Analysis of impacts of road network vulnerability on disaster relief operation

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Vulnerability of road network is a critical issue in planning of disaster relief operation. Broken down roads limit the accessibility to the receivers of the aid operations. In this study, we analyze the vulnerability of road network and its impact to the overall disaster relief operation. The relief operation plan of Aichi prefecture is selected for analysis in this study. We consider the possibility of damage on road network and other lifeline infrastructures due to seismic intensity, the recovery rate of the road network by road classes as well as recovery rate of the lifelines in order to evaluate the plans for relief operation. A Multi-depot, Multi-commodity Vehicle Routing Problem considering the vulnerability of the road network and lifeline infrastructures is proposed and discussed in this paper.

Key Words : *humanitarian, logistics, relief supplies, earthquake, Multi-Depot VRP*

1. INTRODUCTION

Disruption of road network limits the accessibility to provide aids in disaster relief operations. Berdica, 2002[1)] defined the vulnerability of road network as the susceptibility of the network to incidents that can result in a considerable reduction in road network serviceability.

The efficiency of disaster relief operations is very dependent on the quality of the preparation. A well-prepared plan means an increased likelihood of saving lives, while also making more efficient use of resources. Not only to predict the needs of victims in disaster preparedness, an effective relief operation cannot be achieved without a contingency plan to cope with the uncertainty of road network accessibility due to disaster intensity.

Therefore, in this paper, an integrated road network vulnerability, multi-depot, multi-commodity VRP model is proposed as a decision tool to support planning the optimum locations of hubs for the post-earthquake distribution of relief supplies.

The specific objectives of this research are:

1) To develop a model for the evaluation of plans for the distribution of goods in post-disaster situations for Aichi prefecture in response to the predicted Tokai-Tonankai earthquake
2) To consider the possibility of road network disruptions due to earthquake intensity, road network recovery, damages to lifeline infrastructures (water and gas) and their recovery rate into the model.
3) To find the optimum locations of hubs and to estimate the resources requirements for distribution of relive supplies (food and water).

2. MODEL FRAMEWORK

A model framework is proposed as shown in **Fig.1.** We consider three main sources of damages that will affect the relief operation, which are damages to housing, damages to lifeline infrastructures, and damages to road network. Damage to housing and the availability of clean running water are generally considered key elements determining the numbers seeking shelter in the wake of a disaster as in estimation in a report from Gumma prefecture[2]. While, the damage to road network affects directly to the response time as links' travel time substantially increases. Not only damages to the housings, and infrastructures, we also need to consider the recovery rate of the infrastructures. From the aftermath of the previous earthquakes, the work on recovery of road network is performed concurrently with the other relief operations, which informed the changes in road conditions and resulting in improved route travel time. Also, the recovery of lifeline infrastructures also causes the changes in number of victims at shelters. From the previous experiences, the numbers of victims at shelters decreases as the lifeline infrastructures are recovered.

We, therefore, incorporate thus information into our modeling. The model finally results in the optimum locations of hubs and the estimated resource requirements.

