

# Development of a Disaster Relief Logistics Model Minimizing the Range of Delivery Time

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## ABSTRACT

On March 11, 2011, the Great East Japan Earthquake (GEJE) attacked the North-Eastern Parts of Japan and the scale of the earthquake was the largest in recorded history in Japan. Despite Japan's great efforts in this disaster relief operation, relief goods did not reach the affected area. Managing disaster relief operations in the disaster situation like the GEJE is complex. Therefore, it became clear that the logistics system in the situation of a disaster had a lot of problems. In disaster situation like the GEJE, organizing the relief supply operations to afflicted people can be efficiently conducted. There are many disaster relief operations issues that need to be considered and resolved through logistics. Especially, it is very important that the distribution to the many victims is conducted equally. In this study, from the point of flow of distribution relief goods to the victims, we focus on the relationship between the shelter and the secondary collection point. The purpose of this study is to propose a logistics model that achieves the fair distribution for the many victims from the view point of the difference of the arrival time. In the earthquake, there were many routes that were unavailable and there was a limit to the number of cars that was available because of shortage of fuel. While considering these phenomena, we propose the logistics model that minimizes the range of the delivery time that the victims received relief goods from the transportation vehicles. Finally, in order to confirm the effectiveness of the proposed model, we perform the numerical experiments using the data of the Great East Japan Earthquake and the efficiency of the model is confirmed.

**Keywords:** *vehicle routing, the Great East Japan Earthquake, disaster relief operations, range of delivery time*

## 1. INTRODUCTION

On March 11, 2011, the Great East Japan Earthquake (GEJE) hit the North-eastern parts of Japan. Compared with the Great Hanshin Earthquake that occurred on January 17, 1995, the damage from the Great East Japan Earthquake was severe, and the latter was the greatest earthquake disaster in the history of Japan (see news from Kahoku Sinpou, 2011; National Police Agency HP; Hyogo Prefecture HP). Not only the vibration but also the tsunami caused by the earthquake brought considerable damage (report from Land, Infrastructure and Transportation Ministry, 2011). During this disaster event, various media reported that relief goods

did not reach the affected areas (Kuze, 2011). It is believed that considerable damage caused stagnancy in the delivery of goods, and consequently, the hardship of the victims increased (Mine, 2011). After the Great East Japan Earthquake, the Japanese opinion of the disaster has been increasing. The same can be said about the logistics system and further research on the then delivery process has been conducted. Thus, a sound logistics system is critical for the smooth delivery of relief goods to victims. Unlike a commercial situation, where the main purpose of logistics is to reduce the cost, in a disaster situation, besides reducing the cost, logistics must consider numerous other factors. In particular, equal and fair distribution of relief goods to victims is crucial. The purpose of this study is to propose a logistics model that achieves fair distribution for victims from the viewpoint of the difference of arrival time.

## 2. LITERATURE REVIEW

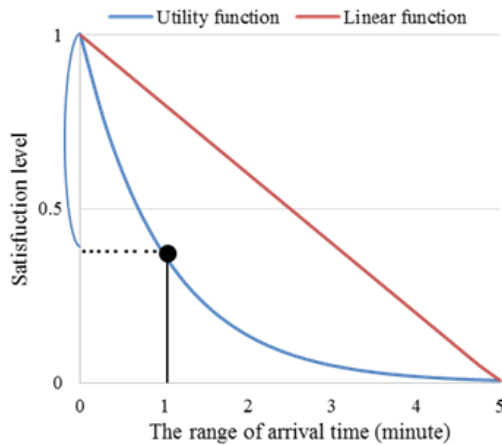
Balcik *et al.* (2008) conducted a study that focuses on last-one-mile, that is, the final stage of delivery of relief goods. They suggest that in the final stage of delivery, the amount of relief supplies to be assigned to each shelter, delivery schedule, and patrol route of the vehicle are the primary factors to be considered. In the disaster situation, unlike the commercial situation, many routes become unavailable, the number of cars becomes limited, and the demand for relief goods significantly surpasses the supply. In this study, we propose a model that aims to resolve these issues in such a situation. The objective of this model is to minimize the unfulfilled demands of victims and the total cost of delivery. In this study, to consider the damage of the infrastructure, the cost of specific routes is set higher than the others. In addition, by considering multi-items and multi-period, the model handles changes of the victim's needs that occur over time.

