Modeling Disaster Response Operations including Road Network Vulnerability

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Abstract: Improved disaster preparedness can help save life, reduce the suffering of survivors, and enable communities to restart normal life more quickly. Vulnerability of road network is a crucial issue in planning of disaster response operations as it strongly impacts the response time. It is important for planners to take into account the possibility of road network disruption due to disaster as well as its recovery. This paper, therefore, proposes a model to evaluate and improve disaster response plans, considering impact of the possible degradation of road network due to disaster and its possible day-to-day recovery. The empirical data from the aftermath of the previous earthquakes is utilized. The model is applied to analyze and evaluate the Aichi prefecture's current plan of the first week to response to the most likely Tokai-Tonankai earthquake disaster. Countermeasures to improve the current operation plans are also discussed in this paper.

Keywords: Earthquake, Disaster, Humanitarian Logistics, Road Network Vulnerability.

1. INTRODUCTION

On Friday March 11th, 2011, a vast area of north eastern Japan was affected by a magnitude 9.0 (M_w) earthquake, the so-called Great East Japan Earthquake and Tsunami, which left more than 18,000 dead or missing and was described by the then Prime Minister the country's most severe crisis since World War 2 (Hongo, 2012). In recent years, disasters have been increasing worldwide in both frequency and severity, having ever larger impacts as the world becomes more interconnected. Many of these disasters are of natural origin, such as earthquakes, floods, and hurricanes. We must also learn how to better cope with the consequences of man-made disasters, both the intentional and the inadvertent. Such events require substantial disaster relief operations, which can benefit from improved contingency planning. The importance of this is most obvious for disasters whose arrival can be predicted with confidence, such as the strongly periodic Tokai and Tonankai earthquake systems in Japan, though the exact timing of these remains unknowable.

Humanitarian logistics is one of the most challenging areas in the field of logistics. The special challenges are due to some unique characteristics, the delivery of multiple

commodities to satisfy highly dynamic demand, through potentially multi-modal networks, under very strict time constraints, requiring the coordination of multiple disparate actors. Notably, time constraints in humanitarian logistics are more crucial than usual, because faster relief operations mean a greater likelihood of saving lives. Further factors that distinguish humanitarian logistics operations include: 1) Distinct phases of operation (including disaster prevention, preparedness, emergency relief, reconstruction, and development, and 2) Particular resource requirements (including materials, goods, and skilled staffs).

In planning disaster response operations, we should take into account the different phases of disaster relief. For example, survivors in temporary housing require a greater variety of goods once their initial needs for food, water and shelter have been met. This operation differs from the immediate response phase when basic survival goods are "pushed" through the supply chain, whereas in the later phase they are rather "pulled" through the supply chain, by the particular needs of those in shelters.

Since the 2004 Indian Ocean earthquake, particular attention has been paid to issues in humanitarian logistics. Much work concerns the planning of logistics operations in response to emergencies. Many discuss important issues and logistics related problems uncovered during previous relief operations (Hulguin-Veras *et al.*, 2007; Whybark *et al.*, 2010). In particular, there is considerable work on estimation techniques for vehicle routing models in relief operations. We can find a variety of choices of objective function, such as minimum cost, minimum unsatisfied demand, minimum total response time, and other performance indicators (De la Torre *et al.*, 2012; Wright *et al.*, 2006).

This literature is limited in comparison to the wider logistics literature, which is surprising for such an important topic. This may be due to the complexity of the problem, particularly the requirement for commitment and cooperation from many disparate actors in order to plan and implement successful relief efforts. Those who work in the field of humanitarian logistics frequently lament the lack of cooperation among the actors involved (Kowacs and Spens, 2007). The actors in the area include victims, government agencies, private sector actors, NGO agencies, donors (both private and institutional), as well as international aid agencies. This lack of cooperation causes unnecessary chaos, duplicated programs, and the wasteful use of precious resources.

There is a lack of knowledge regarding logistics operations in most governmental and NGO agencies. Encouraging cooperation with logistics experts would help to reduce these problems. Resources owned by logistics companies can be very useful in emergency situations. These resources include warehouses, depots, distribution centers, trucks, pallets, forklifts, and critically the skilled workers employed by these firms.

Problems identified by a report into the response to the Great East Japan Earthquake and Tsunami include: insufficient goods in pre-stocks; goods unsuited to the needs of victims; inefficient reception and re-distribution of goods; goods not reaching victims who stayed at home rather than moving to shelters (Iwate Prefecture, 2012). Contingency planning regarding the optimal positioning of distribution centers and warehouses can, as well as speeding deliveries, also help alleviate problems of inadequate appropriate storage space for relief goods. Many goods, and especially food and medical products, need proper storage to maintain their quality. Clearly, there is no adequate substitute for a good contingency plan in the event of a disaster.

Dealing with uncertainty is also one of the most difficult issues in disaster response operation; for example, the impact of road network vulnerability. The vulnerability of road

network is defined as the susceptibility of the network to incidents that can result in a considerable reduction in road network serviceability (Berdica, 2002). This effect is rather crucial; as for example, freight forwarders often face additional costs when delay occurred on goods arrival. The effect will be even stronger especially when the impact is on the disaster relief operation as the delay and losses means the reduced possibility to save more lives.

In this study, we therefore examine the impact of damage on road network as well as its recovery on the disaster relief operation. A model integrated with road network vulnerability is developed and applied to analyze the efficiency of the distribution of relief goods to victims in shelters in Aichi Prefecture, Japan, during the first week after the likely Tokai-Tonankai Earthquake. We analyze and compare three scenarios: 1) a base case which is the current plan of the prefecture, 2) a plan to coordinate with logistics firms is accomplished, and 3) a coordination with logistics firms together with relocation of hubs. Finally, countermeasures to improve the current operation plans are discussed.

2. MODEL STRUCTURE

A model framework is proposed as shown in Figure 1. Here, an overview of the model's structure is provided before describing their detailed implementation in the next sections.

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 (2012). 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 procedure for calculation begins with the initial assumptions to be used in the model. These include: the level of intensity and its distribution by area, locations of delivery hubs and receivers of the goods, types of goods to be delivered to shelters and their characteristics, types of vehicles to be used and their capacities, the road network, damage possibility, recovery rate, and handling times at each facility.

The demand of the goods is estimated from the number of victims in each shelter. In this paper, we utilize a statistical model developed by Nojima and Sugito (2005) to estimate the effects of earthquakes on lifeline infrastructures in a Japanese urban area. The model was developed based on the statistical data gathered in the aftermath of the Great Hanshin and Awaji Earthquake disaster in 1995, which severely affected the city of Kobe. With the estimations of quake intensities in each sub-region of Aichi, we can estimate the percentage of lifeline infrastructure, by type, to be damaged and the time required for their recovery. The number of victims is estimated assuming that the population for whom either running water is unavailable, or their housing is seriously damaged, will need to access aid at shelters.

Next, the estimated number of victims determines the amount of goods required by each municipality. Together with the estimated damage on road network and their recovery, a multi-commodity vehicle routing model (VRP) is applied to estimate the optimum level of

resources to devote to the operation. The resources to be allocated include drivers, trucks, and the expected fuel consumption. The delivery routes must satisfy the constraints of the maximum carrying weight and space of a truck, the total travel time of drivers' routes satisfy the constraint of their maximum working time, and the total running times of a truck should be under the constraint of truck utilization.

