Integrating a Stochastic Failure of the Road Network and a Road Recovery Strategy into the Planning of Goods Distribution in the Aftermath of a Large-Scale Earthquake

Authors:
Wisinee Wisetjindawat (Corresponding Author)
Nagoya Institute of Technology
Gokiso, Showa, Nagoya, Japan 466-8555
Tel: +81-52-735-7423
Email: wisinee@nitech.ac.jp

Hideyuki Ito
P&I logistics
287-2, Tenjin, Kashiwamori, Aichi, Japan 480-0103
Tel: +81-58-781-3561
Email: pi0001@h3.dion.ne.jp

Motohiro Fujita
Nagoya Institute of Technology
Gokiso, Showa, Nagoya, Japan 466-8555
Tel: +81-52-735-5492
Email: fujita.motohiro@nitech.ac.jp

Submission Date: 1st August 2014
Resubmission Date: 15 November 2014.
Word Count: Text (5,557) + Figures/Tables (7*250) = 7,307

94th Annual Meeting of the Transportation Research Board
January 11-15, 2015
ABSTRACT

Disaster relief operations are complex and can benefit greatly from a high level of preparedness. One of the main sources of complexity in disaster operations is uncertainty. This paper presents an analysis of a disaster relief operation in Aichi Prefecture, Japan, in preparing for the periodic so-called Tokai-Tonankai Earthquake. In this study, we consider the possible degradation of the road network by including a stochastic element to represent the possibility of link failure dependent on earthquake intensity in each sub-region. We also integrate a road fixing strategy into the analysis in order to evaluate its impact on the disaster logistics operations. The analysis is performed using the current road network of Aichi Prefecture. The results suggest the best preparation of resources and identify vulnerable destinations that are most likely to be cutoff by the disaster. We also analyze and suggest a relocation of hubs that can reduce the total response time taking into account the possibility of links being broken. This analysis is important to help planners to evaluate their strategies, to identify vulnerable locations, and to be able to prepare in advance the best methods to deal with the uncertainty of road failure.

Keywords: Humanitarian Logistics, Road Network Vulnerability, Stochastic Road Failure, Road Recovery
INTRODUCTION

Natural disasters have caused substantial loss of life as well as large economic costs around the world. In recent years, the frequency and intensity of disasters has been increasing (1). The lessons from previous experiences can help to better cope with the consequences of disasters through a good preparedness; especially, relief operations can benefit enormously from improved contingency planning.

Japan is among the countries in the world who experience disasters at a very high frequency and in various forms including earthquakes, tsunamis, and typhoons. Over many years, the country has put much effort into the improvement of technologies in order to better cope with disasters, through the development of an ITS system to help evacuations, strengthening building and foundation structures, and numerous other technologies. However, a report on the response to the 2011 Great East Japan Earthquake and Tsunami identified many problems due to poor logistics operations. The problems included insufficient goods in pre-stocks, goods unsuited to the needs of victims, inefficient reception and re-distribution of goods, and goods not reaching victims who stayed at home rather than moving to shelters (2). Perhaps, this poor operation performance was caused by the complex nature of humanitarian logistics which requires 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 (3). These actors 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 confusion, duplicated programs, and the wasteful use of precious resources. Contingency planning regarding the optimal pre-positioning of distribution centers and warehouses can, as well as speeding deliveries, also help alleviate problems of inadequate appropriate storage space for relief goods. Clearly, there is no adequate substitute for a good contingency plan in the event of a disaster. Notably, time constraints in humanitarian logistics are more crucial than usual, because faster relief operations mean a greater likelihood of saving lives.

In recent years, much attention has been paid to the field of emergency operations. Much literature can be found regarding the planning of logistics operations in response to a variety of emergency situations. Many discuss important issues and logistics related problems uncovered during previous relief operations (1, 4). In particular, there is considerable work on estimation techniques for vehicle routing models in relief operations. The objective in humanitarian operations is very different to that encountered in normal commercial operations. Various objective functions have been used in this field, for example, minimize cost, minimize unsatisfied demand, minimize latest arrival, minimize total response time, and maximize travel reliability (5,6).

