assignment model can be applied.

However, estimation of OD flows during the disaster is the key issue in this field. One of the representative ways to endogenously determine the OD flows in an industrial and non-industrial sector during the disaster is adopting an inter-regional econometric model. For example, Cho and Gordon et al. (2001) built the econometric model called Southern California Planning Model (SCPM), which determined the OD flows by integrating the transportation network model and input-output model, and people's traffic behavior such as commuting and shipping. Basically the traffic (industry, people) is determined by the distant-decay type of Gravity model considering the network cost. The developed model has been applied to the Los Angels metropolitan Area, which is features five-county, 1527 traffic zones with 19601 links and 308 zones for human activities.

Kim et al. (2002) developed the model called interregional commodity flow model (ICFM), which integrate the transportation network model and multi-regional input-output model. Based on Evan's Algorithm and Wilson's iterative balancing method, the sectoral transportation cost can be calculated. In Sohn et. al. (2003), the model is applied to the 1812 New Madrid earthquake scenario analysis, considering 13 sectors and 36 zones in the United States. As a result, it has been pointed out that the identified critical links from an economic point of view are different from the critical links which can be physically damaged with a high probability.

The IO model part can be extended to the Computable General Equilibrium Model (CGE Model), which can determine the output of each sector and final demand based on the price mechanism (e.g., Tsuchiya et al.). In this case, the transportation cost is reflected in the price of goods in each sector, and the final demand and utility of each household decreased. The utility deterioration could be counted as the economic loss.

In this way, several models and case studies regarding the economic loss and transportation damage are proposed. The spatial scale of obtained data is one of the critical points for applying these models to the locally damaged areas. Arrangement of the models within the limited amount of datasets is necessary to analyze the transportation cost within the damaged region and the model should be checked by the actual post-disaster case studies.

THE INTEGRATED INPUT-OUTPUT AND TRANSPORTATIN NETWORK MODELS

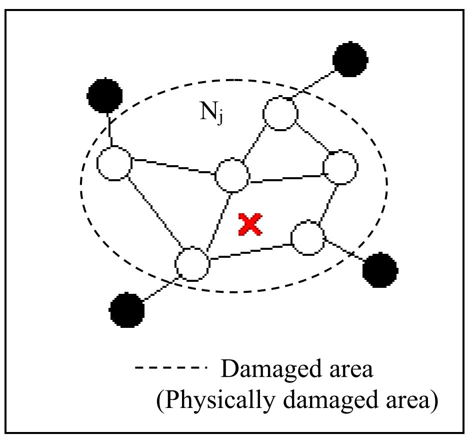

Figure 1: nodes and links inside and outside the damaged areas

We aim to extend the model proposed by Kim et al. (2002) by considering the intra-regional and inter-regional traffic inside the damaged area. Figure 1 shows a simplified structure of the road network, where the nodes (subregions) are divided into two types: nodes in the damaged area and nodes outside the damaged area. Nodes outside the damaged area are arbitrary sub-regions, which are connected by the link (road) to the damaged area.

The characteristic assumption in our model is that the amount of the inbound trading goods must meet inter-industry structure of each node, but the outbound trading goods can reach any nodes outside the damaged area in addition to the basic assumption that the firms prefer to hold transportation costs as low as possible. This assumption is derived from empirical observations such that the firms avoid increased traffic inside the damaged area for a smooth recovery and that it makes more sense in the case that the road network being redundant enough outside the damaged area.

Let x_{ij}^m be the flow (yen) of sector $m \in M$ from Node $i \in K$ to the Node $j \in K$ per day.

where the subregion K consists of two subregions, $\Omega_1 = \{1, 2, 3 \cdots \mathrm{p}\}$: the "damaged" subregion and $\Omega_2 = \{p+1, p+2, \cdots \mathrm{P}\}$:the "non-damaged" subregion so that $k = \{\Omega_1, \Omega_2\}$. Also, let h_{ijr}^m denotes the flow (tons) of sector m per day from subregion i to j by route $r \in R_{ij}$. In addition, let f_a denote the total flow (tons) on link $a \in A$ of the network. Link flow f_a can be defined using h_{ijr}^m as follows:

$$\sum_m \sum_{ajr} h_{ijr}^m \phi_{ijr}^a = f_a \quad . \tag{1}$$

where the $\phi_{ijr}^a = 1$, if route r from i to j used link a, and $\phi_{ijr}^a = 0$,otherwise,