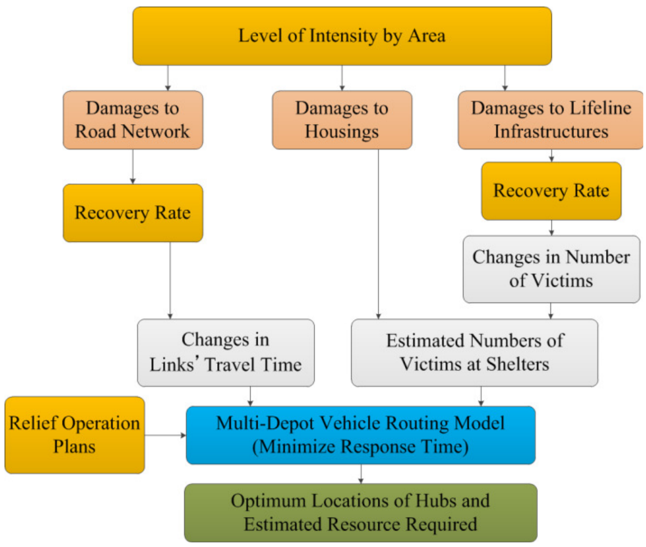

Fig. 1 Model Structure

3. A VRP MODEL WITH ROAD NETWORK VULNERABILITY

This problem is viewed as a multi-depot, multi-commodity vehicle routing problem (VRP). As the operation time is crucial for disaster relief, in this study, the objective function is set to be the optimization of total response time. The vehicle routing simulation provides a sequence for deliveries to stockyards, which minimizes the total response time with constraints on the maximum carrying capacities of trucks and on the maximum working hours of drivers.

$$\text{Minimize } \sum_{k=1}^{m}\sum_{i=1}^{n}\sum_{j=1}^{n}(c_{ij}\cdot p_{ij})x_{ij}^{k} \qquad (1)$$

Subject to

$$\sum_{i=1}^{n} x_{ij} = 1$$
$$\sum_{j=1}^{n} x_{ij} = 1$$
$$w(\mathbf{x}) \le wt_{max}$$
$$t(\mathbf{x}) \le tt_{max}$$
$$s(\mathbf{x}) \le s_{max}$$

$$x_{ij} \in \begin{Bmatrix} 1, \text{if i immediately preceeds j} \\ 0, \text{otherwise} \end{Bmatrix}$$

where,

p_{ij} = adjust factor on travel time of link ij whether the link is broken or fixed and is a function of intensity and road priority levels.
$p_{ij} = \infty$; if link ij is broken
$p_{ij} = 1$; if link ij is not broken or fixed.

c_{ij} = travel time between i and j [hours]

k = depot k.

n = number of receivers [secondary stockyards]

m = number of depots [places]

$w(\mathbf{x})$ = total load on vehicle of driver l [kg]

wt_{max} = maximum carrying weight of a truck [kg]

$t(\mathbf{x})$ = total travel time plus loading and unloading time of a driver [hours]

tt_{max} = maximum working hours of a driver [hours]

$s(\mathbf{x})$ = total volume for loading goods in truck used by a driver [pallets]

s_{max} = maximum space of a truck [pallets]

4. ANALYSIS OF SCENARIOS

(1) The Tokai-Tonankai earthquake

The coupled Tokai-Tonankai earthquake has an expected magnitude of 8.3 (M_w) and the intensity in Aichi prefecture ranges from 4.9 to 6.0 JMA[3]. The intensity distribution by region used here is the website of Gifu University Earthquake Engineering[4]

(2) Estimation of number of victims and demands at each shelter

In general, the number of victims who need to move to shelters are estimated from the summation of (a) victims having housings seriously damaged and (b) victims having water service stopped[2]. In this study, we calculate (a) from the probability of damages on housings by types and (b) from the probability of damages on lifeline infrastructures by types.

The damage to housing is estimated using the distribution of percentage of damages on wood and non-wood housings on various seismic intensities provided by the previous research[5].

For the lifelines, we utilize the statistic model developed by Nojima and Sugito[3] that estimates the level of damage, by seismic intensity level, on each type of infrastructures including electricity, water, and gas. The model was based on the experience of the Great Hanshin Awaji Earthquake in 1995. The model is a binary logit model estimating the probability that an earthquake with a given intensity will disrupt each lifeline utility.

This study analyses scenarios of the operations to provide "food and water" for the victims each day during the first week after the disaster.

The demands of goods by municipality can be determined from the previously calculated number of victims by setting the requirement to provide food and water to each victim for 3 meals a day (for each person, 2 breads + 2 rice balls + 3 bottles of 500ml water bottles).