Uncertainty is the most problematic issue when planning for post-disaster relief efforts. It is extremely difficult to predict correctly the position, timing and scale of damage. De la Torre et al. (5) summarized many challenges related to disaster
operations and suggested that academic work should address the following important topics: 1) destabilized infrastructure, 2) uncertainty in demand, supply, and the time and effort needed to distribute goods, 3) dynamics of the situation, and 4) differences in goals between commercial and non-profit logistics. When planning the post-disaster operation, it is very important to take into account these goals and uncertainties. Many studies have integrated a range uncertainties into the modeling of disaster relief routing. Some studies integrated stochastic demand and supply such in Rawls and Turnquist (7) and Van Hentenryck et al. (8). Another important uncertainty is the possibility of disruptions to important infrastructures; especially, disruption of the transport network can critically impact relief operations. A model for pre-positioning of relief supply inventory proposed by Ukkusuri and Yushimito (9) considered the link reliability after a disaster in order to identify the most reliable locations. Rawls and Turnquist (7) worked on a similar problem; their pre-positioning model integrated the uncertainty of links being usable, from a probability of occurrence of a set of hurricane scenarios in addition to the uncertainties in demand and supply for emergency goods. A set of unusable links was presumed for each scenario.

In this paper, we investigate the problem from another perspective, for the specific case of an expected earthquake in Japan. It is uncertain whether any given link will be usable or not. While the locations of failures cannot be predicted in advance, the failure probability however, can be predicted from the estimated intensity level of the earthquake. Also, another important factor influencing the road usability is the recovery work. In the aftermath of previous disasters in Japan, the road recovery work was performed quickly in parallel with other relief efforts. Thus, road recovery strategy should be taken into account when planning the disaster relief operations too, as planners can estimate the level of impact on relief operations of different recovery strategies. Obviously, pre-positioning the distribution centers at the most reliable locations is very important. Therefore, this paper takes into account the uncertainty of links’ condition by considering the likelihood of the road network being disrupted at different intensity levels, the recovery strategy on different road classes, and their impacts on the logistics operations. This analysis can help in the development of robust preparations to cope with the unavoidable uncertainties of post-disaster relief operations.

MODELING A DISASTER RELIEF OPERATION WITH ROAD NETWORK VULNERABILITY

Here, the overall calculation procedure is summarized. Three main forms of damages that will affect the relief operation are considered, these are damage to housing, lifeline infrastructure, and road networks. The damage to housing and lifelines (gas, water, and electricity) influences the number of victims requiring aid. From previous research (10), the number of victims at shelters in the aftermath of a major earthquake was at its peak on the second and third days after the disaster and later started to decrease every day until the situation improved. We use the recovery rate of lifelines to calculate the trend in the daily number of victims at shelters. The demand for goods in each shelter is taken from the number of victims estimated using a statistical model developed by Nojima and Sugito (11) on the impacts of earthquakes on lifelines in a Japanese urban area. We can estimate the percentage of lifeline infrastructure, by type, to be damaged and the
time required for their recovery from the estimations of quake intensities in each sub-region of Aichi. The number of victims can be estimated by assuming that the population for whom either running water is unavailable, or their housing is seriously damaged, will need to access aid at shelters and is later used to determine demand in each municipality.

