Fundamental Study on a Decision-making Support Method for Railway Transportation Recovery Strategy after Large-scale Disasters

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In a railway business, recovery strategies for quick recovery of railway transportation after large-scale disasters are becoming important more and more. First, this paper describes a mathematical algorithm for calculating a railway network recovery plan constituting a basic part of a decision-making support method of a railway transportation recovery strategy. Secondly, it describes the outline and the result of the recovery simulation conducted to verify the feasibility and validity of the algorithm. Finally, it outlines the development status of other parts of the decision-making support method except the algorithm. It also outlines future development plans of the method.

Keywords: railway network, resilience, large-scale disaster, recovery strategy, decision-making support, mathematical planning

1. Introduction

Supply chains in Japan today center on metropolitan areas, and advanced socio-economic clusters have been constructed throughout the country supported by dense and sophisticated transportation networks. Effective function of these supply chains contributes to maintaining efficient and highly productive societies. However, in recent years, many large-scale disasters have happened due to natural hazards that have far exceeded our expectations such as the Great East Japan Earthquake in March 2011 or the 2018 Japan floods (heavy rainfall in west Japan in July 2018). Some of these disasters resulted in long interruptions in the transportation networks. As a result, these disasters led to stagnating the flow of people and logistics throughout the country and severely impacting people’s lives and production activities.

The experience of these disasters has shown that it is difficult to completely prevent damage from large-scale disasters. On the other hand, the concept of resilience has been gaining attention. The concept of resilience is to maintain normal activities even in the face of unexpected disasters or to reduce damage as much as possible and recover flexibly even if a disaster is unavoidable [1]. The concept of resilience has affected business continuity planning (BCP) in companies, and in the railway business as well, in order to improve resilience, various studies on countermeasures against disasters have been conducted, namely comprehensive disaster contingency planning that combines disaster prevention measures such as strengthening the durability of structures against hazards, measures to minimize damage when hazards exceed a certain scale, and recovery strategies to enable rapid recovery of railway transportation services.

Considering the current situation, we have been developing a method to support decision-making in railway transportation recovery strategy after large-scale disasters. This work is a part of a broader set of technological developments aimed at improving the resilience of the railway business against large-scale disasters. The basis of the decision-making support method is a mathematical algorithm which calculates optimal railway network recovery plans to minimize the lost transportation volume described later (hereinafter, the recovery planning algorithm).

This paper describes the following three main points.

- Theory of the recovery planning algorithm
- Outline and result of a recovery simulation using a virtual railway network conducted to verify the feasibility and validity of the algorithm
- Development status of other parts of the decision-making support method being worked on and future development plans of the method

2. Theory of the recovery planning algorithm

2.1 Definition of the lost transportation volume

The lost transportation volume is defined as the decreased amount of the transportation volume such as the number of passengers or the amount of freight during a recovery period. Note that, the recovery period is a period from a time when a railway network starts to be damaged due to a disaster to a time when the network is completely recovered. Figure 1 shows the definition of the lost transportation volume, indicated with the shaded area.

2.2 Formulation of the recovery planning algorithm

The recovery planning algorithm is constructed to calculate the order of recovery of damage points in a railway network. The purpose of the algorithm is to minimize the lost transportation volume during a recovery period on the basis of the mathematical programming. The unit of calcu-
lation is a link that connects stations (nodes) in a railway network. Links connecting the same stations are defined as a different link for each direction.

The transportation volume of a railway network is set in each OD. Note that an OD is an abbreviation for Origin to Destination and represents a combination of an origin station and a destination station. Even if routes on the way are different, if a combination of an origin station and a destination station are the same, they are all defined as the same OD. Figure 2 shows the relationship between a link and an OD in a railway network.

In the recovery planning algorithm, the rules of recovery are as follows:

- All links are inoperable immediately after a disaster and require inspection
- An undamaged link can resume operation after inspection is completed
- To resume operation of a damaged link, recovery work is also required after inspection is completed
- Recovery happens in two steps: first a damaged link is switched to a temporary recovery link; second the temporary recovery link is switched to a complete recovery link (if there is no major damage to the link, step one is skipped)
- Transportation volume that can pass through a temporary recovery link is limited compared to ordinary operation

Moreover, the following items are given for calculation:

- Transportation volume of each OD during ordinary operation
- Maximum transportation volume that can pass through each link in ordinary operation
- Transportation rate (maximum transportation volume divided by that in ordinary operation)
- Resources required to complete inspection of each link
- Resources required to complete step one in recovery work for each link
- Resources required to complete step two in recovery work for each link
- Maximum available resources per day which can be devoted to inspection or recovery work for each link
- Total available resources per day devoted to inspection or recovery work

Although there are still ongoing discussions about the level of resources required for recovering each link and how to calculate the transportation rate, these are treated as given in this paper. In addition, constraints on the operation of crew members and vehicles and specifications relating to each link such as electrified/non-electrified are not considered. We have also developed a method to quantitatively calculate the resources required for recovery of structures on a railway network on the basis of current conditions [2, 3].