Considering the assumption that trading patterns are determined based on a user equilibrium model with a constraint of input-output model, the Commodity Flow Model considering the inbound and outbound flow to and from the damaged area is expressed as follows:

$$\min_{h,x} Z(h,x) = \sum_a \int_0^a d_a(\omega) d(\omega) + \sum_{mj} d_{jj} \frac{x_{jj}^m}{g^m} + \sum_m \frac{1}{\beta^m g^m} \left\{ \sum_{ij} \left(x_{ij}^m \right) \ln \left(x_{ij}^m \right) \right\} \quad , \tag{2}$$

where the $d_{jj} > 0$, if $j \in K_1$, and $d_{jj} = 0$,if $j \in K_2$

s.t.

$$\sum_i \left(x_{ij}^m \right) = \sum_n a^{mn} \left(\sum_k x_{jk}^n \right) + y_j^m - M_j^m \quad , \qquad \forall m, j, \tag{3}$$

$$h_{ijr}^m \geq 0 \quad , \qquad \forall m, i, j \tag{4}$$

$$\sum_j x_{ij}^m \leq \hat{x}_{i\max}^m \quad , \tag{5}$$

case of disaster

$$\sum_r h_{ijr}^m = \frac{x_{ij}^m}{g^m} \quad , \qquad \forall m, i \in K, j \in K \tag{6}$$

and in case of disaster

$$\sum_r h_{ijr}^m = \frac{x_{ij}^m}{g^m} \quad , \qquad \forall m, i, j \tag{7}$$

where $i \in \Omega_1, j \in \Omega_1$,

$$\sum_j \sum_r h_{ijr}^m = \frac{x_{ij}^m}{g^m} \quad , \qquad \forall m, i, j \tag{8}$$

where $i \in \Omega_1, j \in \Omega_2$,

Equations (8) means commodity flow from damaged subrigion to non-damaged subrigion changes the destination so that the link cost may lower most in case of disaster.
where d_a used the link performance function, hence the first term of the objective function expresses the total link cost (yen) of the inbound and outbound traffic from the damaged subregions. The second term is the intraregional travel cost and the third term is the entropy function, which has an effect on aggregating the same items of commodity flow in the same subregion pairs. The control variables for the objective function are the **h**:vector of the interregional route flow and, the **x**:vector of the interregional flow.

In equations (3)－(8) , the exogenous variables are :
a^{mn} : technical input-output coefficient (input of m for producing one unit of output of sector n) β^{m}: cost sensitivity parameter for sector n, d_{jj}: intraregional travel cost for region j, g^{m}: factor for converting sector m from yen to tons (yen/ton), y_j^m: final demand for sector m in region j (yen). M_j: import from outside the damaged area. For simply looking at the influence of the outbound goods, our case study assumes that value is defined as being proportional to $\sum_j x_{ij}^m, j \in \Omega_2$ and contributes nothing to the transportation cost.

The Kuhn-Tucker conditions are obtained with some modifications of Kim et al. (2003). However, by applying the entropy maximization method such as Wilson's iterative balancing method and flow distribution assignment method such as Evans algorithm, (**h**, **x**) can be iteratively solved. That is, after setting the initial values. This iterative process is continued until the values of the control variables converged.

3.CASE STUDY

3.1 DAMAGE TO THE TRANSPORTATION SYSTEM DURING THE MID-NIIGATA EARTHQUAKE

The Mid-Niigata Earthquake (Magnitude 6.8) occurred in the central mountainous area in Niigata Prefecture, Japan, on October 23rd, 2004. 51 people died and 4,794 people were injured. Evacuees included about 103,000 (October 26), and damage occurred to about 16,000 houses.