Similarly, damage to the road network affects the relief operation as it directly impacts response times, as the travel time can substantially increase when some roads are cutoff. Thus, to model the stochastic failure of the road network, the probability of a link being passable is determined by the estimated level of the intensity of the earthquake. In previous recovery operations, work on restoring the road network was performed concurrently with other relief operations. Improved road conditions resulted in improved route travel times. The recovery rate of the roads by road class is considered in the calculation. Stochastic travel time is used to integrate the probability that some links may be cutoff in the aftermath of the earthquake forcing vehicles to detour or at worst causing some destinations to become inaccessible. The simulation of travel time, under the above described probability of each link being passable within a day, informs whether a destination is accessible from any given origin on that day, at different confidence levels. This information is next used as an input to a vehicle routing model (VRP) to estimate the resources required to satisfy the constraints of the capacity of a truck and of truck utilization. The final result of this model is a required level of resources, in order to access each secondary stockyard with a certain level of confidence, within a 48 hour period after the expected earthquake. The calculation procedure is summarized as shown Figure 1.

**FIGURE 1 Model Structure**
Planning Relief Goods Distribution for Case Study of Aichi Prefecture

This section provides detailed information on the analysis for the case of Aichi Prefecture under the predicted Tokai-Tonankai Earthquake in the region.

The System of Distribution of Relief Goods in Japan

In Japan, in the aftermath of a disaster, many organizations are involved in providing relief goods to victims. These organizations include government agencies, private sector operators, NGOs, and international organizations. In this study, however, we focus particularly on the structure of aid provided by the government sector as this sector plays the most important role regarding pre-disaster preparations and during the early period after a disaster. Relief goods distribution is one part of the national disaster management plan. Based on the prefectural disaster management plan, each prefectural government has a designated location for the storage of relief goods. A primary stockyard is a storage location used to manage goods at prefectural level, and those at municipal level are secondary stockyards. The prefecture has identified primary and secondary stockyards as well as made stocks of relief goods. The primary stockyards which act as hubs in goods distribution include national parks, a sport center, and an airport terminal (12). The secondary stockyards at municipal level are mostly buildings close to the local municipal offices. Most of these facilities are not supported by logistics equipment. Loading and unloading operations must be performed manually. In the current Aichi plan, the locations of primary stockyards have already been decided following the requirement for a space of 10 hectares or more that would be sufficient to allow the landing of a middle size helicopter, parking space, warehouses, and temporary housing.

In the disaster management plan, expressways and important trunk roads are to be reserved for vehicles with specific licenses. Such vehicles include ambulances, police vehicles, and trucks carrying relief goods. Also, these roads are given the first priority for repair. The experience from the aftermath of the Great East Japan earthquake has shown that roads with first priority were repaired quickly, being passable in a day after the disaster struck (13). For Aichi, the prefecture assigns more than 240 km. of expressway, and more than 1,000 km. of trunk roads as first priority roads (14).

Estimation of Number of Victims

The number of victims that need to receive help in shelters is estimated from the probability of damage to housing and to lifeline infrastructure similarly to both (15) and (16). The housing damage is estimated using the relationship of such damage to the seismic intensity provided by (16). The estimations of likely levels of disruption to lifeline infrastructures (such as electricity and water) at various seismic intensities were performed using the probability function developed by Nojima and Sugito (11). Their model was built 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 on the Japanese seismic intensity scale (known as the JMA scale) shall disrupt each lifeline infrastructure in each municipality. The expected earthquake
in Aichi 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 (11). The expected seismic intensities for each municipal area are obtained from this website (17), maintained by Gifu University. The distribution of seismic intensities is used as an input to the probability function and results in the estimated numbers of people seeking aid in shelters under the responsibility of each municipality.

**Stochastic Failure of Road Network**

Under a disaster situation, the constraint on the capacity of the road network is whether links are usable or not (7, 9). Therefore, in this study, a stochastic failure of each link in the road network is considered based on a constant failure rate by intensity level. The failure rate is derived from the aftermath of the previous Great East Japan Earthquake in 2011. Applying a similar idea to an analysis of the vulnerability of the power transmission network by Kroger and Zio (18), the probability that a link, which connects between nodes $q$ and $r$, is passable is formulated as follows:

$$p_{qr} = e^{-\lambda_{qr}}$$  

(1)

Where, $p_{qr}$ is a probability that link $qr$ is passable after an earthquake.

