Impact Assessment on Transportation Network and Sectoral Freight Flow Caused by Volcanic Ash Fall

Shogo ISO[1] ・Tomoki ISHIKURA[2]

[1]non Member of JSCE, Dept. of Civil Eng., Tokyo Metropolitan University （Minamiosawa 1-1, Hachioji-shi, Tokyo 192-0397, Japan）
E-mail: iso-shogo@ed.tmu.ac.jp
[2]Member of JSCE, Associate Professor, Dept. of Civil Eng., Tokyo Metropolitan University （Minamiosawa 1-1, Hachioji-shi, Tokyo 192-0397, Japan）
E-mail: iskr@tmu.ac.jp

Out of the all effects produced by a volcanic eruption, volcanic ash fall especially causes widespread damage over a short term period. In general, ash fall has huge impacts on a traffic network, which results in sudden and significant regional economic loss due to delivery delay and a declined trading volume. This paper explores impacts on transportation network and commodity flow caused by volcanic ash fall by applying the three sector ICFM to two hypothetical scenarios, the eruption of Mt. Asama and Mt. Fuji. The results show changes of shortest paths, OD transport cost and OD commodity flow.

Key Words: *volcanic ash fall, transport network, interregional trade, interregional commodity flow model*

1. Introduction

A volcanic eruption is one of the natural disasters that cause catastrophic damage. In Japan, which has 111 active volcanoes[1)], a number of eruptions have been witnessed so far. In 2014, the sudden eruption of Mt. Ontake was responsible for 63 fatalities including missing people[2)].

Eruptions in general produce not only a stream of lava and a pyroclastic flow but also a volcanic mudflow, cinder and volcanic ashes[3)]. Moreover, the extent of the destruction depends on the type of effect. Out of the effects mentioned above, volcanic ash fall is especially known as one of the effects which lead to widespread damage over a short term period.

Back in 1707, the eruption of Mt. Fuji, which was called the "Hoei eruption[4)]" changed vast farmland around the mountain into barren lands due to volcanic products. Around Mt. Saint Helens in 1980[5)], the ash fall caused by the destructive eruption of Mt. Saint Helens in the U.S. posed temporary problems for transportation operations. Interstate 90 from Seattle to Spokane and Washington was closed to traffic for a week due to poor visibility and ashes on the land.

As mentioned above, volcanic ash fall has huge impacts on the facilities in traffic network. Disruption in some sections of road network system subsequently results in the problems of freight traffic conditions. For example, it may cause a delivery delay and force to find the new supplier or customer. Thus, the regional economic activities may suddenly and significantly decline due to the ash fall.

The economic impact in a certain region spreads across regions via inter-regional and inter-industrial interaction. Therefore, assessing the inter-regional network and economic impacts helps secure evacuation routes and specify the vulnerable sections in the road network.

This paper builds a multi-sectoral integrated commodity flow model (ICFM) for the impact assessment of volcanic ash fall in Japan. We furthermore examine the estimation of the economic impacts on traffic network and freight flow caused by several equption scenarios for Mt. Asama and Mt. Fuji.

2. Literature Review

(1) Measurement of Hazard Risk of Volcanic Ash Fall

Ash fall produced by volcanic eruption directly causes physical damage on the infrastructure and properties. Quantification of the hazard risk plays an important role to prepare the decision making of recovery strategy and disaster assistance. Volcanic disaster causes much damage. In order to cope with this catastrophic disaster, evaluation plays an important role. Torisawa and Yashiro[6] created the probabilistic hazard map of ash fall caused by the eruption of Fuji volcano and evaluated the risk of road network disruption due to volcanic ash fall. Tamaki and Tatano[7] have developed functional fragility curves for traffic regulation based on the data from the 2011 eruption at Shinmoe-dake of Mt. Kirishima as well as they have proposed a method for evaluating road resilience and restoration planning after volcanic eruptions.