Campbell *et al.* (2008) assert that in a disaster, fastness and the fairness is very important. There are many existing tools for solving vehicle routing problems, and most of them focus on minimizing the total cost to conduct the delivery. They suggest that minimizing the total cost to conduct the delivery is not suitable to consider the fastness and fairness; furthermore, in a disaster, if the delivery aims at minimizing the total cost, the arrival of relief goods may be delayed

extremely to reduce the cost, which consequently leads to suffering and life-and-death situations. They focus on the arrival time of relief goods and examine two alternative objective functions for the classic vehicle routing problems: one that minimizes the maximum arrival time and the other that minimizes the total arrival time.

### 3. PROBLEM FORMULATION

In this section, we introduce the notations and required parameters for the formulation. Subsequently, the decision variables of the mathematical model are defined. In previous studies, the model that considers the delivery time when relief supplies arrives at shelters has been proposed. However, the purpose of those models is minimizing the sum of arrival time and the disparity of the arrival time is not considered. Therefore, in this study, in order to consider the unfairness of the arrival time of each shelters, we proposed a model that minimizes the range of delivery time. Under chaotic circumstances in the event of a disaster, satisfaction level of victims does not increase linearly. In our study, we consider satisfaction level as utility function. **Figure 1** shows the relationship between satisfaction level and the range of arrival time. In commercial situation, a few minutes improvement might be worthless. But in disaster situation, satisfaction level is increased remarkably, even just a minute improvement.



**Figure 1** Relationship between satisfaction level and the range of arrival time.

*Sets*

- $N$  set of shelters
- $V$  set of all nodes
- $K$  set of cars

*Parameters*

- $t_{ij}$  travel time between nodes  $i$  and  $j$
- $d_i$  demand of nodes  $i$
- $Q$  loading capacity of vehicles
- $T$  sufficient large number

*Decision variables*

- $x_{ijk}$  binary variables equal to 1 if vehicle  $k$  travels from node  $i$  to node  $j$
- $a_{ik}$  arrival time at node  $i$  by car  $k$
- $a_{\min}$  fastest arrival time
- $a_{\max}$  latest arrival time
- $y_{ik}$  binary variables about the fastest arrival time

*Objective function*

$$\text{Minimize } a_{\max} - a_{\min} \tag{1}$$

The objective function in equation (1) minimizes the range of delivery time of relief goods from transportation vehicles.

*Subject to*

$$\sum_{k \in K} \sum_{j \in V} x_{ijk} = 1 \quad \forall i \in N \tag{2}$$

$$\sum_{j \in V} x_{0jk} = 1 \quad \forall k \in K \tag{3}$$

$$\sum_{i \in V} x_{ihk} - \sum_{j \in V} x_{hjk} = 0 \quad \forall h \in V, k \in K \tag{4}$$

$$\sum_{j \in V} x_{i0k} = 1 \quad \forall k \in K \tag{5}$$

$$t_{ij} + a_{ik} \leq a_{jk} + T(1 - x_{ijk}) \quad \forall i, j \in V, k \in K \tag{6}$$

$$a_{ik} - T(1 - x_{0ik}) \leq t_{0i} \leq a_{ik} + T(1 - x_{0ik}) \quad \forall i \in N, k \in K \tag{7}$$

$$a_{\max} \geq a_{ik} \quad \forall i \in N, k \in K \tag{8}$$

$$a_{\min} \leq a_{ik} + T(1 - y_{ik}) \quad \forall i \in N, k \in K \tag{9}$$

$$\sum_{i \in N} d_i \sum_{j \in V} x_{ijk} \leq Q \quad \forall k \in K \tag{10}$$

$$x_{ijk} \in \{0,1\} \quad \forall i, j \in V, k \in K \tag{11}$$

$$T y_{ik} \geq a_{ik} \quad \forall i \in N, k \in K \tag{12}$$

$$\sum_{k \in K} \sum_{i \in N} y_{ik} = n \tag{13}$$

$$y_{ik} \in \{0,1\} \quad \forall i \in N, k \in K \tag{14}$$

Constraint (2) ensures that each node is visited by a vehicle. Constraint (3) ensures that all of the vehicles must leave from the depot. Constraint (4) specifies that a vehicle arriving at node  $i$  must leave it. Constraint (5) specifies that all of the vehicles must return to the depot. Constraints (6) and (7) specify that  $a$  represents the appropriate arrival times. Constraint (8) indicates inequality related to the latest arrival time. Constraint (9) indicates inequality related to the fastest arrival time. Finally, Constraint (10) ensures that the total load per route must not exceed the loading capacity of vehicles.