Finally, the estimated resource requirements can be obtained, along with expected delivery times to each destination.
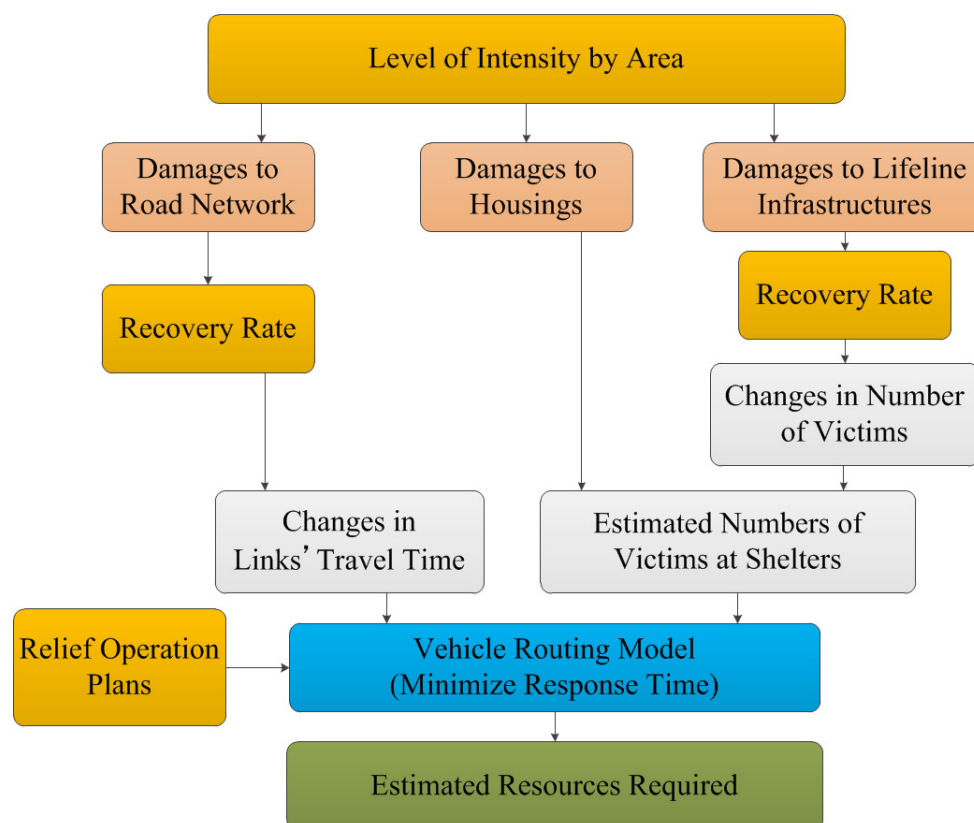

Figure 1. Model framework

2.1 Level of Intensity

The expected earthquake in this region is the so-called *Tokai-Tonankai* Earthquake with an expected magnitude of 8.3 (M_w), which would mean intensities of 4.9 to 6.0 JMA in Aichi (Nojima and Sugito, 2005). The expected seismic intensities for each municipal area are obtained from the website of Gifu University Earthquake Engineering (2012). The seismic distribution is used as an input, resulting in the estimated numbers of people seeking aid in shelters under the responsibility of each municipality and level of damage on road network.

In previous earthquakes, the demand for relief goods decreased and then ended at the same rate as the recovery of lifeline infrastructures (Tamura *et al.*, 2005) In order to capture the variations in demand due to time, we also estimate the daily distribution of victims in each shelter by assuming that victims having no housing damage resume normal life and leave shelters when electricity and water services have been recovered.

2.2 Damages to Housings and Lifeline Infrastructures and Their Recovery

In general, the number victims that need to move to shelters is estimated from the probability

of damages on housings and on lifeline infrastructures such as in a report from Gumma prefecture (2012) and from Kyoto Disaster Prevention Office (2005). We estimate the damage to housing using the relationship of this to seismic intensity provided in the report from Kyoto Disaster Prevention Office (2005).

Estimations of likely levels of disruption to lifeline infrastructures (such as electricity and water) by an earthquake in Japan of various seismic intensities were made by Nojima and Sugito (2005). 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, P, that an earthquake with a given intensity on the Japanese seismic intensity scale shall disrupt each lifeline infrastructure in each municipality. The model for each type of lifeline infrastructure is given below:

$$P = \frac{\exp(b_0 + b_1 I)}{1 + \exp(b_0 + b_1 I)} \tag{1}$$

For electricity, $b_0 = -19.72$; $b_1 = 3.75$;   mean $= 5.26$;   std. $= 0.48$

For water, $b_0 = -26.95$; $b_1 = 4.72$;   mean $= 5.71$;   std. $= 0.38$

where, I : seismic intensity in JMA units

Electricity is more sensitive to earthquakes than water or gas. This model, together with the estimations of seismic intensity for the possible Tokai-Tonankai Earthquake, is used to estimate the number of people who will seek aid at shelters. Assuming that people for whom either housings are seriously damaged or both water and electricity lifeline infrastructures have been disrupted will seek aid at shelters, we calculate the expected number of victims at each shelter.

In addition to estimations of disruptions to lifeline services, Nojima and Sugito (2005) also proposed a statistical model to estimate the expected duration of disruptions. Their model is presented below:

$$\text{Mean Stop Duration [days]} = a_0 + a_1 I + a_2 I^2 \tag{2}$$

For electricity (Intensity ranges between 5.2 and 6.8),
       $a_0 = 44.58$; $a_1 = -17.01$; $a_2 = 1.64$

For water (Intensity ranges between 5.0 and 7.0),
       $a_0 = 228.93$; $a_1 = -89.82$; $a_2 = 9.04$

where, I : seismic intensity in JMA units

2.3 Damages to Road Network and its Recovery

The damage on road network by intensity level is assumed based on the previous aftermath of the Great East Japan Earthquake and Tsunami. According to the report by East Nippon Expressway Company Limited (NEXCO), on the day of the earthquake, approximately 2,300 km of expressway from the total of 3,570 km was shut down due to the calamity (NEXCO, 2011). This number accounts for approximately 65 percent from the total. The damages mainly spread in the area with the intensity of more than 5.5 JMA. The road recovery operation was started soon after the damage was confirmed. In Japan, according to the disaster prevention plan, expressways and important trunk roads are to be reserved for vehicles with specific licenses in case of an emergency. Such vehicles include ambulances, police vehicles, trucks carrying relief goods. These roads are given the first priority for repair. In the aftermath of the Great East Japan Earthquake and Tsunami, more than 85 percent of damages on the priority expressway have been recovered after 24 hours (NEXCO, 2011);

while, normal roads are fixed gradually according to their priorities. The recovery rates of road by day and by type of road can be found in the report from the Ministry of Land, Infrastructure, Transport and Tourism (2012).