(2) Economic Impact Estimation

Kim, Ham and Boyce[8] have estimated economic impacts of transportation network changes caused by a catastrophic earthquake in the U.S. by implementing a combined transportation network and input-output model called the ICFM (Interregional Commodity Flow Model).

Kajitani et al.[9] have developed the model further to estimate the changes in trade volume when the great Hanshin earthquake happened. Kajitani et al.[9] classified Japanese economy into 9 regions based on the regional classification of the interregional Input-Output table in Japan.

Whereas these researches estimated the impacts caused by an earthquake, Ishikura and Oyama[10] estimated the ones caused by volcanic ash fall. In their work, the study area, Japan excluding one prefecture, Okinawa, is divided into 46 regions, all prefectures other than Okinawa. Ishikura and Oyama[10] applied ICFM to the two hypothetical volcanic disasters, the eruption of Mt. Fuji and Mt. Asama. However, they assumed one industrial sector economy, therefore inter-industrial interaction was not considered.

This paper develops the framework of Ishikura and Oyama[10] by extending two aspects. The comparison between 4 researches mentioned in this chapter is shown in **Table 1**.

3. Model: ICFM

(1) Outline of the ICFM

The ICFM developed by Kim et al.[8] is the integrated model of trip distribution and traffic assignment with the constraints of an input-output relationship, commodity flow and a traffic network. The model converts commodity flows from value term of trade flow into tonnage of freight transport flow. By this characteristic, a change in commodity flows is appropriately described when transportation cost dramatically changes due to a disaster such as volcanic ash fall.

In the original model of Kim et al.[8], the input coefficient, of national I-O table, is represented as a^{mn}, which means that the quantity of input demand for goods in sector m required to produce one unit of sector n. Therefore, the production technology is assumed to be indifferent over regions. Since inter-prefectural Input-Output table is available in Japan, we classify the difference of the technology by adopting regional input coefficient, a_j^{mn}. The formulation of ICFM is defined as a following optimization problem.

$$\min_{\boldsymbol{h},\boldsymbol{x}} Z(\boldsymbol{h},\boldsymbol{x}) = \sum_a \int_0^{f_a} d_a(\omega)\,d\omega + \sum_{mj} d_{jj}\frac{x_{jj}^m}{g^m} + \sum_m \frac{1}{\beta^m g^m}\sum_{ij} x_{ij}^m \ln x_{ij}^m \quad (1)$$

s.t.

$$\sum_i x_{ij}^m = \sum_n a_j^{mn}\sum_k x_{jk}^n + y_j^m \quad \forall mj \quad (2)$$

$$\sum_r h_{ijr}^m = \frac{x_{ij}^m}{g^m} \quad \forall mij \quad (3)$$

$$h_{ijr}^m \geq 0 \quad \forall mrij \quad (4)$$

In an objective function(1), the first term is is the Beckmann type user optimal route choice model and $d_a(\omega)$ is the link performance function of link a. The model uses BPR type function commonly used in the traffic assignment models,

$$d_a(\omega) = d_a^0\{1.0 + p(\frac{\omega}{C_a})^q\} \quad \forall a \quad (5)$$

where $d_a(\omega)$ is travel cost on link a, d_a^0 is travel cost on link a with free flow ($f_a = 0$), ω is flow on link a, C_a is capacity for link a, and p, q are parameters.

Link flow f_a (mins) denotes the total flow (tons) on link $a \in A$ and is defined as

Table1 Comparison between researches

	Kim et al.	Kajitani et al.	Ishikura et al.	This paper
Type of disaster	Earthquake	Earthquake	Volcanic ash fall	Volcanic ash fall
Study area	US	Japan	Japan	Japan
# of region	36	9	46	46
# of sector	13	12	1	3

$$\sum_m \sum_{ijr} h^m_{ijr} \phi^a_{ijr} = f_a \quad \forall a \in A \tag{6}$$

where h^m_{ijr} is the flow (tons) of sector m from subregion i to j by route $r \in R_{ij}$ and $\phi^a_{ijr} = 1$, if route r from i to j uses link a, and $= 0$, otherwise.