$\lambda$ is a constant failure rate of a link by intensity level [locations/km].

$L_{qr}$ is the length of link $qr$ [km].

The constant failure rates ($\lambda$) vary with the intensity level of the earthquake and are obtained from a report by the Disaster Management Working Group under the Cabinet Office (19). These numbers derived from a survey on the road failures caused by the 2011 Great East Japan Earthquake. An earthquake of an intensity of 4 JMA or below caused no damage to roads. An intensity of 5 JMA (Weak) caused 0.035 locations of failure per km. An intensity of 5 JMA (Strong) caused 0.11 failure locations per km. An intensity of 6 JMA (Weak) caused 0.16 failure locations per km. An intensity of 6 JMA (Strong) caused 0.17 failures per km. Finally, the intensity of 7 JMA has caused 0.48 failures per km. These values are used for the above equation based on its location and the expected intensity in the region.

**Road Recovery**

In Japan, expressways and important trunk roads are designated as first priority roads, which have the highest priority for repair. In the aftermath of the Great East Japan Earthquake, the road recovery operation started soon after the damage was confirmed and more than 85 percent of damaged priority roads were recovered after 24 hours (20). Other broken roads with lower priority were fixed subsequently.

The probability that a link is passable 24 hours after an earthquake, $p_{qr}^{24}$, is formulated as:

$$p_{qr}^{24} = e^{-\lambda_{qr}} \cdot p_{qr}$$  

(2)

Where, $p_{qr}^{24}$ is a probability link $qr$ is fixed and passable after 24 hours after an earthquake.
Stochastic Travel Time

An earthquake may cause failures on some links in the network and hence a longer than usual travel time between an OD pair. Sometimes the damage can cause a destination to become inaccessible. To include such a possibility in the analysis, the probability of each link in the network being passable within 24 hours after an earthquake is calculated from Equation (2) in which the recovery rate is incorporated, as described earlier. Later, the stochastic travel time between each OD pair in the road network is calculated based on the above probability of the road being passable.

This study adopts a stochastic shortest path method to calculate the probability distribution of the shortest path time under the possibility of road disruption. The method is adapted from the hybrid intelligent algorithm for calculation of $\alpha$-shortest path proposed by Ji (21). In his work, each link’s travel time has its own distribution function; but here we derived the link’s travel time distribution based on the previous passable probability. Next, a stochastic simulation is performed by producing N trials of occasions (800 draws were used in this study) for the link’s travel time distribution. The procedure is as shown in Figure 2. For each trial, the generated link’s travel times of all links in the network are used to determine the shortest path between a given OD pair. Instead of using a Genetic Algorithm to find the shortest path as proposed by Ji (21), here we use the Dijkstra algorithm to determine the shortest path between an OD pair from the generated link’s travel time at each iteration. This can save substantial calculation time for a complex real network such as ours. The N trials generated travel times between each OD pair, which are later used to construct the travel time distribution for the OD pair. These travel time distributions were used to determine the travel time between each OD pair at a given confidence level-$\alpha$. This information is used for the route planning analysis which will be described in the next section.

**FIGURE 2 Stochastic shortest path procedure.**
Route Planning for Distribution of Relief Goods

Route planning is performed as a multi-depot multi-commodity vehicle routing problem. In this case, response time is considered to be the most crucial factor during the disaster operation. Here, the objective function is to minimize the total response time. The route planning provides a sequence of delivery, which minimizes the total response time under the constraints of the maximum carrying capacity and maximum utilization of a truck. The route planning simulation is performed using a Java-based program called jsprit developed by Schröder (22). This program is one of a very few open source softwares available for solving VRP problems. Not limited to the classical problem, this software can be applied to VRP related problems including: Multiple depots, Heterogeneous fleets, pickup and delivery, and problems with time-windows. Another important advantage of this program is that this software allows free modification of the constraints related to the VRP problem, which is very important for our study where roads become unusable due to disruption. The algorithm behind this software is the Ruin and Recreate principal proposed by Schrimpf et al. (23) which increases the chance to obtain good quality results in optimization problems.