For Aichi prefecture, the network of priority roads is shown in Figure 2. The prefecture assigns more than 240 km. of expressway, and more than 1,000 km. of trunk roads as first priority roads (Aichi Disaster Prevention Office, 2009). In this study, this priority network is assumed to be fixed at the same rate as the recovery of the priority roads in the Great East Japan Earthquake and Tsunami. Similarly, for normal roads, we assume they are fixed at the same rate as the recovery of normal roads in the aftermath of the Great East Japan Earthquake and Tsunami.
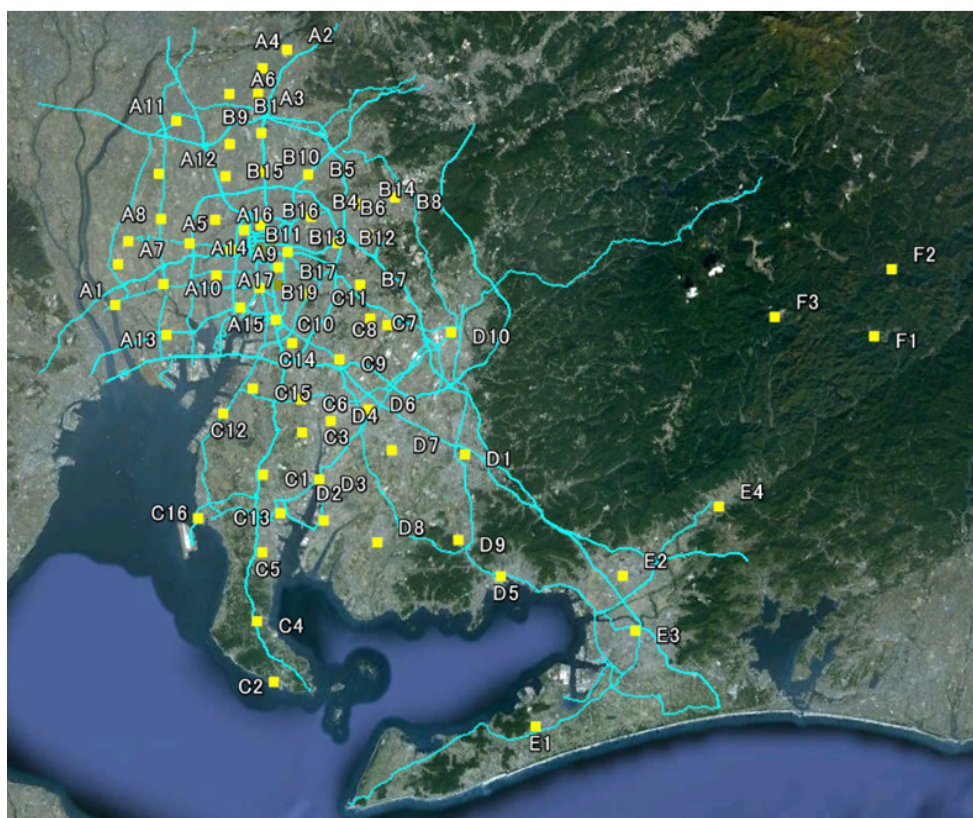

Figure 2. Priority roads and locations of city offices

2.4 Vehicle Routing Model

In this study, we assign secondary stockyards to each major depot (the primary stockyards). Our problem is a multi-commodity vehicle routing problem. As the operation time is crucial for disaster relief, we set the objective function 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. We also apply an adjust factor on travel time of each link to consider the level of damage and day-to-day recovery situation on the link which is a function of intensity level and road classes.

Minimal total route travel time:
$$\text{Min} \sum_{i \in R} \sum_{j \in R, (j \neq i)} c_{ij} x_{ij} \tag{3}$$

s.t.
$$\sum_{i \in R} x_{ij} = 1$$

$$\sum_{j \in R} x_{ij} = 1$$

$$w(\mathbf{x}) \leq wt_{max}$$

$$t(\mathbf{x}) \leq tt_{max}$$

$$s(\mathbf{x}) \leq s_{max}$$

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

Shortest path:

$$c_{ij} = Min \sum_{(m,n) \in A} p_{mn} d_{mn} f_{mn} \qquad (4)$$

s.t.
$$\sum_{m} (f_{mk} - f_{kn}) = \begin{cases} 1, & k = i \\ -1, & k = j \\ 0, & k \neq i, j \end{cases}$$

$$f_{mn} \geq 0, \quad (m,n) \in A$$

where,

A : network nodes

R : stockyards

p_{mn} : adjusted factor on travel time of link *mn* when links are broken or fixed in each day

$p_{mn} = \infty$; if link *mn* is broken

$p_{mn} = 1$; if link *mn* is not broken or fixed.

d_{mn} : travel time of link *mn* [hours]

c_{ij} : travel time between stockyards *i* and *j* [hours]

$w(\mathbf{x})$: total load on a truck [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]

2.5 Estimation Technique

For the estimation of vehicle routing, we need to optimize Equation (3). Equation (4) is a shortest path model which is solved using Dijkstra's algorithm. From the shortest path for each pair of stockyards in each day, the VRP model in Equation (3) is performed. VRP is one of the most complicated problems in logistics. The more pickup and unloading points the greater the difficulty to find the optimal solution. There are several methods available of this optimization problem and most of them are heuristic approaches since it is very costly in time to calculate the complete set of solutions. Heuristic approaches are known to be capable of

finding near-optimal solutions in reasonable calculation times. A heuristic approach is an iterative method involving a procedure to both evaluate and search among candidate solutions.

Genetic algorithms is one of the most popular heuristic methods. This technique is inspired by the Darwinian principle of natural selection (Wen, 2010) and examples for algorithms to solve VRP can be found in the works of Wen (2010) and Surekha and Sumathi (2011). In this study, we utilize a genetic algorithm to tackle the multi-commodity VRP problem. The algorithm is as follows:

Step 0 (Initialization): Chromosome representation of VRP path, where each chromosome represents a stockyard location. The chromosomes are listed in order they are to be visited. An example of the chromosomes of a path is (0 1 2 0 4 3 5 0), where zero indicates the supplying hub.

Step 1 (Clustering): Grouping stockyards by Clark & Wright saving method
Saving Distance between stockyards i and j, from depot q:

$$SV(i, j) = D(q, i) + D(q, j) - D(i, j) \tag{5}$$

where, $SV(i, j)$: saving distance between i and j.

$D(i, j)$: distance between i and j.

q : depot.

The total weight or number of pallets for receivers in each cluster should not exceed the maximum carrying weight and space of the truck.

Step 2 (Scheduling): Scheduling stockyards in each cluster by assigning higher probabilities that closer stockyards are visited next.

Step 3 (Fitness Evaluation): Evaluate the total delivery distance and time. Our objective function is to minimize the total delivery time required to deliver to every stockyard.

Step 4 (Selection): The best two candidates are selected based on the best fitness values (minimum total response time) to be parents for producing an offspring.

Step 5 (Crossover): An offspring is created by randomly selecting chromosomes from the parents. It is also checked for fitness and replaces the location of the father or mother if it has a better fitness.

Step 6 (Mutation): Mutation is allowed with a given percentage in order to help improve the best solution found so far. Two chromosomes of the offspring are randomly selected and have their locations swapped in the sequence of stockyards that forms the route. The new offspring has its fitness evaluated and once again replaces the location of the father or mother if it provides a better fitness.

Step 7 (Re-clustering): The routes are checked for violations of the constraint of drivers' maximum working hours and re-clustering is performed again when necessary.

3. ANALYSIS OF SCENARIOS

3.1 Relief Goods Distribution in Japan

During the Great East Japan Earthquake, there were many organizations supplying relief goods to the victims, including, government agencies, private sector operators, NGOs, and international organizations. In this study, we focus particularly on the structure of aid provided by the governmental sector. In Japan, there is a national disaster prevention plan, which is authorized by the disaster preparedness law (Fukami and Hisamoto, 2010). Implementation of disaster prevention is divided into three levels: The national, prefectural,

and municipal levels. At the national level, the cabinet and disaster prevention council jointly develop the standard for disaster prevention throughout the country. At the regional level, the prefectural governments have their own specific disaster prevention plans and work together with the city disaster prevention councils and city fire brigades. The disaster prevention plans differ across prefectures in order to cope with the specific regional disaster risks and local circumstances. Prefectural disaster prevention councils play an important role in designing local plans, including forecasting the likely impacts of disasters, coordinating the agencies involved in relief efforts, and directing actual implementations.