The subsets and subscripts, the given variables, the decision variables (controllable variables), the objective function, and the constraints (conditions of ranges of decision variables) are explained in the following sections individually.
Maximum total available resources which can be devoted to inspection or recovery work on day $d$.

### 2.2.3 Decision variables

- $\bar{q}_{n_{ij}}^d$: Transportation volume passing through link $ij$ on OD $n$ on day $d$.
- $\bar{q}_{s_{n_k}}^d$: Transportation departure volume at station $k$ on OD $n$ on day $d$.
- $\bar{q}_{a_{n_k}}^d$: Transportation arrival volume at station $k$ on OD $n$ on day $d$.
- $r_{ij}^d$: Resources required for inspection or recovery work of link $ij$ on day $d$.
- $c_{ij}^d$: Integer variable that is 1 if the inspection of link $ij$ has already been completed on day $d$ or 0 otherwise.
- $s_{ij}^d$: Integer variable that is 1 if the first step of the recovery work for temporary recovery of link $ij$ has already been completed on day $d$ or 0 otherwise.
- $n_{ij}^d$: Integer variable that is 1 if the second step of the recovery work for complete recovery of link $ij$ has already been completed on day $d$ or 0 otherwise.

### 2.2.4 Objective function

The aim of the objective function given in (1) is minimization of the lost transportation volume on a railway network. Equation (1) gives the sum of differences between transportation departure volume at each origin station in each OD on each day during ordinary operation and the same of these differences during a recovery period.

Minimize $\sum_n \sum_k \sum_d (q_{s_{n_k}}^{od} - \bar{q}_{s_{n_k}}^d)$ \hspace{1cm} (1)

### 2.2.5 Constraints

#### a) Constraint on the transportation volume that can pass through each link

The transportation volume passing through link $ij$ on day $d$ is less than or equal to the maximum transportation volume that can pass through the link, as given in (2). The right side is 0 if link $ij$ is inoperable ($s_{ij}^d = 0$ and $n_{ij}^d = 0$) on day $d$, $q_{cap_{ij}} d_{ij}^d$ if link $ij$ is in temporary recovery ($s_{ij}^d = 1$ and $n_{ij}^d = 1$), and $q_{cap_{ij}}$ if link $ij$ is in complete recovery ($s_{ij}^d = 0$ and $n_{ij}^d = 1$).

$$\sum_{n_{ij}} q_{s_{n_k}}^d \leq q_{cap_{ij}} \left( d_{ij}^d s_{ij}^d + (1-d_{ij}^d) n_{ij}^d \right) \hspace{1cm} \forall i, j, d$$ \hspace{1cm} (2)

#### b) Constraint on the flow of transportation of each OD

The flow of transportation for OD $n$ on day $d$ has the relationship given in (3). The transportation departure and arrival volumes at station $k$ in OD $n$ are given in (4) and (5).

$$\sum_{j_{n_{ij}}} q_{s_{n_k}}^d - \sum_{j_{n_{ij}}} \bar{q}_{s_{n_k}}^d = \bar{q}_{a_{n_k}}^d - \bar{q}_{a_{n_k}}^d \hspace{1cm} \forall k, n, d$$ \hspace{1cm} (3)

$$q_{s_{n_k}}^{low} \leq q_{s_{n_k}}^d \leq q_{s_{n_k}}^{ord} \hspace{1cm} \forall k, n, d$$ \hspace{1cm} (4)

### d) Constraint on the recovery works of each link

As given in (8), the cumulative resource to be devoted to work on link $ij$ by day $d$ reaches the level of resources required to complete the work on the link in day $d$.

$$\sum_{r_{ij}} r_{ij}^d \geq r_{cap_{ij}} c_{ij}^d \hspace{1cm} \forall i, j, d$$ \hspace{1cm} (8)

Moreover, as given in (7), the resources which can be devoted to inspection or recovery work on link $ij$ on day $d$ are less than or equal to the maximum total available resources which can be devoted to recovery work on link $ij$.

$$r_{ij}^d \leq r_{cap_{ij}} \hspace{1cm} \forall i, j, d$$ \hspace{1cm} (7)

Note that, as given in (11), the inspection of link $ij$ must be completed by the time step one of recovery work on the link begins. Likewise, as given in (12) and (13), inspection and step one of recovery work on link $ij$ must be completed by the time the step two of recovery work begins.

$$c_{ij}^d \leq s_{ij}^d \hspace{1cm} \forall i, j, d$$ \hspace{1cm} (11)

$$c_{ij}^d \leq n_{ij}^d \hspace{1cm} \forall i, j, d$$ \hspace{1cm} (12)

$$s_{ij}^d \geq n_{ij}^d \hspace{1cm} \forall i, j, d$$ \hspace{1cm} (13)
3. Outline and result of a recovery simulation

In order to verify the feasibility and validity of the recovery planning algorithm, a recovery simulation after a large-scale disaster was conducted using a virtual railway network. The calculation target was freight transport. In addition, the amount of transport and resources for inspection or recovery work were converted into a number of containers and worker-days.