Additionally, in order to examine the efficacy of the proposed model to conduct fair delivery in terms of arrival time of relief goods from the transportation vehicles, we perform a comparison with two classic models. One of them aims to minimize the total cost of transportation and the other aims to minimize the total arrival time. Equations (15) and (16) are their objective functions.

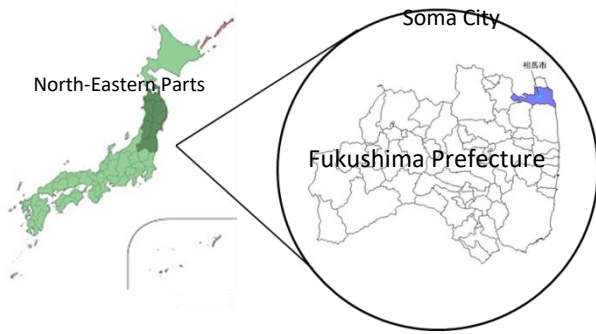
$$\text{Minimize } \sum_{i,j \in V} \sum_{k \in K} t_{ij} x_{ijk} \tag{15}$$

$$\text{Minimize } \sum_{i \in N} \sum_{k \in K} a_{ik} \tag{16}$$

## 4. NUMERICAL EXPERIMENT

### 4.1 Case study 1

In this section, a numerical experiment is conducted to examine the efficacy of the proposed model using data from the Great East Japan Earthquake. We focus on the number of shelters in Soma City, Fukushima Prefecture, an area affected by the Great East Japan Earthquake. We show the positional relationship between the North-eastern parts of Japan and Soma City, Fukushima Prefecture in **Figure 2**.

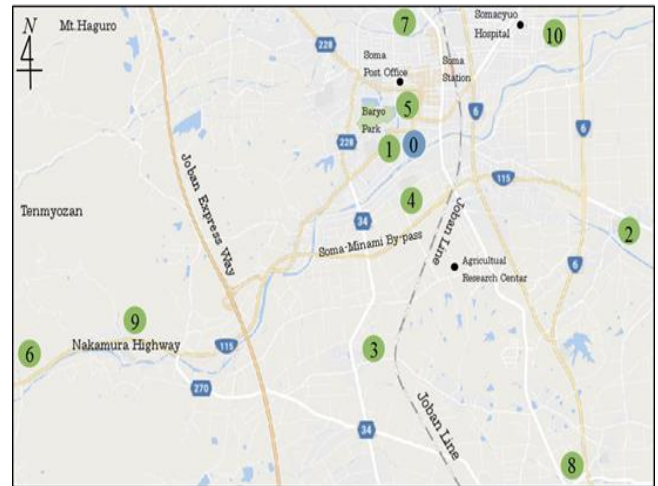


**Figure 2** Positional Relationship Between the North-Eastern and Soma City

The number of shelters is set based on the research of Soeta *et al.* (2015). We regard a city hall of Soma City as a secondary collection point. We show the demand for each shelter in Table 1. During the Great East Japan Earthquake, under the influence of the collapse, crack, and liquefaction, many routes became unavailable, and consequently, the delivery of relief goods was delayed. In this kind of situation, using large vehicles such as 2t trucks and vans for delivery is not suitable. Therefore, in this study, the loading capacity of vehicles is set to 750 kg. In addition, only one commodity is considered. In order to examine the changes of the value caused by changes in the number of vehicles, we change the number of available vehicles from 3 up to 8. **Figure 3** shows a map of Soma City quoted from Google Maps. We show the positional relationship between a secondary collection point and each shelter by putting marks on this map. A blue circle represents the location of a secondary collection point and green circles represent the location of each shelter. We show the travel time between each shelter in Table 2. The travel time between nodes *i* and *j* is set based on the value obtained by researching Google Maps. **Figure 4** shows that the relationship between the number of vehicles and the range of delivery time of relief goods. **Figure 5** shows the relationship between the number of vehicles and the total cost of transportation.