Relief goods distribution is one part of the national disaster prevention plan. Based on the prefectural disaster prevention plan, each prefectural government has a designated location for the storage of relief goods (usually at government offices or a pre-contract with suppliers who undertake to have goods available when needed). The primary stockyard is a storage location used to manage goods at prefectural level, and those at municipal level are secondary stockyards. The procedures for providing relief supplies to victims of a disaster are as follows: 1) Victims seek aid at shelters, 2) Shelters request relief goods from the relevant municipal government. The goods, which are stocked in the secondary stockyard by the municipal government, will be the first delivered to shelters. When stocks are low, requests are made to the relevant prefectural government, 3) the prefectural government delivers goods stocked in the primary stockyard to the secondary stockyards. When these stocks are not insufficient, requests are made to the national government and/or to private sector actors, and 4) the national government, and/or private sector companies, deliver goods to distribution centers and from these to the primary stockyards of the affected prefectures.

3.2 Performance Evaluation for Delivery of Relief Sets for the First Week for the Aftermath of Tokai-Tonankai Earthquake

In order to ensure that victims receive enough food and water, we set the requirement to provide 3 meals a day and 3 bottles of drinking water (size 500ml bottle). In our simulations, the speed of vehicles impacts the results. In order to obtain the speeds, we conducted an interview survey on June 25th, 2012 with freight forwarders in Sendai who delivered goods in the aftermath of the Great East Japan Earthquake. The truck drivers were asked to provide information on delivery routes, departure and arrival times at each pickup and delivery points, handling times, time needed to enter and leave expressways, amongst other questions. From the survey, information on 79 separate delivery tours, performed by 21 different drivers, were obtained. Truck drivers reported reduced travel speeds because of disrupted roads or reduced traffic lanes available. However, as the roads were reserved for emergency traffic only, traffic congestion was not a problem. Thus, the delivery trucks could drive at an average speed of 42.3 kph on expressways and 16.0 kph on normal roads. These values are used here.

Our model proposes delivery routes for the distribution of goods from primary to secondary (city office) stockyards. Modules for network interruption and for multi-commodity VRP were developed and added to the MATSim traffic simulator. MATSim is an open source multi-agent simulator, which simulates the behavior of individual vehicles in a transport network, and is well-suited for both for the analysis conducted and the presentation of results.

The assumptions regarding the VRP are presented here. In Japan, 4 ton-trucks or smaller are generally used for delivery for short and intermediate distances, as roads are often rather narrow. Here the use of 4-ton trucks to ensure access to all roads is assumed. (4 ton trucks predominated in the 2011 post earthquake relief operation, though some 10 and 2 ton trucks were also used.) For handling times, from the survey results handling times for the loading

and unloading of a full 4-ton trucks by hand at a city office takes an hour while, in general, handling times with forklifts at logistics facilities takes 10 minutes. Considering time for parking and administration, we assume loading and unloading times with forklifts at warehouses to take 20 minutes and manual handling a non-warehouse facility, 70 minutes.

Model Assumptions

Loading at warehouse (4-ton truck)	0:20	hours
Loading and unloading at a non-warehouse facility (4-ton truck)	1:10	hours
Max. daily working time for drivers	6	hours/person
Maximum utilization of a truck	24	hours/day
Truck size	4	ton
Max. capacity	3,500	kg
Max. space	8	pallets
Goods Characteristics		
Water bottles (500ml)	576	kg/pallet
Breads & Japanese rice balls	320	kg/pallet
Driving speed		
Expressway	42.3	kph
Normal roads	16.0	kph

Goods supplied for a person per day
    2 Japanese rice balls + 2 Breads + 3 Bottles of water
Road network: A day-to-day road condition based on damage level and recovery rate.

The simulation model is applied to the analysis of three scenarios: 1) The base case, which is the current prefectural disaster response plan, 2) Our first plan using existing logistics facilities for the relief operation, and 3) Our second plan to use existing logistics facilities for relief operation as well as to utilize the knowledge of the possibility of using an additional facility in order to increase operational efficiency. The details of the scenarios are as follows:

Scenario 1: Base case (Prefecture's plan for locations of hubs)

This scenario is set according to the prefectural disaster prevention plan for the locations of hubs. Aichi prefecture locates hubs at 4 places including Nagoya Airport, Odaka Park, Okazaki Central Park, and Ichinomiya sports center (Aichi Emergency Response Office, 2009). The secondary stockyards are city offices, which are grouped into 4 clusters based on their locations relative to the four hubs. The locations of hubs and city offices are as shown in Figure 3a). Group F is excluded in the analysis of deliveries by truck as it is located in a mountainous area, which is unlikely to be reachable shortly after the disaster due to blocked roads. We suggest treating this group differently, for example, making deliveries by helicopter. Parks and a sports center are designated as primary depots. Therefore, it is not possible for a proper handling with logistics equipment, and manual handling is thus required. Hence, the loading time at these facilities is 70 minutes. Unloading at secondary stockyards, the city offices that are also not logistics facilities, the manual unloading time is 70 minutes.

Scenario 2: Using logistics facilities as hubs for delivery

In this scenario, the private sector warehouses are used as depots for the operation instead of parks and a sports center. The locations of hubs are as same as Scenario 1. Similarly, Group F is suggested to be treated separately and excluded in the analysis as it is unlikely to

be reachable shortly after the disaster due to blocked roads. In this scenario, warehouses are used as depots, loading times using logistics facility is 20 minutes at every hub. However, unloading locations remain city offices, where manual handling time is 70 minutes.
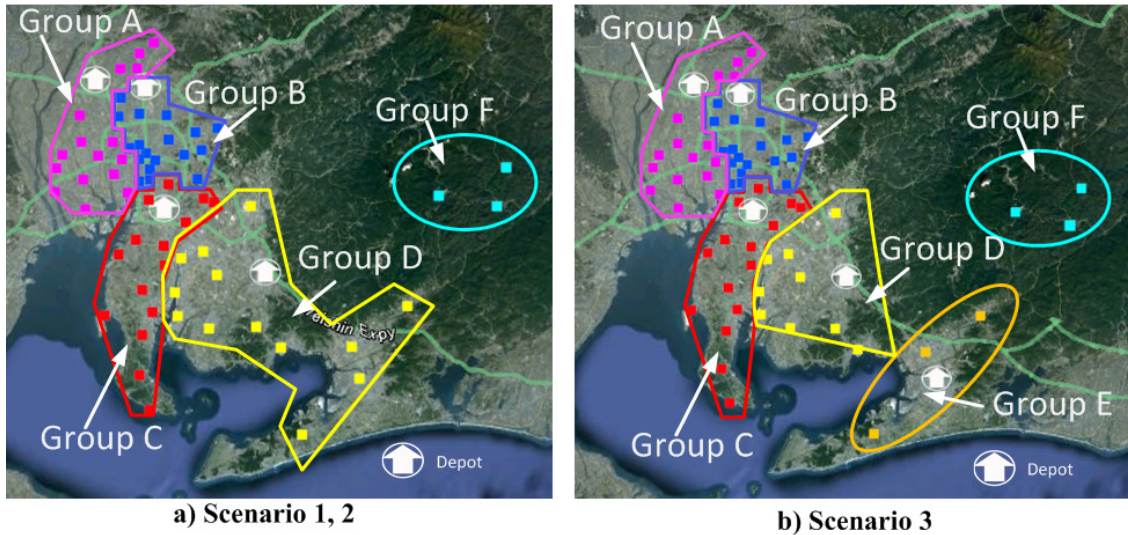

a) Scenario 1, 2   b) Scenario 3

Figure 3. Locations of city offices and delivery hubs

Scenario 3: Using logistics facilities as hubs for delivery and relocation of hubs

In addition to Scenario 2, Group D is divided into 2 groups; as from the second day, the warehouse in this region becomes available due to the predicted recovery of electricity. Similarly, Group F is excluded in the analysis due to their requirements for special treatment. The depots are located based on the presence of warehouse companies in each region. The depots and the groups are as shown in Figure 3b). Since warehouses are used as depots, loading times in this scenario is 20 minutes at every hub. Unloading locations remain city offices, where manual handling is unavoidable.