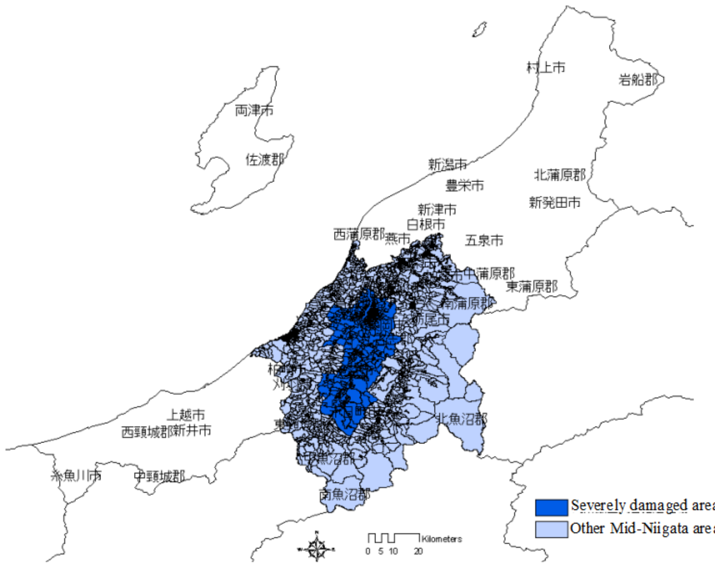

Figure 2: Mid-Niigata and Severely Damaged Areas

The Transportation network was devastated in many places. The damage to roads was mainly caused by landslides. Basically, there are a lot of landslide-warning areas in Mid-Niigata. In addition to this natural feature, heavy rainfalls before the earthquake and large-scale aftershocks are thought to induce and enhance the landslides.

However, the redundancy of the trunk road network contributed to reducing the losses in the Japan-wide interregional trading. The Kan'etsu expressway was damaged so that the traffic between Niigata and Tokyo was restricted for a long time, but the "Shin'etsu" expressway and the recently constructed "Ban'etsu" expressway could substitute for the traffic flow on the Kanetsu expressway. The more serious problem that existed in the traffic flow was inside the damaged region.

3.2 DATA SET

For the case study, the Mid-Niigata region was divided into 22 sub-regions by the administrative boundaries of the city, town and village levels. Figure 3 depicts the 22 sub-regions as nodes, which are connected by 49 trunk roads. 6 nodes outside the region were set in the extended area of the main roads. Damage information on Oct. 23rd in Figure 3 illustrates that more than half of the links lost their functions.

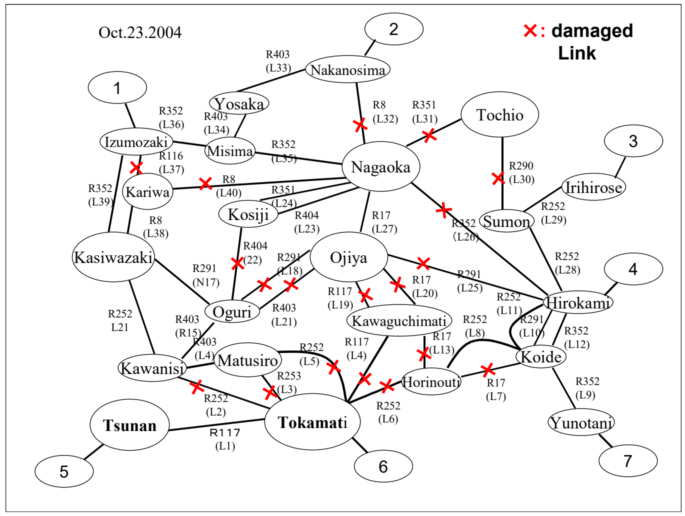

Figure 3: Topological structure of the Mid-Niigata Area used in the case study. Damage information is as of Oct.23rd, 2005