According to these figures, we found that the proposed model can minimize the range of delivery time. In addition, we found that the larger the number of vehicles, the smaller the value we got. But, according to **Figure 5**, we found that the largest value is obtained using the proposed model in terms of cost.

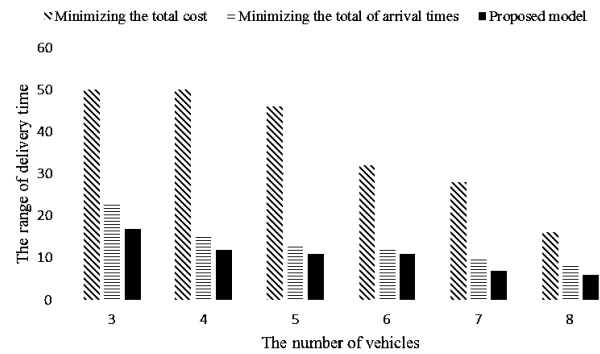
**Figure 6** and **Figure 7** shows the route of vehicles to deliver relief goods using the proposed model and the model aims to minimize the total arrival time when five vehicles can be used. Arrows represent the flow of vehicles.



**Figure 3** Positional Relationship Between the Secondary Collection Point and Shelters in Soma City

**Table 1** Each Shelter's Demand (kg)

Shelter's Name	Demand	Shelter's Name	Demand
1. Nakamura first primary school	210	6. The old man diverticulum house	20
2. Iitoyo elementary school	70	7. Hamanasu welfare center	230
3. Yahata elementary school gymnasium	70	8. Nittaki community center	30
4. Koyo junior high school	210	9. Yamagami community center	10
5. Sport Arena Soma	120	10. Somahigashi high school	230



**Figure 4** Relationship Between the Number of Vehicles and the Range of Delivery Time

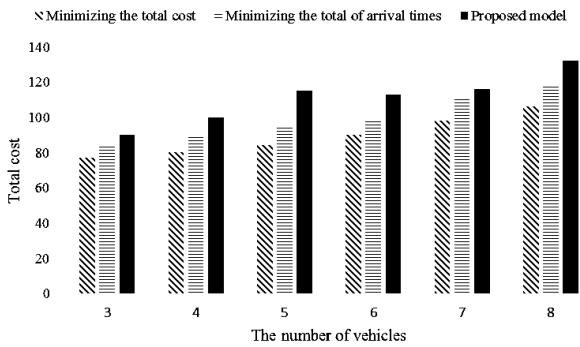


Figure 5 Relationship Between the Number of Vehicles and the Total Cost of Transportation

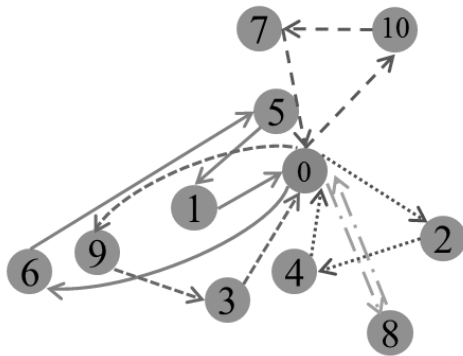


Figure 6 Route of Vehicles Using the Proposed Model

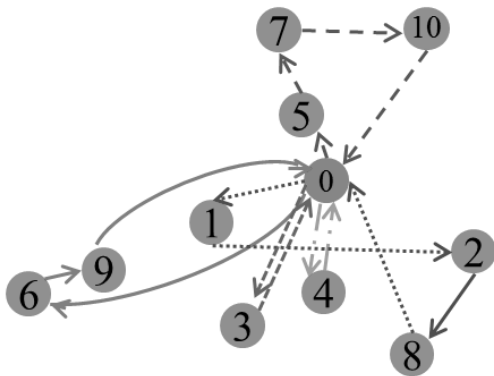


Figure 7 Route of Vehicles Using the Model Aims to Minimize the Total Arrival Time

From these figures, we can read the characteristics of using each model. we find that the delivery to the shelter near the secondary collection point such as Nakamura first primary school, Sport Arena Soma and Yahata elementary school is prioritized using the model aims to minimize the total arrival time. However, as a result, there is possibility that the arrival time of some shelters may be late. On the other hand, we find that the shelter near the secondary collection point is not prioritized necessarily using the proposed model. In our model, vehicles tend to go the shelter far from secondary collection point such as The old man diverticulum house, Itoyo elementary school and Somahigashi high school at first. As a result, the range of the delivery time is reduced.