Estimated Day-to-day Road Network Conditions

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-to-day road network condition for the first week after the disaster.
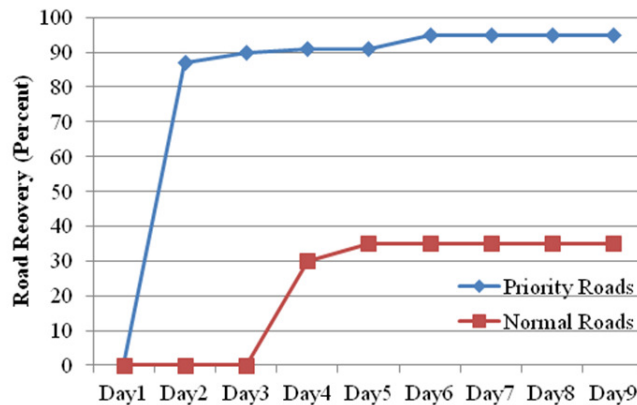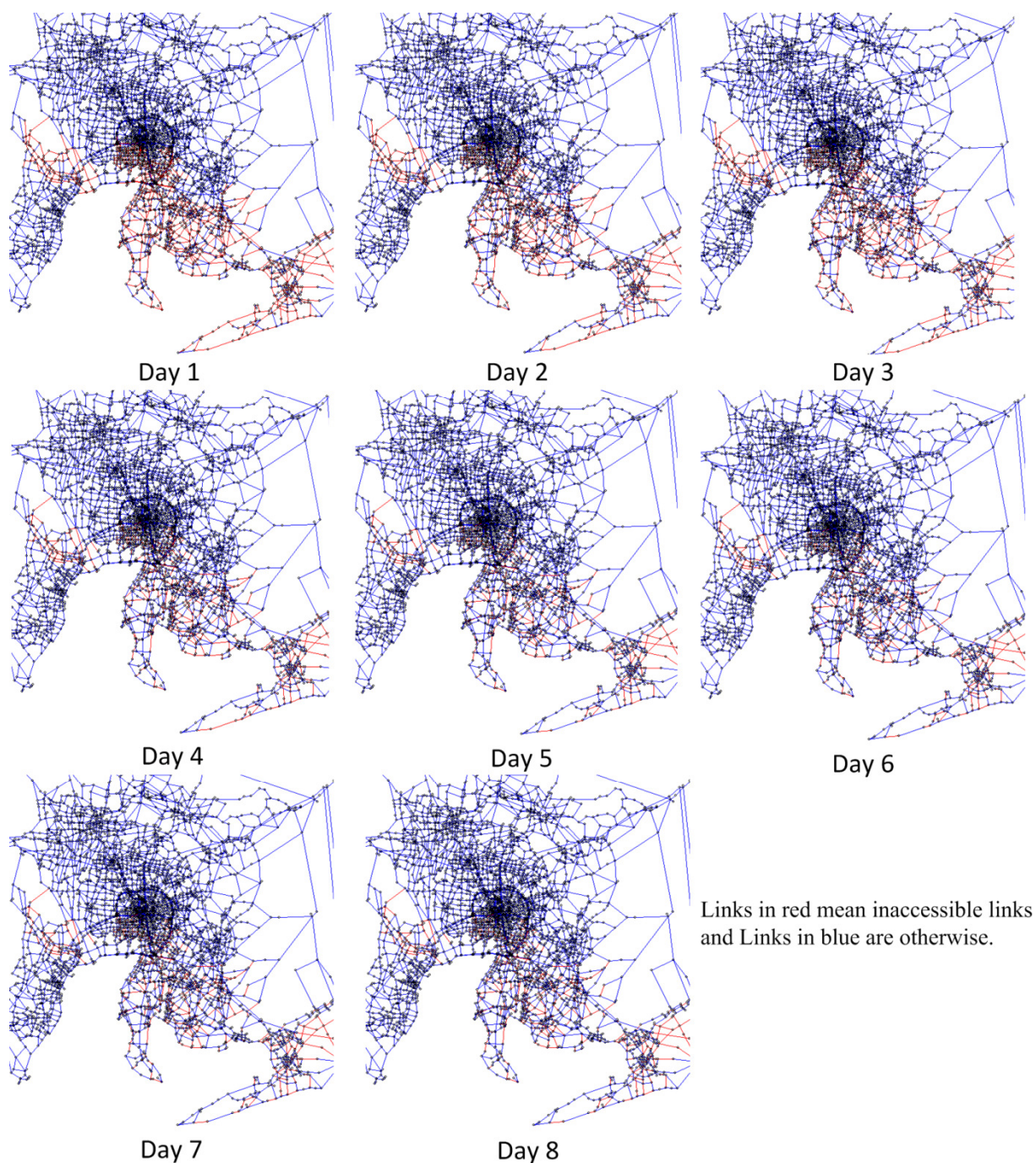

Figure 4. Road recovery rate by road classes

Day 1   Day 2   Day 3

Day 4   Day 5   Day 6

Links in red mean inaccessible links and Links in blue are otherwise.

Day 7   Day 8

Note: the recovery rate is as same as ones from the aftermath for the Great East Japan Earthquake and Tsunami.

Figure 5. Estimated day-to-day road network conditions

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 Figure 4 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-to-day road network condition for the first week after the disaster is as shown in Figure 5. 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-to-day condition of road network as an input into the simulation.

4. FINDINGS AND DISCUSSIONS

The estimated resources requirements for the three scenarios, including the required numbers of drivers, trucks, total operation hours and predicted fuel consumption, for each day for a week after the disaster are shown in Figures 6, 7, 8, 9, respectively. From the previous disasters and the relief distribution procedure in Japan as described in Section 3.1, the distribution of relief sets were started approximately from the second day as the level of damages are confirmed. In the first day, victims relied on the relief stocks at each of the municipalities. In this study, we therefore start to simulate the operation from the second day until the eighth day after the disaster