The second term of the RHS of the objective function corresponds to the total intraregional travel cost (mins). Let d_{jj} be the intraregional travel costs (mins) within subregion j. They are assumed as a half of travel cost to the nearest subregion. Let x^m_{ij} be the flow (JPY) of sector $m \in M$ from subregion $i \in I$ to subregion $j \in J$. The exogenous constants g^m (JPY/tons) are factors converting commodity flows from Japanese yen of regional flows to tons of network flows.

The third term of the RHS enables to disperse flows between all pairs of subregions. With the dispersion of flows, concentration of commodity flow on the same route can be avoided. β^m is cost sensitivity parameter for sector m.

The first constraint (2) is commodity balance constraint, which states that the aggregated flow of sector m into subregion j equals the use of that commodity for making other commodities, intermediate demand, plus subregional final demand.

a^{mn}_j is the quantity of inputs from sector m required to produce one unit of output of sector n in subregion j. y^m_j denotes the final demand (JPY) for output of sector m in region j.

$$x^m_{ij} = \sum_n z^{mn}_{ij} + y^m_{ij} \tag{7}$$

$$a^{mn}_j = \frac{z^{mn}_j}{X^n_j} = \frac{\sum_i z^{mn}_{ij}}{X^n_j} \tag{8}$$

The second constraint (3) is conservation of flow. This shows that the sum of flows (tons) of sector m over all paths r from i to j equals the trade flow (JPY) of sector m from subregion i to subregion j in tonnage term. g^m (JPY/tons) is the factor that converts the value of commodity trade flows.

The third constraint (4) refers to non-negativity.

The Kuhn-Tucker optimality conditions yield the equilibrium commodity flow,

$$x^m_{ij} = \delta^m_i \varepsilon^m_j \exp\left(-\beta^m \mu^m_{ij}\right) \quad \forall mij, i \neq j \tag{9}$$

$$x^m_{jj} = \delta^m_j \varepsilon^m_j \exp\left(-\beta^m d_{jj}\right), \quad \forall mij, i = j \tag{10}$$

where

$$\delta^m_i = \exp(-\beta^m g^m \sum_l \gamma^l_i a^{lm}_i - 1.0) \tag{11}$$

$$\varepsilon^m_j = \exp(\beta^m g^m \gamma^m_j) \tag{12}$$

are the balancing factors which are solved to determine the interregional and intraregional commodity flows. $\boldsymbol{\gamma}$ and $\boldsymbol{\mu}$ are Lagrange multipliers for commodity balance (2) and conservation of flow (3), respectively. The complimentary slackness condition with respect to h^m_{ijr} can be derives as

$$h^m_{ijr} > 0, \mu^m_{ij} = \sum_a d_a(f_a)\phi^a_{ijr} \tag{13}$$

$$h^m_{ijr} = 0, \mu^m_{ij} \leq \sum_a d_a(f_a)\phi^a_{ijr} \tag{14}$$

The multiplier μ^m_{ij} can be interpreted as the shipment cost of the commodity in sector m from i to j.

Substituting the two balancing factors in commodity balance (2) yields the another formula with respect to ε^m_j,

$$\varepsilon^m_j = \frac{\sum_n a^{mn}_j \sigma^n_{jk} + y^m_j}{\sum_{i \neq j} \delta^m_i \exp\left(-\beta^m \mu^m_{ij}\right) + \delta^m_j \exp\left(-\beta^m d_{jj}\right)} \quad \forall mj, \tag{15}$$

where

$$\sigma^n_{jk} = \sum_{k \neq j} \delta^n_j \varepsilon^n_k \exp\left(-\beta^n \mu^n_{jk}\right) + \delta^n_j \varepsilon^n_i \exp\left(-\beta^n d_{jj}\right) \quad \forall njk, j \neq k. \tag{16}$$

(2) Solution Algorithm

Since ICFM is a class of the combined trip distribution and assignment problem, solution algorithms for the transport network equilibrium models can be applicable. This paper uses Evans's algorithm as well as Kim et al[8]. See

Table2 Interruption probability of a link by Tamaki and Tatano [7] and capacity for a link

Ash thickness	Interruption probability	Capacity
1 cm	10 %	90 %
2 cm	40 %	60 %
3 cm	80 %	20 %
4 cm	90 %	10 %
5 cm	100 %	0 %

Evans[11] and Wilson[12),13] for the details of the methods.