Location Routing Problem

We also try to analyze whether it is possible to relocate the hubs to better locations. Here, a Location Routing Problem (LRP) is used in order to identify the most suitable locations of hubs for delivering relief goods to the secondary stockyards. An LRP model such as one proposed by Berger et al. (24) was used to identify the locations of hubs considering distance constraints. On the other hand, Ukkusuri and Yushimito (9) proposed an LRP model to help identify the most reliable locations of distribution centers. Here, we apply an LRP model to relocate the hubs to those locations that minimize the total response time under the uncertainty that some links may be cutoff by the disaster. The results from the stochastic travel time obtained previously are utilized. Following Ukkusuri and Yushimito (9) and Berger et al. (24), an uncapacitated LRP problem is formulated as follows:

Minimize \[ \sum_{j} f_j x_j + \sum_{j} \sum_{k} c_{jk} y_{jk} \]  
Subject to \[ \sum_{j} \sum_{k} a_{jk} y_{jk} = 1, \forall i \]
\[ x_j \geq y_{jk}, \forall j, \forall k \]
\[ x_j, y_{jk} \in \{0,1\} \]

Where, \( f_j \) is fixed cost of hub \( j \).
\( c_{jk} \) is cost of route \( k \) associated with hub \( j \).
\( x_j = 1 \) if hub \( j \) is selected and 0 otherwise.
\( y_{jk} = 1 \) if route \( k \) associated with hub \( j \) is selected and 0 otherwise.
\( a_{ijk} = 1 \) if a secondary stockyard \( i \) is assigned to hub \( j \) through route \( k \), and 0 otherwise.
In this case, the cost is the operation hours, including handling time at hubs and at destinations, and time required for travel. When a destination becomes inaccessible, we apply 24 hour penalties to each truck required to delivery supplies to this destination. The problem is solved as an uncapacitated single allocation problem using a Genetic Algorithm. Single allocation means that each receiver is assigned to only one hub. Similar to Berger et al. (24), only one customer is assigned to each delivery route for ease of the calculation. However, later the real travel route will be calculated using the routing planning described previously. Here, we assume uncapacitated hubs since the new hubs’ locations are unknown.

The calculation algorithm starts with the generation of a set of populations with random locations of hubs. The remaining locations are recipients, which are each assigned to the hub with the lowest connection cost. Similar to other problems solved by Genetic Algorithms, the algorithm includes procedures for selection, crossover, and mutation. Two members from the population are selected using roulette wheel selection to ensure that all members have a chance to be selected and those with a better fitness are more likely to be selected than others. The selected members are 'crossed over' and produce offspring. The offspring will replace the worst member in the population if it has a better fitness. A mutation rate is also applied to increase the chance to obtain a high quality solution.

SCENARIOS

Scenarios are analyzed in order to evaluate the distribution plans under different confidence levels of travel time due to the possibility of road disruption by the predicted Tokai-Tonankai earthquake in Aichi prefecture, Japan.

The assumptions are set as shown in Table 1. We focus mainly on the basic relief supplies including ready meals, water, and medical kits. In practice, the relief supplies are generally prepared in sets containing all the necessary items together. In this case, the relief bundles for 1,000 people would consume a space of 5.6 m$^3$. We assume 4-ton trucks with a capacity of 14.57 m$^3$ to be used in the operation in order to ensure access to all roads. The driving speed in a disaster situation is very different from the normal situation due to road disruption or reduced traffic lanes available. In this simulation, we use the values obtained from our interview survey on June 25th, 2012 with freight forwarders in Sendai who delivered goods in the aftermath of the Great East Japan Earthquake. The delivery trucks could drive at an average speed of 42.3 kph on expressways and 16.0 kph on normal roads. There was no congestion reported on the priority roads during the aftermath of the earthquake since the roads were reserved only for the emergency traffic. For handling times, loading and unloading of the commodity bundles from a 4-ton truck manually would take an approximate of 40 minutes. The average length of links of this network is 1.09 km.