(a) Scenario 1

(b) Scenario 2

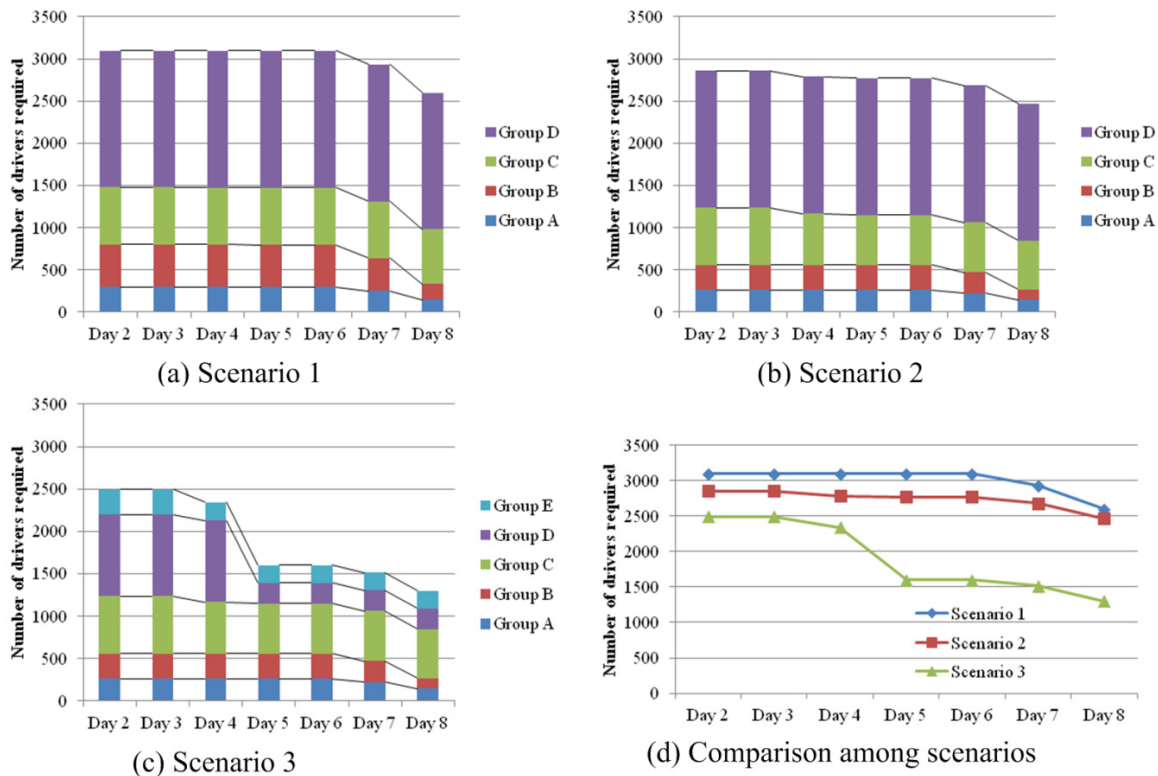(c) Scenario 3

(d) Comparison among scenarios

Figure 6. Estimated number of drivers required

We assume each driver works for 6 hours a day in order to be best suited with the truck utilization of 24 hours a day. During the emergency, the relief operations generally will be conducted 24 hours a day. The simulation also calculates delivery routes for each driver as well as their driving times. This information can used to calculate the fuel consumption each

day, which can be used to prepare this resource, and avoid fuel shortages previously experienced during post-earthquake relief operations.
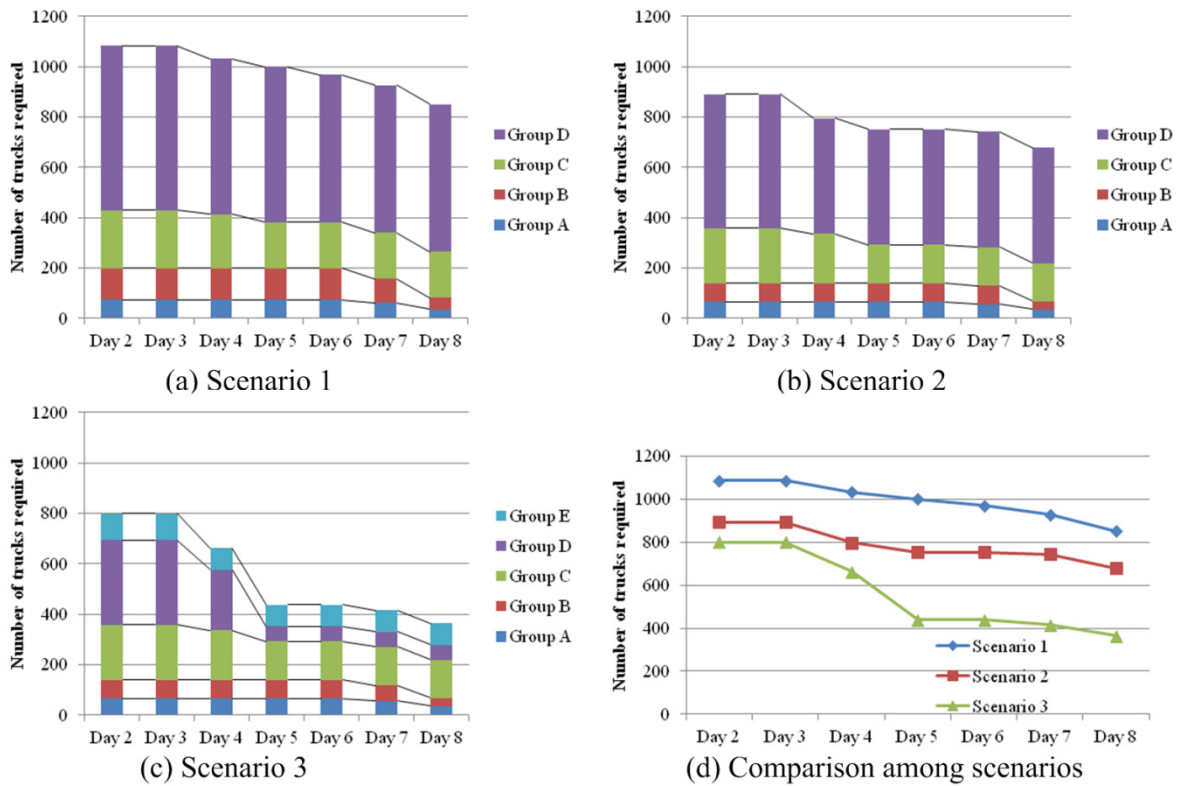

(a) Scenario 1

(b) Scenario 2

(c) Scenario 3

(d) Comparison among scenarios

Figure 7. Estimated number of trucks required
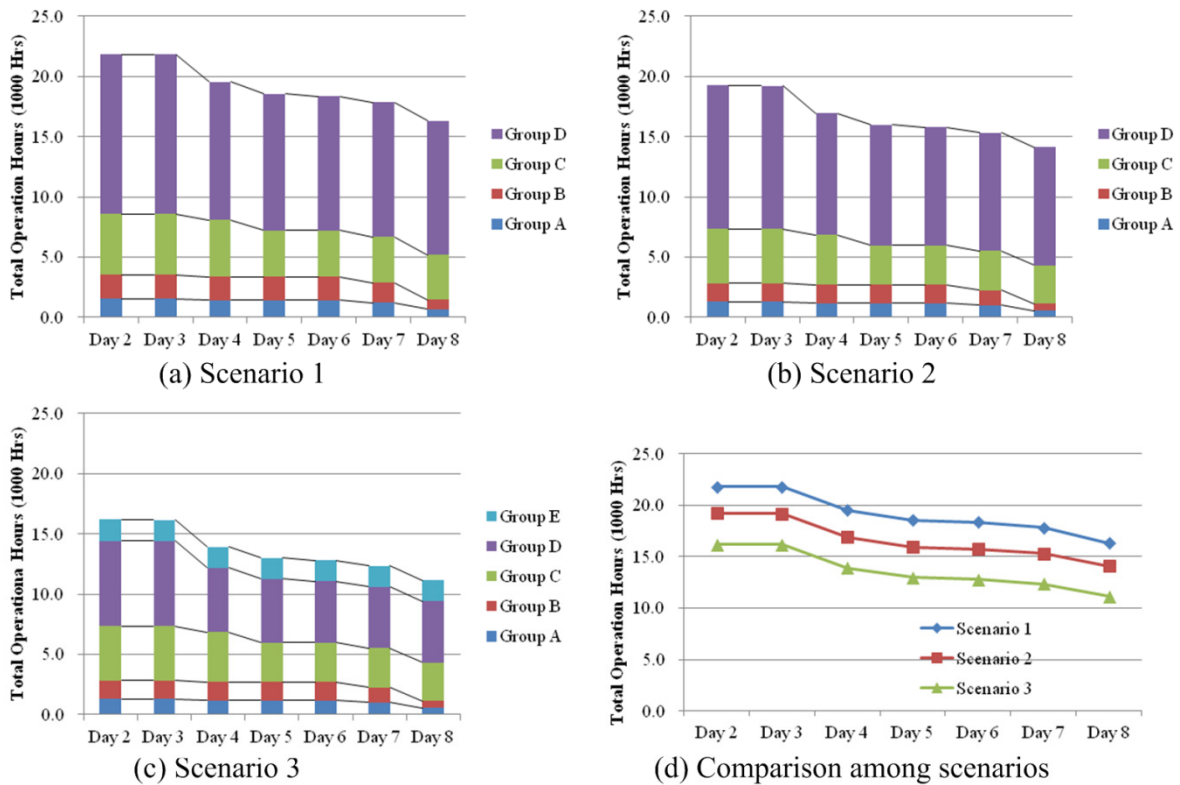