4. Implementation of the Impact Assessment

(1) Assumptions and Data

a) Assumptions with regard to the Disaster Shock and Freight Transport

This section applies the ICFM to the case studies of Mt.Fuji and Mt.Asama. We interpret that interruption probability of the road network caused by volcanic ash fall as a capacity reduction of the affected links in the network. For example, when a certain road section is exposed 40 % of interruption probability due to volcanic ash fall on the link, we assume that the capacity for the link falls to 60 % of the capacity during the normal status. The relationship between volcanic ash thickness and interruption probability has been discussed by Tamaki and Tatano[7] (**Table 2**).

Although the amount of traffic for passenger travel also has changes when a disaster happens, this research considers only changes in freight traffic. This is because of the lack of the general traffic data. Thus, we assume that passenger traffic has no change during disaster and no impact to logistics.

We assume all of the interregional tradable goods are shipped by road transport. Interregional freight transport has various alternatives of modes such as air, maritime and rail. Actually, the modal share of the road transport is dominant in Japan.

The sensitivity parameter regarding path cost, β^m, is assumed to be unchanged before and after the disaster case.

b) Network Data

Our study area, the entire Japanese economy, is divided into the prefecture level regional classification. Okinawa prefecture is excluded because of no land transport connection to other regions. Each prefecture has one node at their seat of local government. When the border between the prefectures has trunk road connections or the ferry connection is operated between the prefecture-pair, we assume the nodes are connected by a link.

We extracted the shortest vehicle travel time between the nodes by using Google Map Distance Matrix API at 10:00, 18th of October, 2017. This travel time is the proxy of the travel cost of the link with free flow.

The capacity for the link is set by the procedures below.

- Based on Road Traffic Census[14].
- Type of connection 3 (prefectural border) is picked up.
- 24-hour large-sized vehicle traffic capacity is formulated by following steps below.
  - (a) Compute traffic capacity of all types of cars (cars/12h). (The amount of traffic of all types of cars (cars/12h) / the congestion degree)
  - (b) Traffic capacity of all types of cars (cars/24h) is formulated by doubling the capacity (cars/12h)
  - (c) Compute 24-hour large-sized vehicle inclusion rate. (24-hour amount of traffic of large-sized cars / amount of traffic of all types of cars)
  - (d) Compute 24-hour traffic capacity of large-sized vehicle by the multiplication of 24-hour traffic capacity of all types of cars and 24-hour large-sized vehicle inclusion rate.
  - (e) To distinguish upstream and downstream, 24-hour traffic capacity of large-sized vehicle is divided by 2.
- Exception:
  - (a) Chiba-Kanagawa: Use the data of Tokyo Bay Aqua Line instead.
  - (b) Hokkaido-Aomori: Assume that 6108 tons per 24 hours, which is the sum of all capacity from Hokkaido to 45 other prefectures.
  - (c) Tokyo-Yamanashi: The data of Chuo expressway is used.
  - (d) Shizuoka-Kanagawa: The data of Tomei highway is included.

c) Exogenous parameters

As the link performance function, the BPR type is used as mentioned in the previous section,

$$d_a(\omega) = d_a^0\{1.0 + p(\frac{\omega}{C_a})^q\} \quad \forall a. \qquad (17)$$

where $d_a(\omega)$ is travel cost on link a, d_a^0 is travel cost on link a with free flow ($f_a = 0$), ω is flow on link a, C_a is capacity for link a, and p, q are parameters.