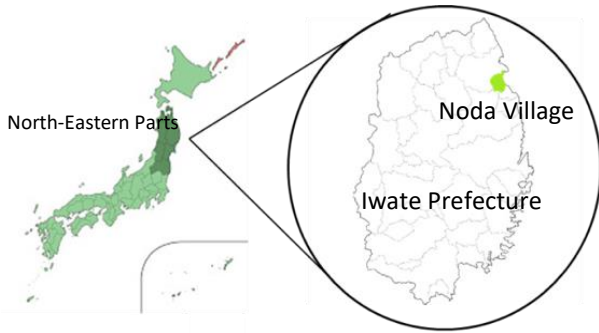
4.2 Case study 2

Next, we carry out a numerical experiment using other regions' data to examine how the results differ regionally. As in the Soma City case study, we use data regarding the Great East Japan Earthquake.

We focus on the number of shelters in Noda Village, Iwate Prefecture. We regard a city hall of Noda Village as the secondary collection point. We show the positional relationship between the Northeast parts of Japan and Noda Village, Iwate Prefecture, in Figure 8. We show the demand of each shelter in Table 3. Figure 9 shows a map of Noda Village obtained from Google Maps. We show the positional relationship between the secondary collection point and each shelter by placing marks on this map. The blue circle represents the secondary collection point and the green circles represent the shelters. We show the travel time between each shelter in Table 4. The travel time between nodes *i* and *j* is set based on the value obtained from Google Maps. Other parameters are the same as in Case Study 1. Figure 10 shows the relationship between the number of vehicles and the delivery time range of relief goods. Figure 10 shows the relationship between the number of vehicles and total transportation cost. Figures 12 and 13 show the routes vehicles use to deliver relief goods using the proposed model; the model aims to minimize total delivery time when five vehicles are used. The arrows represent the flow of vehicles.

Table 2 Travel time (minutes)

	0	1	2	3	4	5	6	7	8	9	10
0. Secondary collection point											
1. Nakamura first primary school	1										
2. Itoyo elementary school gymnasium	10	5									
3. Yahata elementary school gymnasium	7	7	11								
4. Koyo junior high school gymnasium	8	7	10	9							
5. Sport Arena Soma	1	1	10	9	9						
6. The old man diverticulum house	9	8	13	10	11	9					
7. Hamanasu welfare center	4	4	11	11	11	3	11				
8. Nittaki community center	9	10	7	8	11	10	10	12			
9. Yamagami community center	9	8	13	10	11	9	2	11	11		
10. Somahigashi high school	9	10	13	15	13	10	17	10	15	17	



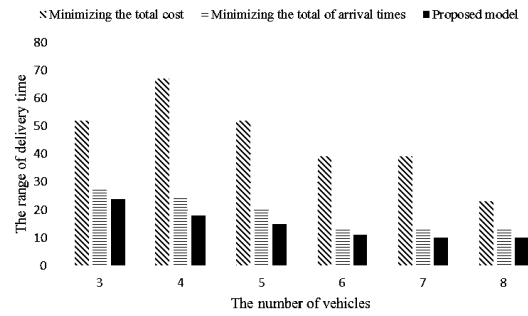
**Figure 8** Positional Relationship Between the North-Eastern and Noda Village



**Figure 9** Positional Relationship Between the Secondary Collection Point and Shelters in Noda Village

**Table 3** Each shelter's demand (kg)

Shelter's Name	Demand	Shelter's Name	Demand
1.Noda elementary school	262	6.Niiyama firefighting station	46
2.Noda junior high school	296	7.Eboshiso	341
3.Kuji industry high School	214	8.Maita community center	261
4.Kaizoin	200	9.Niiyama nursery school	28
5.Nakahira community center	89	10.Nakazawa community center	45