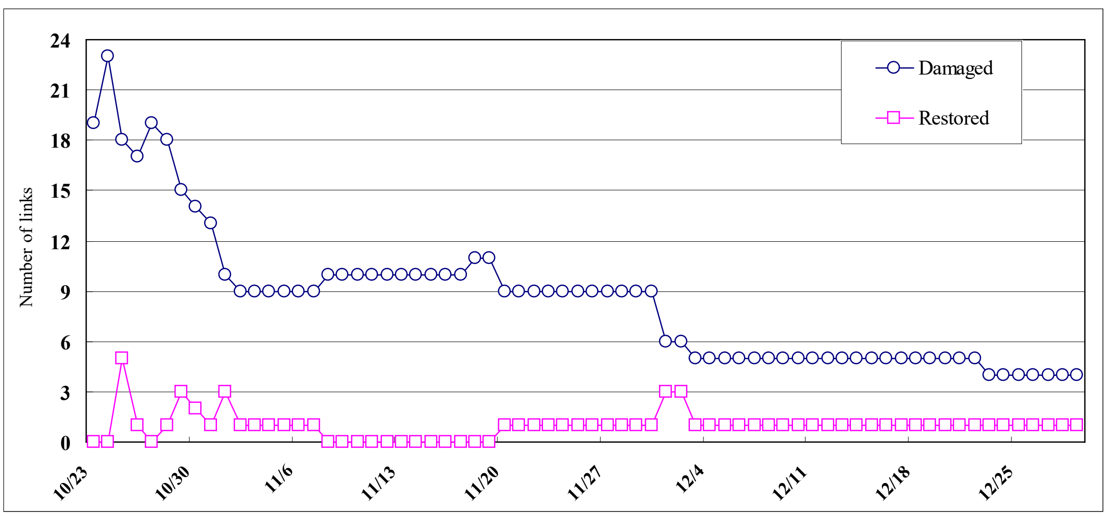

Figure4: Number of restored links per day and number of damaged links to be recovered

Figure 4 is a graph of the number of restored links per day and number of damaged links to be recovered. The restoration of the link was not advanced by the influence of the aftershocks within one week from the earthquake occurrence date. About 50% of the links were restored in November, and about 75% were completed in December.

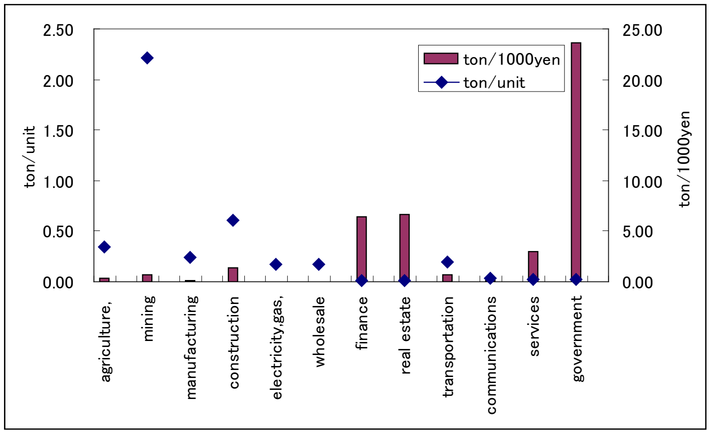

Figure 5: Factors for converting from money to tons and one unit(trip) to tons for each sector

Figure 5 shows g^m, the factor for converting sector *m* from money (thousand yen) to tons and the factor for converting sector *m* from one unit(trip) to tons. The other datasets and assumptions are as follows:

- Input-output coefficients in each node are the same as the one in the Niigata prefecture.
- The amount of exporting goods are determined according to the number of firms' employees based on statistics in Niigata local government (2005a). In more detail, the percent of exports in the total output is proportional to the fixed values classified by sector and number of employees.
- Final demand is assumed to be proportional to the population in each node.
- The interregional trade between the damaged area and non-damaged area in Niigata Prefecture is determined to satisfy the input-output structure and to import the least amount of goods (to determine M_j in equation (4)). That is, we basically assume that the damaged area tries to consume products and service, which are produced and offered in the damaged area.
- Output per day is obtained by dividing the output per year by 365 days for convenience.
- 12 sectors are used in our case study.
- Traffic from inside the damaged region to outside the damaged region was assumed to be one-way traffic in the analysis.
- After the earthquake, the production activity does not stop and the final demand does not decrease.

3.3Application

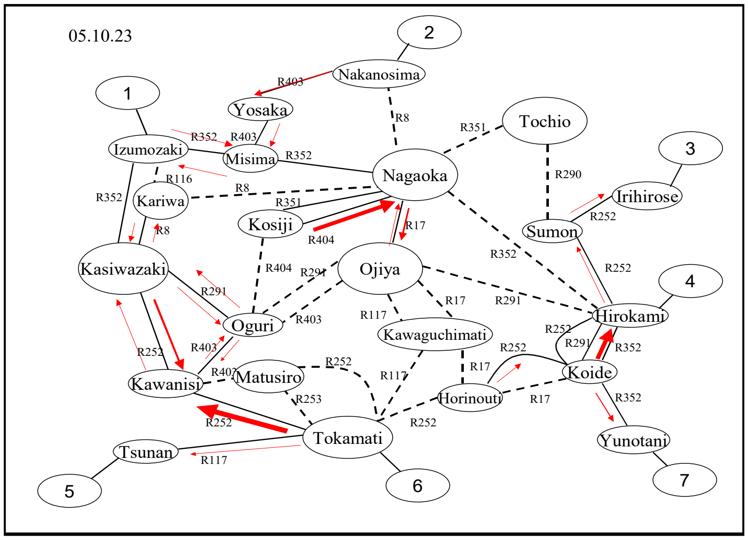

Figure 6: Amount of increased traffic cost (after the disaster/before the disaster) on October 23, 2004