(3) Damages to road network and its recovery

The road network may be damaged due to the seismic level and causing the impacts on accessibility and a consequence increase in operation time. As the work of recovery is performed concurrently with the other relief operations, this improves accessibility of road network. Based on the information from the damages and the recovery rate of the road network by road classes from the previous earthquake, we estimated the day-by-day road network condition for the first week after the disaster.

Based on the previous experience, we assume the roads in area expected to face the seismic of more than 5.5 JMA will have the possibility of being broken or shutdown. We randomly select the links as being broken using the probability with Monte Carlo Simulation. In the similar way, for the recovery of the broken links, we use the recovery rate by day and by priority class as an input and randomly select the links among the broken links to be fixed.

The recovery rate used in the analysis is as shown in **Fig. 2.** These numbers are based on the previous operation in the aftermath of the Great East Japan Earthquake and Tsunami. In this study, we assume the recovery rate at the same rate as previously.

The estimated day-by-day road network condition for each day after the disaster is as shown in **Fig 3.** In the figure, the links appear in red color mean the shutdown sections; while, the links in blue color are roads with no damage or are resumed back to be accessible again. The area in along the coastline is expected to be affected the most by the Tokai-Tonankai earthquake. According to the previous experience, the priority roads were given the first priority to be fixed with more than 85 percent were fixed on the second day and gradually fixed from the third day; while, normal roads were started to be fixed little by little from the third day. In this study, we use this recovery rate and results in the day-by-day condition of road network as an input into the simulation.

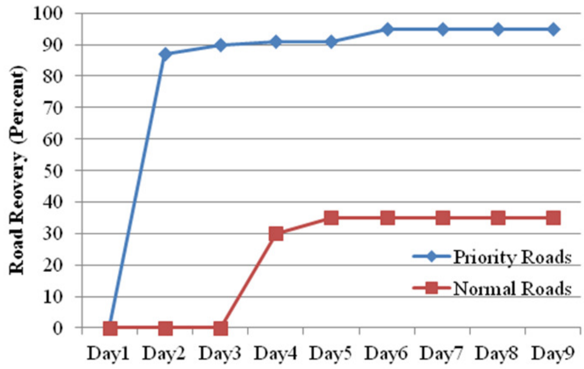

Fig. 2 Road Recovery Rate

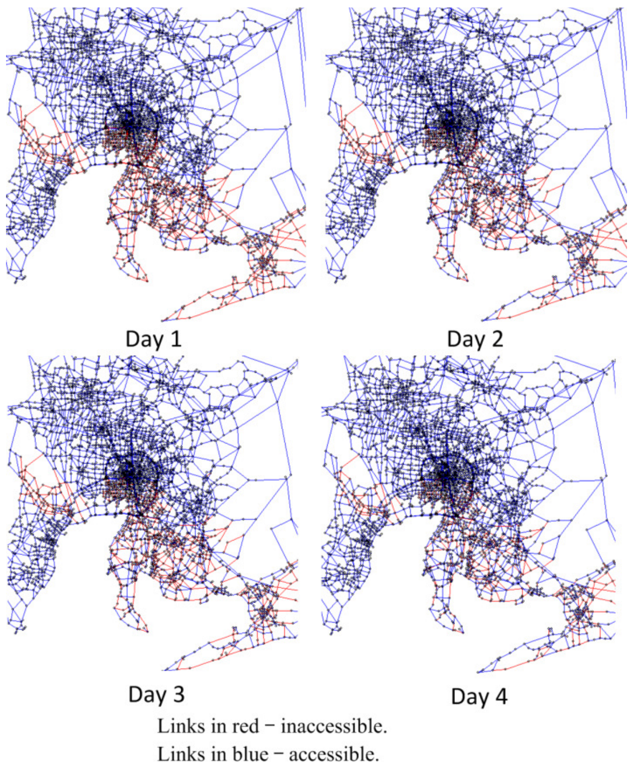

Fig. 3 Estimated Road Condition by Days After Disaster

(4) Initial parameter settings

In this study, we assume using 4-ton trucks (capacity of 3,500 kg. or 8 pallets) for the operation in order to ensure their accessibilities to all types of roads. As we consider minimizing the total response time, therefore, timing required for handling goods (loading or unloading) at each facility are included. Based on the survey, the operations during the Great East Japan earthquake in Sendai require approximately 70 minutes for loading or unloading of goods of a full 4-ton truck manually at a non-warehouse facility; while, in general, it takes 20 minutes for the same works at a warehouse with forklifts.