### 3.1 Outline of the simulation

The following assumptions were made in the simulation:

- The simulation included four scenarios, listed in Table 1. Note that, for example, “0 ⇔ 1” in the Table represents both directions: 0 → 1 and 1 → 0. The same applies in Table 2 and Table 3.
- The virtual railway network is shown in Fig.3, and each number in the Figure is the maximum number of containers that can pass through each link.
- The number of containers transported along each OD during ordinary operation is shown in Table 2.
- The total number of possible worker-days to be devoted to inspection or recovery work for each link, are shown in Table 3.
- The total number of possible worker-days to be devoted to inspection or recovery work is 1,500 worker-days.
- The transportation rate for each link is 0.5.
- The target calculation period began from the moment of the disaster to the 40th day.

### 3.2 Result of the simulation

The calculation program for the recovery planning algorithm is written in Python (Ver.3.6.1), and Spyder (Ver. 3.1.4) and an integrated Python environment is used for execution. The COIN-OR branch and bound, which is the default solver included in the Python library PuLP (Ver. 1.6.8), is used to execute the optimization calculation. The specification of the PC used for the calculation is OS: Windows 10 Professional 64 bit, CPU: Intel Core i7-6700 3.40 GHz, RAM: 8 GB. The time taken for the optimization calculation for each scenario is shown in Table 4.

Since all the calculations converge quickly, the recovery planning algorithm is considered to have high feasibility.

The number of days required to complete recovery of the railway network and the lost transportation volume (number of containers) during the recovery period for each scenario are shown in Table 5. In addition, Fig. 4 is a graph showing the recovery process of the amount of transportation on day 40 for each scenario. Note that, the recovery process of the amount of transportation and resource to be put in each OD are also calculated for each scenario. Compared to scenario I, in scenario II, both the number of days required to complete recovery of the railway network and the lost transportation during the recovery period are significantly reduced. Furthermore, in scenario III, the number of days required to complete recovery of the railway network is the same. However, since less resources are required for inspection, the amount of transportation recovers somewhat quicker and the lost transportation volume is reduced accordingly. On the other hand, in scenario IV:

#### Table 1 Description of four scenarios

| Scenario | Description |
|----------|-------------|
| I        | Basic scenario  
- Links: 0⇔1 (both 0→1 and 1→0), 0⇔7 and 6⇔7 are damaged due to a large-scale earthquake and a derailment (major damage) occurs in 0⇔7.  
- Since all links except 0⇔7 have no major damage, step one in recovery work is skipped. |
| II       | Disaster prevention scenario  
- Since structures on the railway network have already been strengthened against earthquakes, the number of worker-days required to complete the recovery work is lower than in scenario I.  
- Since major damaged was avoided on 0⇔7 because of structure reinforcement, step one in recovery work is skipped like with other links. |
| III      | Disaster reduction scenario  
- An early earthquake warning system has already been introduced on the railway network, therefore information can be gathered about the detail of each area of damage.  
- The number of worker-days required to complete inspection of undamaged links and 0⇔7 is lower than in scenario I. |
| IV       | Limited recovery resource scenario  
- The maximum number of possible worker-days to be devoted to inspection or recovery work per day is lower than scenario I. |

| OD     | Number of containers per day |
|--------|------------------------------|
| 0⇔2    | One direction: 225 Both directions: 450 |
| 0⇔4    | One direction: 20 Both directions: 40 |
| 0⇔6    | One direction: 100 Both directions: 200 |
| 2⇔4    | One direction: 15 Both directions: 30 |
| 2⇔6    | One direction: 6 Both directions: 12 |
| 4⇔6    | One direction: 5 Both directions: 10 |
| Total  | One direction: 371 Both directions: 742 |