Table3 Parameters and sources

Parameters	Sources
C_a	Road Traffic Census 2015[14]
d_a^0	Distance Matrix API
h_{ijr}^m	Freight Flow Census 2015[15]
a_j^{mn}, x_{ij}^m	Multi-Regional Input Output table[16]

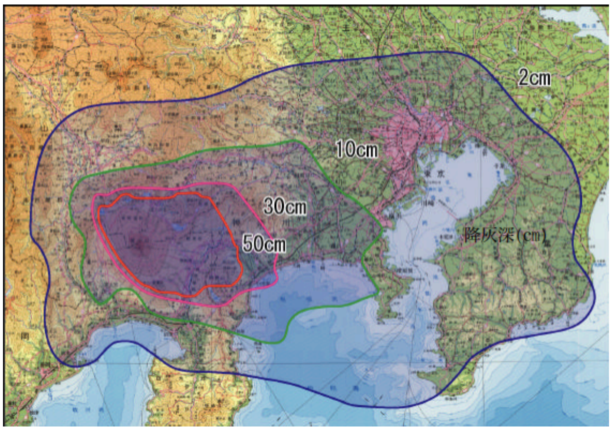

Fig.1 Hazard map for the eruption of Mt.Fuji[17]

We have some exogenous variable as shown in **Table 3**.

(2) Scenarios

The research area is set in the Kanto area. The effect of an ash fall would be huge when it happened in the Kanto area because the Kanto area has a number of residents and infrastructures. Thus, evaluating the impact in the Kanto area plays a crucial role to minimize the negative impact of the disaster. In this study, the eruption of 2 active volcanoes which affect the Kanto area are chosen as a scenario. These are Mt.Fuji and Mt.Asama.

For the eruption of Mt.Fuji, the medium-scale eruption which is described in the report of the investigation committee about hazard map for Mt.Fuji[17] is supposed. The hazard map is shown below. In this case, we assume that a link under the area of 10cm-thick ash is disrupted. The assumed disrupted links are Tokyo-Yamanashi, Yamanashi-Kanagawa and Kanagawa-Shizuoka.

Next, we assume that the medium-scale eruption of Mt.Asama. The hazard map created by Infrastructure and Transport Tone River System Sabo Work Office[18] is used for the assumption. In this case, a link under the area of 5cm-thick ash is assumed to be close to traffic. The assumed interrupted link is Nagano-Gunma.

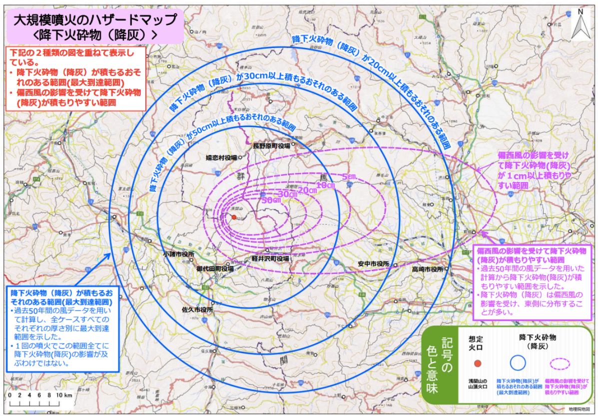

Fig.2 Hazard map for the eruption of Mt.Asama[19]

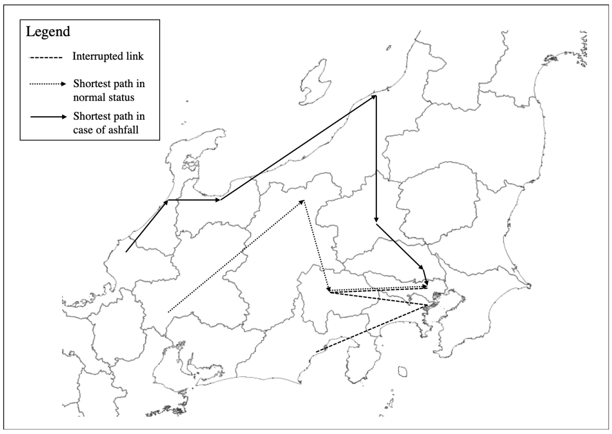

Fig.3 The change of the shortest path from west side of Japan to Tokyo

(3) Results and Discussions

a) Scenario 1: Mt.Fuji

The hypothetical eruption of Mt.Fuji has a huge impact on networks and logistics widely. First of all, the shortest route has several changes. To go to Tokyo from western Japan, you need to have waypoints unlike the shortest path during normal condition.