(a) Scenario 1

(b) Scenario 2

(c) Scenario 3

(d) Comparison among scenarios

Figure 8. Estimated total operation hours
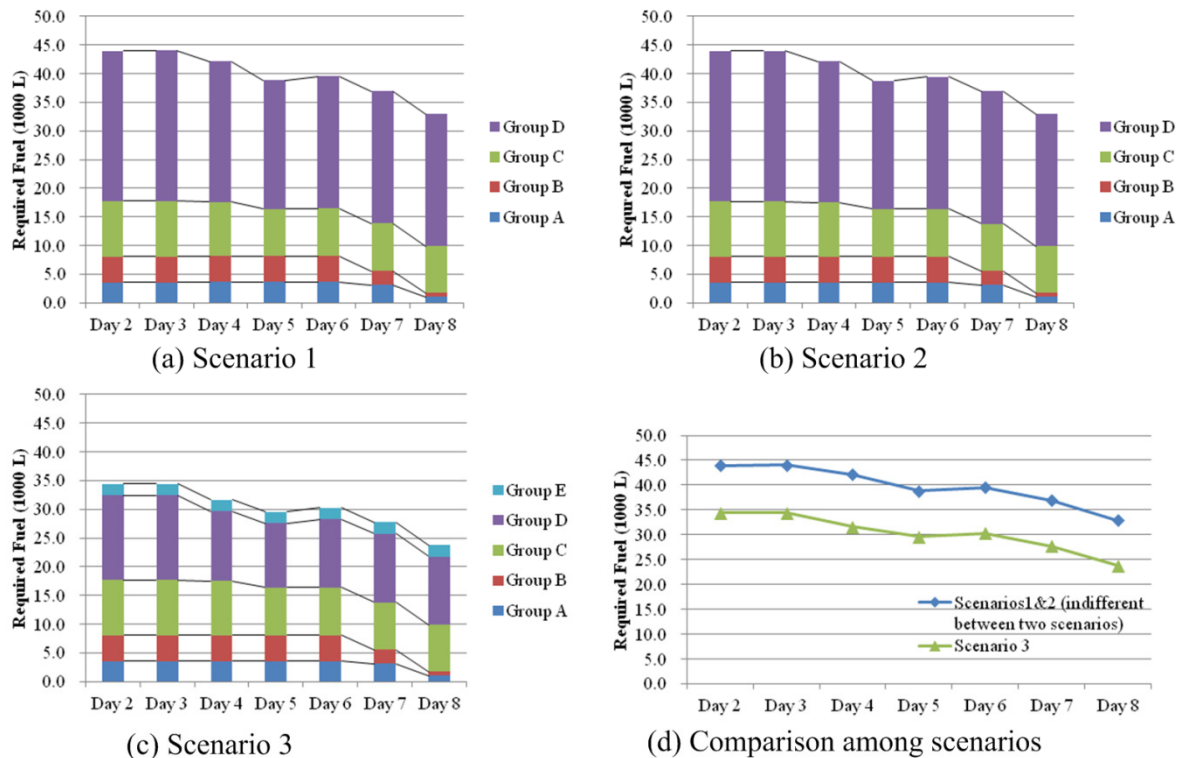
Figure 9. Estimated fuel requirement

Comparing Scenarios 1 and 2, the results suggest that using private sector logistics facilities with handling equipment as in Scenario 2 would reduce the total resource requirements as well as reduce total response times. Comparing with Scenario 1, Scenario 2 can reduce requirements for drivers by 8.6 percent and for trucks by 20.8 percent. This is because the handling time becomes shorter so that drivers can double delivery tours, which results in an improve truck utilization. However, only improved handling time does not shorten delivery routes, therefore, there is no change in fuel consumption.

Comparing Scenarios 1 & 2 with Scenario 3, the depot of Group D in Scenarios 1 and 2 has to handle a very large area in addition to the large number of expected victims as this region in the coastline is likely to be affected the most. As from the second day, the recovery of electricity at the warehouse of Group E is predicted. If this possible in the reality, the results show the wisdom of dividing Group E from the previous Group D as Scenario 3 performs better results in all resource requirements. Therefore, dividing Group E from the previous Group D as in Scenario 3 can help safe more time as well as truck and fuel resources. Scenario 3 can help saving 43.6 percent of number of trucks, and 23.9 percent of fuel requirement. With the recovery of road network as well as the recovery of electricity and water services are predicted to recover in some areas, resulting in gradually decreased aid requirements which conform to the real situation.

Figure 10 shows sensitivity analyses for delay in handling time comparing between the handling times in the assumption and their delays by 20 percent. The results show that although there is indifferent on the number of drivers required in each scenario for the delay, but the more numbers of trucks are required to compensate for the delays (34.3, 44.5, and 47.2 percents more for Scenarios 1, 2, and 3 respectively) as the total operation hours increased. Fuel requirement for Scenarios 1 and 2 are generally indifferent as the travel routes for both are the same but only handling times are different; however, a very large difference can be seen for these two scenarios, especially on Days 2 and 3, when the handling times are
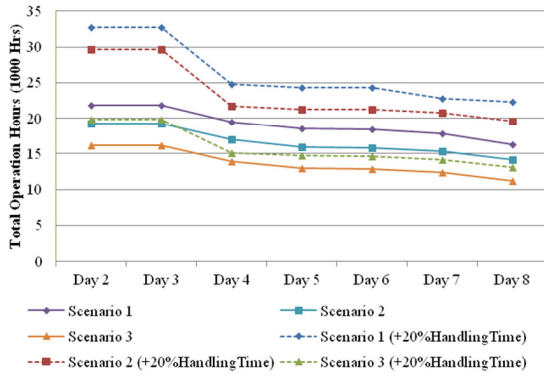
delayed due to the increased truck routes to compensate for these delays. Except Scenario 3, these delays do not impact on its fuel requirement because the truck travel routes are not too long.
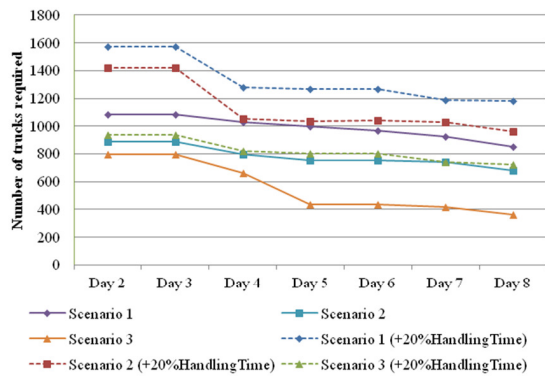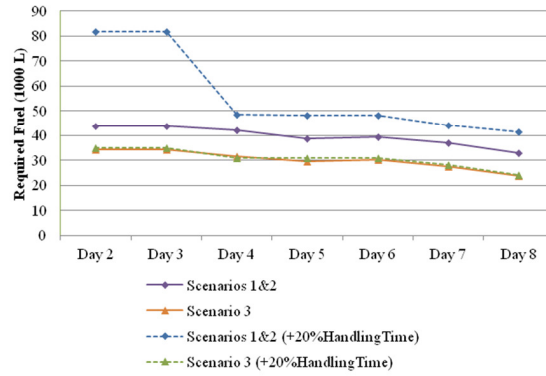