We assume a recovery strategy in which the recovery work on the expressway goes very well and all expressways can be passable after 24 hours, and the trunk line first priority roads are recovered at differing rates (ranging from 60 percent to 90 percent per day). The impact of these recovery strategies when using the prefecture’s designated hub locations to deliver goods to the secondary stockyards on the second day after the disaster are as shown in Figure 3. Many secondary stockyards are unlikely to
be accessible within 24 hours of the expected earthquake occurring when most of the road recovery has not yet been performed. Therefore we recommend that pre-stocks of relief goods are stored for the first 24 hours post-disaster at each shelter. This is why we concentrate on the logistics of providing additional relief goods from hubs to secondary stockyards within 48 hours of the disaster. The locations of hubs are set according to the prefectural disaster management plan. Aichi prefecture locates hubs at 4 places including Nagoya Airport, Odaka Park, Okazaki Central Park, and Ichinomiya sports center (12). Obviously, the numbers of inaccessible destinations increases when we reduce the recovery rate and hence the operation hours’ penalties increase. The recovery rate of 90 percent can significantly improve the performance comparing with the rate of 85 percent experienced during the Great East Japan Earthquake.

**TABLE 1 Model Assumptions**

<table>
<thead>
<tr>
<th>Loading and unloading of a 4-ton truck</th>
<th>40 minutes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum utilization of a truck</td>
<td>24 hours/day</td>
</tr>
<tr>
<td>Truck size</td>
<td>4 ton</td>
</tr>
<tr>
<td>Max. space</td>
<td>14.57 m³</td>
</tr>
<tr>
<td>Goods Characteristics</td>
<td></td>
</tr>
<tr>
<td>Relief supplies bundles</td>
<td></td>
</tr>
<tr>
<td>(food, water, medical kits)</td>
<td>5.6 m³/1,000persons</td>
</tr>
<tr>
<td>Driving speed</td>
<td></td>
</tr>
<tr>
<td>Expressway</td>
<td>42.3 kph</td>
</tr>
<tr>
<td>Other roads</td>
<td>16.0 kph</td>
</tr>
<tr>
<td>Road Network</td>
<td></td>
</tr>
<tr>
<td>Different recovery rates for expressway, priority roads, and normal roads</td>
<td></td>
</tr>
</tbody>
</table>

**FIGURE 3** Cumulative probabilities of the total hours needed for the goods to reach the secondary stockyards at different road recovery rates after 24 hours when using the prefectural plan for hubs locations.
Next, we assume a recovery rate of a 90 percent on the trunk line priority roads and try to relocate the hubs in order to reduce the total response time. Two scenarios are analyzed and compared for the operations, including:

**Scenario 1:** the current prefectural plan for locations of hubs.

**Scenario 2:** proposed locations of hubs based on location routing model.

Figures 4(a) and 4(b) show the accessibility of stockyards within 48 hours of the earthquake occurring at a 95 percent level of confidence for Scenarios 1 and 2, respectively. Link color indicates the level of probability that a link is unusable. The color ranges from green to red. Green indicates the probability that the link is unusable at less than 5 percent in Figure 4 and at less than 1 percent in Figure 5, while red indicates a probability that the link is cutoff of more than 50 percent. The hubs are depicted as white circles in the figures. No signs (a red circle with a diagonal line through it running from top left to bottom right) in the figure represent the locations of stockyards which are likely to be inaccessible by trucks. From the results at a confidence level of 95 percent in Figure 4, the municipalities located in the mountainous area are likely to be cutoff after the disaster as they rely on only a single road to connect to the rest of the network. A municipality in the southeast coastal area is also possibly inaccessible because it is likely to be impacted by the earthquake at a very high intensity. When increasing the confidence level to 99 percent in Figure 5, one more municipality in a mountainous area in the north is likely to be inaccessible after the disaster.