For road travel speed, we use the values based on our questionnaire survey among freight forwarders in Sendai who distributed goods during the aftermath of the Great East Japan earthquake conducted on June 25, 2012. From the survey, information on 79 separate delivery tours, performed by 21 different drivers, were obtained. Based on the survey results, the average driving speed of trucks during emergency was 42.3 kph on expressway and 16.0 kph on normal roads.

The delivery routes are different day-by-day depending on the estimated road condition (broken, unbroken, or fixed). The maximum working hours of each driver is set to 6 hours in this case in order to give the best efficiency with the total 24 hours utilization of trucks in a day.

5. RESULTS

In this study, the total number of 4 delivery hubs is used to distribute relief supplies to receivers (in this case are other city offices) which is the same to the Aichi prefecture' plans but the locations here are ones determined from our proposed model. The proposed network vulnerability integrated VRP model was solved using Genetic Algorithm for the total of 66 locations of city offices.

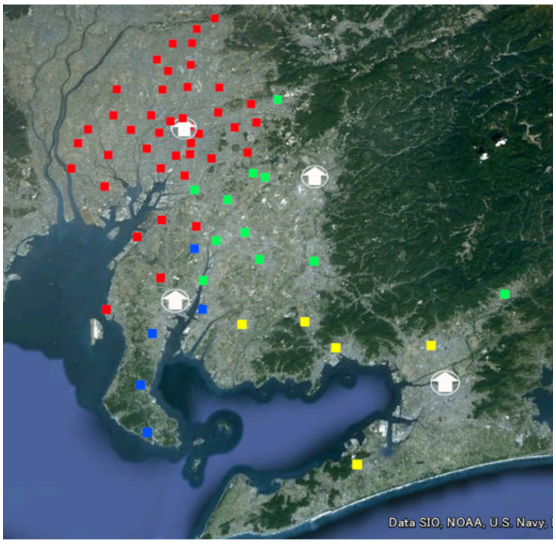

Fig. 4 Result of depots' locations and their groups

We performed the model for the second day after the assumed Tokai-Tonankai earthquake attacked the region. The model considers the intensity level that varies in each region to estimate damages on road links and also consider the recovery rate of roads by each road type. Also, by the estimated intensity level and its impact on other lifelines, we predict the number of victims to determine the demands as well as the recovery rates of the lifelines.

The results of depots' locations as well as cluster patterns are demonstrated in **Fig. 4** in which this allocation pattern results in the minimum total response time of 9,532 hours. This allocation pattern suggests the requirement of resources in total of 756 trucks for the second day.

6. CONCLUSION

It is important to consider the vulnerability of road network in the contingency plan of disaster response operations. In this paper, a multi-depot, multi-commodity VRP model integrated with road network vulnerability was developed. Not only to estimate the damages on lifelines (water, electricity, and road network), the day-by-day recovery of the infrastructures was also considered.

The model was used to determine the optimal depots' locations and their clusters for delivery of relief supplies in response to the Tokai-Tonankai earthquake scenario for Aichi prefecture. The model also calculates resource requirements, which are important for planning disaster relief efforts. It is better have reliable estimates of resource requirements in order to avoid the shortages which followed previous earthquakes. Simulation models of relief efforts can help planners to better estimate the resources required, the optimal placements of hubs and stockyards, and how to adapt to disruptions in these facilities or the transport network.

However, in this present model, we still yet consider the capacity of the depot facilities. This issue remains for the future improvement.

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