Normally, the shortest route is western Japan → Gifu → Nagano → Yamanashi → Tokyo. On the other hand, in the event of a disaster, the shortest path is estimated to be western Japan → Fukui → Ishikawa → Toyama → Nigata → Gunma → Saitama → Tokyo.

From Shizuoka to Tokyo, while the shortest path during a normal condition which has one waypoint in Yamanashi, the shortest path in the event of a disaster is estimated to be Shizuoka → Aichi → Gifu → Nagano → Nigata → Gunma → Saiama → Tokyo.

In addition to changes of traffic networks, changes of logistics also have been observed.

- **To Tokyo**

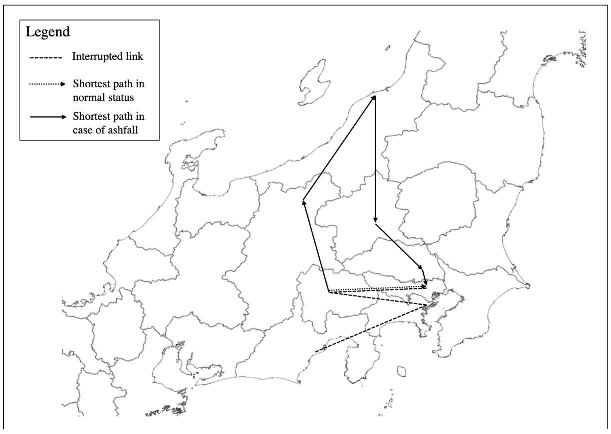

Fig.4 The change of the shortest path from Yamanashi to Tokyo

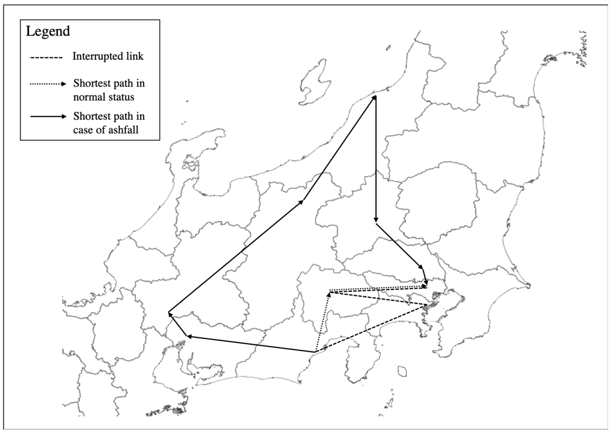

Fig.5 The change of the shortest path Shizuoka to Tokyo

OD cost from Yamanashi, Shizuoka and Nagano have increased the most (12 times, 8 times and 4 times more respectively) because of a large detour. Overall, compared to OD cost from the Tohoku area (approximately 1.5 times more), OD cost from western Japan showed increase (about 3 times more). For logistics, Tokyo is estimated to have less commodity flow of primary industry from most of the prefectures while trade from Kanto area is estimated to increase. For secondary industry, most of the prefectures are estimated to have less commodity to Tokyo. On the other hand, trade from Kanagawa and Tokyo is estimated to increase. Tokyo is likely to trade with neighboring prefectures for both primary and secondary industries.