We considered relocating hubs to better locations in order to minimize the total response time. Only the locations of hubs are relocated, the locations of secondary stockyards are fixed. The results from the location routing model suggest the relocations as shown in Figure 4(b) and Figure 5(b) at confidence levels of accessibility of 95 percent and 99 percent respectively. As Nagoya City (the area in the center and the north) is likely to be impacted at a lower intensity, a single hub would be enough to deal with all the requirements in the region. On the other hand, it is perhaps better to prepare the hubs’ locations closer to the recipients in the south and the peninsula area to cope with a large demand in this region as it is likely to be impacted at a higher intensity.

![FIGURE 4 Hub locations, grouping, and locations inaccessible by truck after 48 hours at a 95% level of confidence.](image-url)
Figure 6 shows the cumulative probability of the total hours required to accomplish the operations. These values also include the penalties for the inaccessible destinations. As stated previously, the penalty for each truck required to deliver to the inaccessible location is set to 24 hours. Based on this result, the new locations of hubs can reduce the total operation time from the current prefectural plan by approximately 23 percent at a 95 percent confidence level and by 21 percent at 99 percent confidence level. Under an emergency situation, each truck will be used for 24 hours a day; we would thus require a total of 102 trucks to delivery to all destinations that can be accessible by trucks at 95 percent confidence level for Scenario 1 and 74 trucks for scenario 2. 125 trucks would be required at 99 percent confidence level for Scenario 1 and 93 trucks for scenario 2 in order to prepare for possible detour trips. In addition, the results suggest the need to prepare other transport modes (such as air transport) to access destinations more likely to be inaccessible, or to increase the level of pre-stocks at such destinations, in order to ensure that the victims in these regions can receive relief goods.

FIGURE 6 Cumulative probabilities of the total hours needed for the goods to reach the secondary stockyards after 24 hours.
CONCLUSION

So far, this paper has presented an analysis of disaster relief operations considering the probability of roads being disrupted at different intensity levels of the predicted Tokai-Tonankai Earthquake in Aichi prefecture. The analysis has taken into account the consequences of road failure on travel times due to detour trips and inaccessible destinations. The road recovery strategy was integrated into the analysis as well in order to analyze its impact on the emergency operation. The analysis results suggested the level of preparation of resources at different confidence levels in order to accomplish the delivery tasks. The results point to the wisdom of preparing other transport options to vulnerable destinations that are likely to be inaccessible by road. Assuming a possibility to relocate the hubs, we tried to relocate them to better locations in order to minimize the total response time. The total response time was selected as the criteria for decision making in this study. During the very first stage of a relief operation, the faster aid is delivered to victims, the greater the likelihood of saving lives. As the damage is likely to be more severe in the southern region and in the peninsula, it is perhaps better to consider relocating some hubs closer to the likely demand. This simulation can help planners to evaluate and make strategic planning to improve the efficiency of relief operations.

However, we have not considered the possibility of damage to the hubs' capacity by the aftershock to provide relief goods, which could impact on our recommendation to position the hubs. In addition, the travel time in this study was calculated only from the likely impact of links being cutoff due to the disaster, and assumes the average travel speed based on the previous actual operations. To add more realism, it is perhaps better to simulate the traffic conditions from the expected numbers of ambulances, police patrols, and relief aids trucks who would share the roads during an emergency. We need also to examine scenarios such as earthquakes of varying intensities as well as the possibility of a tsunami, as they are likely to happen together. These issues remain for future study.

REFERENCES

22. Schorder S. Jsprit project. [https://github.com/jsprit/jsprit](https://github.com/jsprit/jsprit)