**Figure 10** Relationship Between the Number of Vehicles and the Range of Delivery Time

**Table 3** Travel Time (minutes)

	0	1	2	3	4	5	6	7	8	9	10
0. Secondary collection point											
1. Noda elementary school	1										
2. Noda junior high school	10	5									
3. Kuji industry high School	7	7	11								
4. Kaizoin	8	7	10	9							
5. Nakahira community center	1	1	10	9	9						
6. Niiyama firefighting station	9	8	13	10	11	9					
7. Eboshiso	4	4	11	11	11	3	11				
8. Maita community center	9	10	7	8	11	10	10	12			
9. Niiyama nursery school	9	8	13	10	11	9	2	11	11		
10. Nakazawa community center	9	10	13	15	13	10	17	10	15	17	



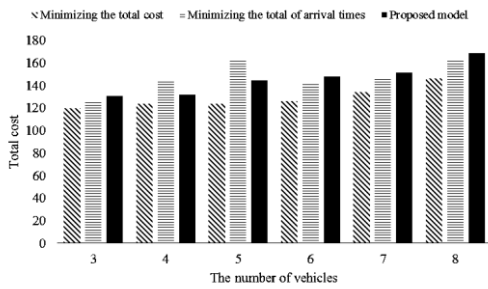


Figure 11 Relationship Between the Number of Vehicles and the Total Cost of Transportation

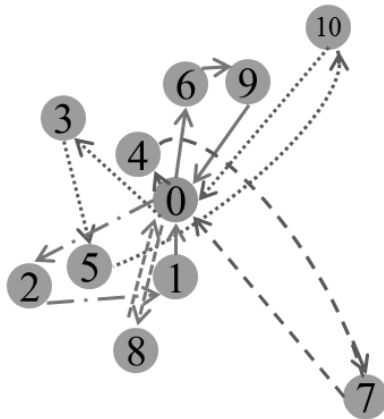


Figure 12 Route of Vehicles Using the Proposed Model

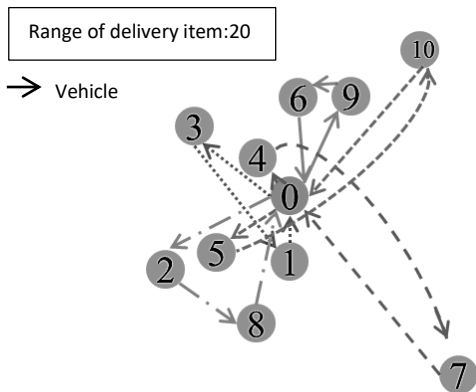


Figure 13 Route of Vehicles Using the Model Aims to Minimize the Total Arrival Time

From these figures, as in the Soma City case study, we can obtain the smallest value of the delivery time range using the proposed model. Additionally, a similar trend is exhibited by transportation cost. When we use the proposed model, we can conduct optimal delivery in terms of the arrival time of relief goods. However, the total cost of the proposed model is higher compared to the other model.

From these figures, we can see that delivery from the secondary collection point closest to the shelter is not necessarily prioritized in the proposed model. However, delivery to the shelter near the secondary collection point is prioritized using the model, aiming to minimize total arrival time. We find that we can reduce differences in delivery times using the proposed model. In disaster circumstances, even a few minutes of improvement in the arrival time can result in increased satisfaction. Therefore, we think that the

proposed model can facilitate optimal delivery in terms of the arrival time of relief goods for the victims.

## 5. CONCLUSION

In this study, we proposed a humanitarian logistics model that minimizes the range of delivery time of relief goods. We performed numerical experiments to examine the efficacy of the proposed model using data from the Great East Japan Earthquake. In this numerical experiments, we consider satisfaction level as utility function. We assume that in a disaster situation, satisfaction level of victims does not increase linearly and satisfaction level is increased remarkably, even just a minute improvement. Using proposed model, we can conduct fair delivery in terms of the arrival time of relief goods. When we use proposed model, vehicles tend to go the shelter far from secondary collection point at first. We performed experiments for two foreign regions. In either case, similar trends were shown. However, the total cost of the proposed model is higher than the other model. We found that the larger the number of vehicles, the smaller the value of the range of delivery time. We also focused on the relationship between the shelter and the secondary collection point. However, to analyze a more realistic situation, we should consider not only the last mile but also the earlier phases. We plan to continue our research considering the delivery of bigger networks and analyzing the situation where the demand significantly surpasses the supply of relief goods. In addition, we should propose the model that can evaluate the satisfaction level of victims with indicators other than arrival time of relief goods.

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