- **To Aichi**

OD cost from most of the areas is estimated to increase. However, OD cost from Shizuoka is 0.4 times lower. As a result, Aichi, which has one of the largest industrial areas called Chukyo Industrial area, relies on the commodity flow from

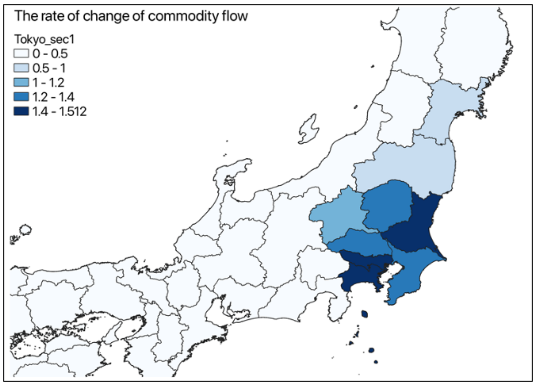

Fig.6 The rate of change of commodity flow of primary industry to Tokyo

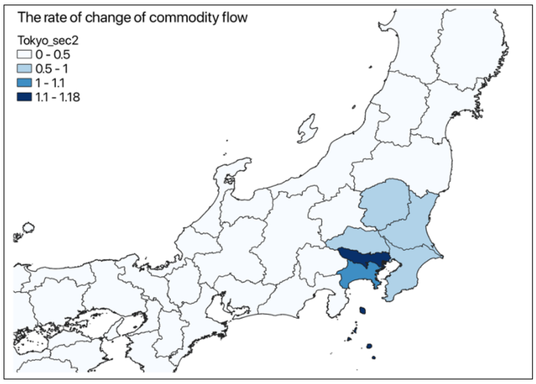

Fig.7 The rate of change of commodity flow of secondary industry to Tokyo

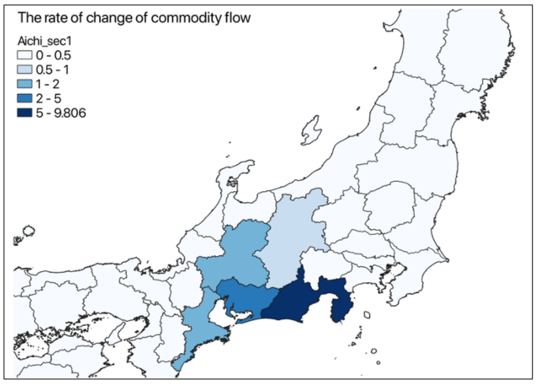

Fig.8 The rate of change of commodity flow of primary industry to Aichi

Shizuoka for both industrial sectors. Plus, neighboring prefectures would have more supplies to Aichi for both industries.

b) Scenario 2: Mt.Asama

At the time of the assumed eruption of Mt.Asama, the impact on a traffic network and logistics is smaller compared to the case of the eruption of Mt.Fuji. Looking at the results of the changes of the shortest path shown in 10, the

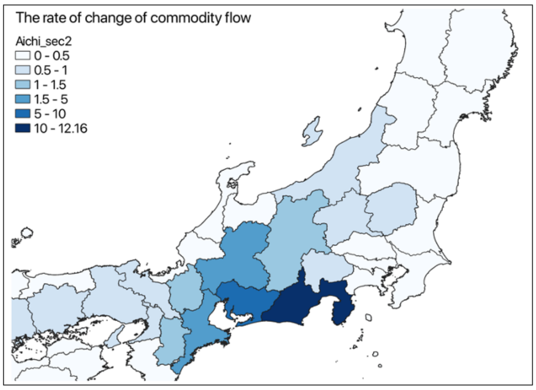

Fig.9 The rate of change of commodity flow of secondary industry to Aichi

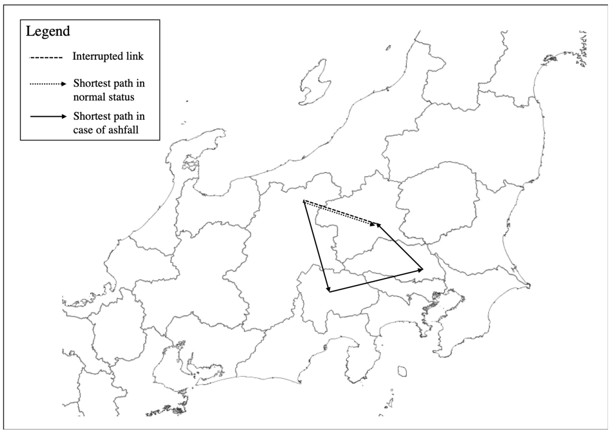

Fig.10 The change of the shortest path from Nagano to Gunma

shortest path from Nagano to Gunma needs to be changed due to the disrupted link, Nagano-Gunma. During ashfalls, the shortest route has 2 stopovers, Yamanashi and Saitama. Besides that, the clear change is not observed.