QR of RTRI, Vol. 61, No. 4, Nov. 2020

252
Table 3 List of the number of worker-days required to complete inspection or recovery work of each link in each scenario

| Link   | Maximum number of possible worker-days to be devoted per day | Number of worker-days required to complete inspection | Number of worker-days required to complete step one in recovery work | Number of worker-days required to complete step two in recovery work |
|--------|-------------------------------------------------------------|------------------------------------------------------|-------------------------------------------------------------------|-------------------------------------------------------------------|
| 0→1    | 1,000 1,000 1,000 500                                       | 8 8 8 8                                             | 0 0 0 0                                                            | 795 402.5 795 795                                                  |
| 0→7    | 1,000 1,000 1,000 500                                       | 148 148 8 148                                       | 1,700 0 1,700 1,700                                               | 8,665 1,612.5 8,665 8,665                                         |
| 1→2    | 1,000 1,000 1,000 500                                       | 8 8 8 8                                            | 0 0 0 0                                                            | 392.5 197.5 392.5 392.5                                           |
| 6→7    | 1,000 1,000 1,000 500                                       | 8 8 8 8                                            | 0 0 0 0                                                            | 1,200 600 1,200 1,200                                             |
| Other links | 1,000 1,000 1,000 500                                      | 4 4 2 4                                            | 0 0 0 0                                                            | 0 0 0 0                                                          |

Fig. 3 Virtual railway network

Table 4 Time taken for optimization calculation for each scenario

| Scenario | I | II | III | IV |
|----------|---|----|-----|----|
| Time     | 101'14” | 9’58” | 25’47” | 0’57” |

Table 5 Number of days required to complete recovery of the railway network and the lost transportation volume during the recovery period for each scenario

| Scenario | I | II | III | IV |
|----------|---|----|-----|----|
| Number of days | 18 | 5  | 18  | 23 |
| Number of lost containers | 2,107 | 962 | 2,012 | 2,697 |

IV, since the available resources to be devoted to work are limited, both the number of days required to complete recovery of the railway network and the lost transportation volume during the recovery period increase. The results are considered to appropriately reflect the positive effect of disaster prevention/reduction measures and the negative effect of the resource constraints set in the scenarios. Therefore, the recovery planning algorithm is also considered to have the validity. Furthermore, for example, differences between the lost transportation volume during the recovery period in scenario II and in scenario I, could be considered to be the quantification of the effect of disaster prevention measures. So, it is also considered that the algorithm can be used to calculate the cost effectiveness of disaster prevention/reduction measures.

4. Development status of other parts of the decision-making support method being worked on and future development plans of the method

4.1 Consideration of transportation detours during recovery period

In order to improve the resilience of the railway business, it is important to consider detours in transportation using undamaged links and which have sufficient capacity during recovery periods. An algorithm has been therefore designed to calculate optimal detour routes to minimize the lost cost (hereinafter, the detour planning algorithm). The lost cost, for example, in the case of freight transportation, can be incurred due to delay or cancellation of freight transport. The relationship between the recovery plan and the detours is shown in Fig. 5. A detour route for each day is calculated according to a recovery plan on each corresponding day.

4.2 Development of the decision-making support system implementing the recovery planning algorithm

To conduct recovery simulations on various railway networks, a prototype decision-making support system has been developed, as shown in Fig. 6. The recovery planning algorithm was implemented in the system. To support calculations in various conditions, the railway network can be freely set on the system. Moreover, various constraints such as the maximum transportation volume that can pass through each link can also be adjusted. The system then automatically calculates an optimum recovery plan under a given set of conditions. The calculation result also gives other information: progress in the recovery of total transportation volumes, transport volumes passing through each link on each day and the resources required for each link on each day. In addition, the system can display the information on a GUI.

The system will be expanded by additional implementation of the detour planning algorithm described above. The expanded system can simultaneously calculate a recovery plan on each day and a detour plan that depends on...
a recovery plan on each corresponding day. The practicality of the system must be verified by reproducibility simulations using actual records of recovery processes and transport detours actually used on railway networks that have experienced disasters.

5. Conclusion

We have been developing a decision-making support method as part of a railway transportation strategy for post large-scale disaster recovery, as a part of a broader set of technological developments. The decision-making support method contributes to improving the resilience of the railway business against large-scale disasters. This paper first describes the recovery planning algorithm constructed as a basic part of a decision-making support method. The algorithm was designed to calculate an optimal recovery plan for links on a network damaged by a disaster, with the purpose of minimizing the lost transportation volume during a recovery period. Secondly, the paper describes a recovery simulation using a virtual railway network. The simulation included four scenarios with different disaster countermeasures and recovery conditions. The simulation results confirmed the feasibility and validity of the algorithm. Thirdly, the paper outlines the status of a detour planning algorithm and a decision-making support system which are still being developed. Finally, it outlines how this method may be further developed in future.

In addition to the developments described in this paper, it seems necessary to further expand the system to enable the calculation considering alternative transportation...
using other transportation modes.

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