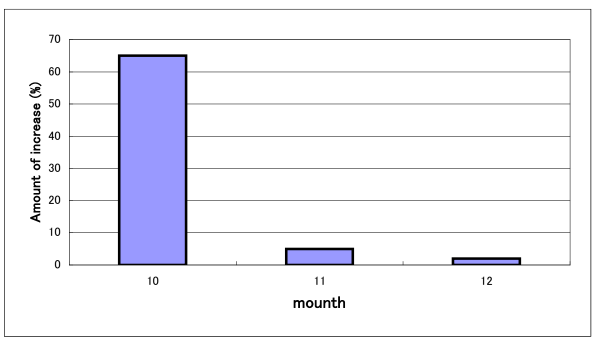

Figure 7: Monthly average increased route cost (after the disaster/before the disaster)

Figure 6 shows an increase in the link cost on the October 23, 2004. Damaged links are indicated by the dotted lines. The ratio of the link cost after the disaster to the link cost before the disaster is shown by the thickness of the line. It is understood from the figure that increases in the route costs from the damaged area to outside the damaged area are significant. In other words, damage to the transportation network hasa great influence on the outbounded traffic to the damaged area. Figures for the link costs after October 23 are omitted in this paper due to the page limitation, but these link costs decreased with the passage of time (see Figure 7). The link cost in December became almost the same as the value before the earthquake.

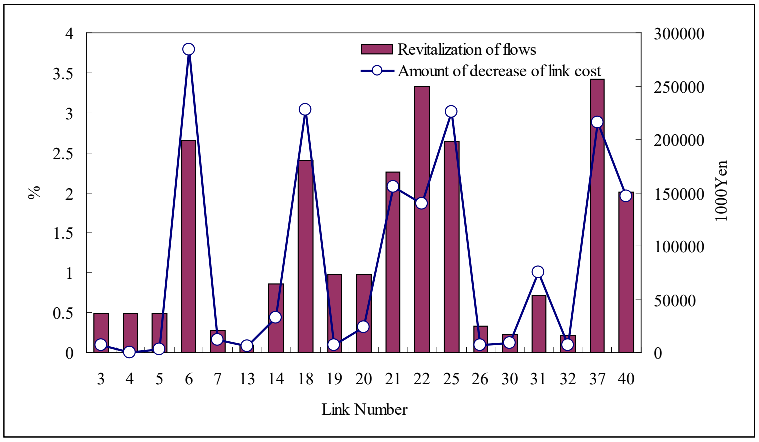

Figure 8: A ratio of the recovery of traffic flow and amount of decreased link cost by the recovery of one specific damaged link

Figure 8 shows a ratio of the recovery of traffic flow (yen) and amount of decreased link cost when only one specific damaged link was repaired on October 23. The ratio of the recovery flows such as on the 22nd and the 40th links is high. On the other hand, in the actual recovery work, the 7th, the 31th, and the 40th recovered the earliest after the earthquake. Our case study shows that the recovery of the 40th link was efficient in terms of reducing the economic loss, but others are different from the suggested links by the model. However, this analysis basically does not include the cost of reconstruction works and the recovery priority should be discussed by the cost-benefit sense.

4.CONCLUSION

The Loss estimation caused by the transportation network damage is a great tool to determine the strategy for the reinforcement and recovery of a road network after large-scale disasters. However, the affected area is usually very local, and usually only a limited amount of OD flow data is available. In addition, in the disaster case, the trading pattern itself could be temporarily or permanently changed.

Therefore, we focused on the combination of the input-output model and transportation model and modifies the models focusing on the inbound and outbound traffic inside the damaged areas. The model was applied to the actual Mid-Niigata earthquake disaster, which occurred on October 23rd, 2004. After constructing the database of damage and recovery situations of links and some economic data, the increased link costs were calculated. It is shown that the link costs in the damaged area increases in a greater amount within one week from the earthquake occurrence time, but almost converges to the daily link cost in the following month. The priority of links to be recovered, which is suggested by the model, is compared with the actual recovery pattern of the damaged links. The Actual recovery patterns are different from the onessuggested by the model. As a future task, the analysis should include the cost of the reconstruction work, people’s travel behavior and so on, and discuss the recovery priority by in the cost-benefit sense.

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