(a) Comparison of number of trucks required
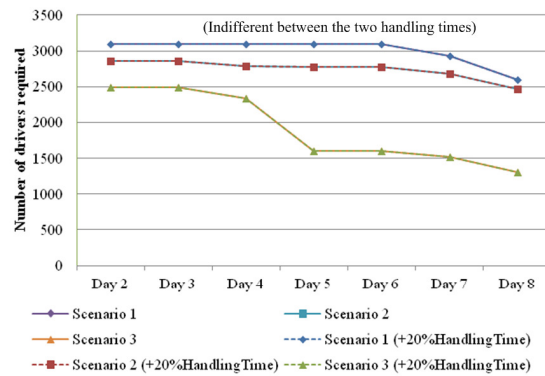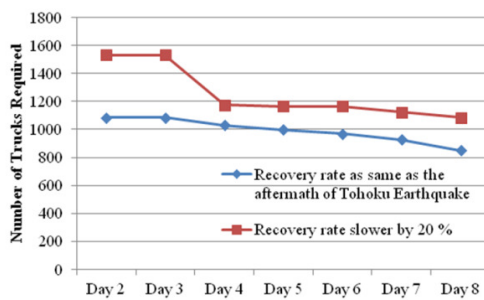
(b) Comparison of number of drivers required

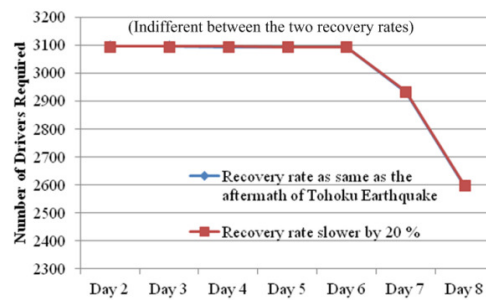(c) Comparison of total operation hours
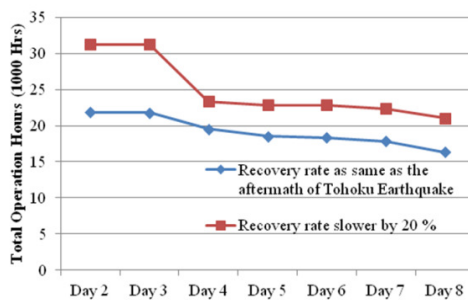
(d) Comparison of required fuel

Figure 10. Sensitivity analyses for delay on handling times
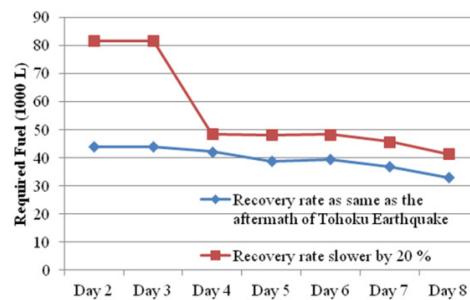

(a) Comparison of number of trucks required

(b) Comparison of number of drivers required

(c) Comparison of total operation hours

(d) Comparison of required fuel

Figure 11. Comparison of resource requirement of different network recovery rates

Figure 11 depicts a comparison of resource requirements for Scenario 1 for the two different recovery rates of network; including 1) recovery rate as same as the previous operation in the aftermath of the Great East Japan Earthquake and Tsunami and 2) recovery of the 20 percent slower than the former one.

The results show that the recovery of road network is very crucial to the operation. For requirement of number of drivers, the result shows no different between ones for the two recovery rates. However, due to increased time required to access to city offices, this causes drivers to drive longer routes and increases operation time, resulting in decreased truck utilization. Thus, for other resources including trucks and fuel, we will need to prepare 20.9 percent more trucks and 29.6 percent more fuel to cope with the case of slower recovery rate by 20 percent.

Considering together with the recovery rate in Figure 4, the estimated resource requirement starts to reduce from Day 4 as the recovery of normal roads has started. This trend can be seen clearly when reducing the recovery rate down by 20 percent. It can be interpreted that although the recovery rate of the first priority roads is rather high; however, the rate is still low for normal roads. As the city offices still need to be accessed by normal roads, these access roads become very vulnerable and cause considerable impact on the overall operation.

5. CONCLUSION

This paper has presented a model and an analysis for planning and evaluation of goods distribution in disaster response operations by considering the vulnerability of road network. This simulation can help planners to evaluate and improve the efficiency of relief operations. In this paper, we demonstrate the application of our model to the analysis of scenarios; first is the prefecture current plan and second and third are our proposed plans. It may currently be common for the government to use parks or government facilities for the operation as cooperation the private sector may be difficult. However, cooperation with private sector actors (especially within the logistics sector) will significantly improve the operation performance. The simulation results prove that handling the operation with proper logistics facilities, locations, and equipment (as in Scenarios 2 and 3) performs significantly better.

In addition to the scenarios presented here, this simulation model also can be applied to various other problems, for example, finding the optimal location of hubs, finding the optimal clusters of stockyards for each hub to serve. In this paper, we simulate the delivery between the hubs to city offices; it is also possible to extend the model to consider the deliveries between city offices and shelters, when the benefit of using proper logistics facilities as secondary stockyards when possible would likely be significant. The changing requirements for the relief operation over time could be included in a model with a longer time horizon.

From the scenario, the recovery rate of road network is very crucial for the operation. Not only paying attention to the expressway and priority roads, but we also need to consider the accessibility of access roads to the locations of city offices (as receivers). These roads are considered highly vulnerable to the overall operation due to its less priority and the vehicles still need to use these roads to reach to the final destinations. The issues on identifying the vulnerability level of each location (hubs and receivers) are to be considered in the future research.

In addition, driving speed is a crucial factor in the analysis. Here, this study used the values from a survey in which the samples still too small in numbers. There is other way to obtain the values from traffic simulation as conducting survey for case of disaster is perhaps

not easy. Also, the analysis presented here still used an available VRP approach. We suggest constructing the model to be able to represent more the complexity of the topic such as the priority of receivers and so on. Each of the scenarios presented here should also be examined in details as to assess to the consequent costs and possibilities for the implementation. Considering the damage on road network, the level of damage does not only depend on the seismic level, but also relies on many reasons such as road structure, soil liquefaction, and so on. Also, recovery of roads utilized here is performed randomly. It is suggested to consider more the reality of road recovery work, and to integrate soil liquefaction and durability of road structure into the model. These topics are remained for the future study.

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