From the view point of logistics, minor impacts have been estimated.

- **To Tokyo**

OD cost from eastern Japan has increased and OD cost from western Japan has decreased. Especially from Nagano, Ishikawa, Toyama and Nigata showed bigger increase of OD cost. The volume of commodity flow from Nagano, Ishikawa, Toyama and Nigata has decreased for both industries. This is because of increased OD cost from there to Tokyo. For secondary industry, commodity flow from Aichi shows big increase while commodity flow of primary industry has slight increase. This indicates that Tokyo relies on Aichi more for secondary industry during the disaster.

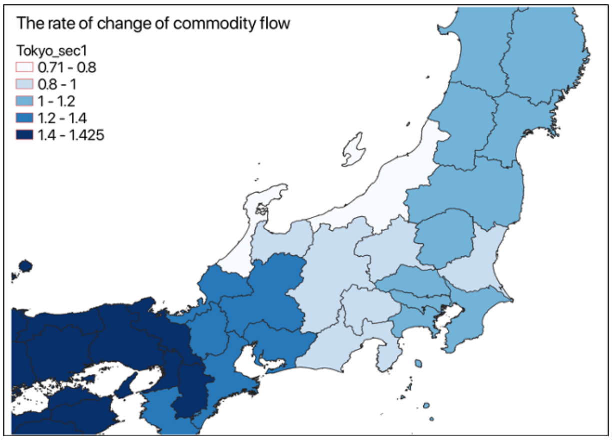

Fig.11 The rate of change of commodity flow of primary industry to Tokyo

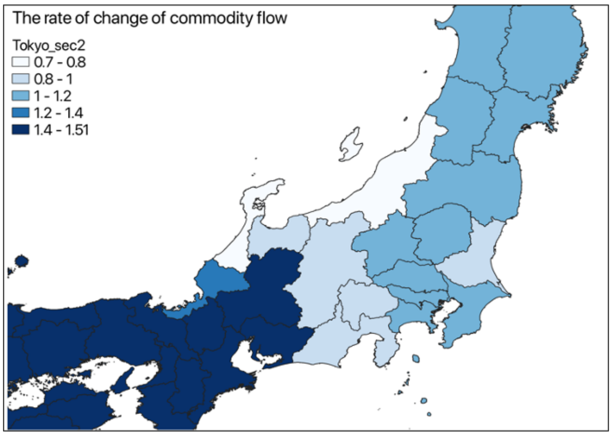

Fig.12 The rate of change of commodity flow of secondary industry to Tokyo

5. Conclusion and Future Studies

The ICMF has been developed further to implement to assess the impacts from volcanic ash falls on traffic networks and logistics in Japan along with a more detailed input-output structure which differentiates 3 sectors. As a result, in 2 hypothetical scenarios of 2 active volcanoes, estimations of traffic networks which include OD transport cost, link transport cost and the changes of shortest path, and logistics, that is the change of commodity flow, are formulated. Overall, because reasonable results can be observed, the present study suggested that the improved ICFM is applicable to the estimation of impacts from volcanic ash falls on traffic networks and logistics in Japan.

However, this research has some improvements. First, the model does not include personal trips and underestimates the impact. Second, the constraints of suppliers due to damage from a disaster are not considered. Thus, the concentration of a supplier can happen in this model, which is not realistic. For an input-output structure, imported commodity is included into final demand, so that when imported commodity is large enough to affect commodity flow, commodity flow might be negative, which does not happen in a real world. Also, the rough traffic network causes less realistic estimation which results in slight unrealistic shortest path changes.

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