IMPACT OF TRANSPORTATION NETWORK DISRUPTIONS CAUSED BY THE GREAT EAST JAPAN EARTHQUAKE ON DISTRIBUTION OF GOODS AND REGIONAL ECONOMY

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The Great East Japan Earthquake that occurred on March 11, 2011 caused disruptions to transportation network such as roads and railways. In general, transportation network disruptions make distribution of relief goods difficult and are considered to have negative impact on the economy of the stricken region owing to a decrease in transportation accessibility.

Focusing on Iwate Prefecture, which experienced significant damage to its transportation network, this paper analyzes the distribution of goods, especially demand and supply of food items, for three weeks following the earthquake. Considering the relationship between transportation network disruptions and reconstructions, it develops a regional econometric model that can analyze the time-series impact of transportation network disruptions and reconstruction-related demand, etc. on the regional economy, and conducts simulation analyses.

The results of the analyses indicate that upgrades to supply systems, including the opening of transport routes, are critical toward ensuring a sufficient supply of food, and the impact of transportation network disruptions in the long term on the gross regional product is as large as the impact of actual damage on production equipment, labor supply, etc. and reconstruction-related demand after the earthquake.

Key Words: transportation network, distribution of goods, supply-demand gap, econometrics, the Great East Japan Earthquake

1. INTRODUCTION

The Great East Japan Earthquake that hit Japan on March 11, 2011 resulted in a tsunami, causing ground liquefaction and extensive damage to a nuclear reactor, in addition to significant direct damage due to the shaking. This resulted in tremendous human, material, and economic damage. The total cost of damage, excluding unsubstantiated costs related to the nuclear reactor disaster, has been estimated to be JPY 16-25 trillion1. This paper focuses on the damage related to disruptions in the transportation network.

Damage to transportation infrastructure include the rendering of expressways such as the Tohoku Expressway as well as national highways impassable. In particular, traffic along National Highway 45 following the Pacific coast was disrupted at many locations. In an attempt to secure transportation routes in damaged regions along the Pacific coast, the Ministry of Land, Infrastructure, Transport and Tourism first ensured that the Tohoku Expressway and National Highway 4, which run parallel to the coast, were functional one day after the earthquake. The Ministry then rolled out a “teeth of the comb” strategy, opening inland roads running parallel to the coast, moving to those running from the east to the west toward the coast. Ninety-seven percent of National Highway 45 was open for traffic by March 18, and all of Tohoku Expressway was open by March 24. As for the other high-speed transportation facilities that form the core of the inter-regional transport system, the Tohoku Shinkansen Line, which suffered line derailments and damage to station platforms,
required 49 days to restart normal operations. In addition, the Sendai Airport, which was inundated from the tsunami, required 174 days; and the Joban Expressway required 48 days. Portions of Japan Railways’ Joban, Senseki, Ishinomaki, Kesennuma, Ofunato, and Yamada Lines, as well as Sanriku Railways’ Minamimiasu and Kitariasu Lines had not yet been fully restored as of February 2013. Expressways, national highways, Shinkansen Lines and other railways in the Tohoku area are shown in Fig. 1.

In general, disruptions to transportation networks due to natural disasters complicate relief efforts as well as the transportation of emergency supplies immediately following the disaster. These disruptions also increase the inter-regional travel time, which in turn affect the regional economy in various ways.

There are a few existing researches on the impact of great earthquakes on relief logistics in Japan. Kotani (1997) analyzed the actual condition of urban freight transport of relief goods and food items in one-and-a-half months after the Great Hanshin-Awaji Earthquake, which occurred on January 17, 1995. Tamura et al. (2006) investigated the distribution of relief goods in two weeks after the Chuo-Osaka Earthquake in Niigata, which occurred on October 23, 2004. They also conducted a comparative analysis of demand and supply for food items, and pointed out the problems on responsiveness of the local government. As for the Great East Japan Earthquake, while Okimura (2011) reported the system of emergency freight transport and quantities of imported and exported goods at the temporary depot, there has been no research on demand and supply analysis for food items or analysis considering the relationship between the distribution of goods and damage and restoration of transport facilities.

As for the economic impact of great earthquakes, there are some existing reports and researches on the Great East Japan Earthquake. The Cabinet Office of Japan (2011) estimated the direct damage to housing, private capital stock and public infrastructure, and calculated the decrease in gross domestic product caused by decrease in private capital stock using the capital share. Hayashida et al. (2011) and Takeda and Morishige (2012) estimated the damage to housing, private capital stock and public infrastructure, and analyzed the impact on Japanese economy with macro econometrics. Okiyama et al. (2012) calculated the decrease in production caused by decrease in export, etc. and the economic impact of the restoration on the stricken region using SAM (Social Account Matrix) between two areas. However, there has been no research on the time-series impact of the earthquake and restoration in the stricken region or analysis focusing on the transportation network disruptions.

This paper focuses on Iwate Prefecture, which experienced significant damage to its transportation network because of the Great East Japan Earthquake. Transportation network is considered to play a very important role both in carrying emergency supplies in the short term after natural disasters and in carrying goods and passengers, which have large impact on the regional economy in the long term. In this paper, therefore, the impact of transportation network disruptions both in the short term and in the long term are analyzed. Specifically, we analyzed the situation of the distribution of goods, especially for food items, in Iwate during the three weeks following the earthquake. We then developed a regional econometric model that could analyze the impact of transportation network disruptions, reconstruction demand, etc. on the regional economy. The model examined the impact of hypothetical long-term disruptions on the transportation network, the impact of actual damage on production equipment, labor supply and transport facilities and the effect of reconstruction demand.

2. IMPACT ANALYSIS ON THE DISTRIBUTION OF GOODS

(1) Outline

Historically, it has been assumed that supplies of goods from outside the region following a disaster will not arrive within a 72-hour period following the event. Therefore, it is also assumed that relief efforts must manage, to the extent possible, with relief items stored within the disaster area, or with inventory.
from local stores, during this 72-hour period\(^9\). However, inventories in the coastal areas of Iwate Prefecture were almost entirely wiped out by the tsunami, intensifying the need for emergency relief.

This paper estimates the trends in transportation quantities of alpha rice, cup noodles, rice balls, bread, and other staple food items, and analyzes supply-demand gaps for food in seven Iwate Prefecture towns along the coast (Rikuzentakata, Ofunato, Kamaishi, Otsuchi, Yamada, Miyako, and Iwaizumi). The location of Iwate Prefecture and these seven towns is shown in Fig.2. Moreover, this paper considers the relationship of these trends with supply systems, including those in which transportation networks are being rebuilt.

To compile a time-series dataset representing the quantity of transported food, we aggregated orders from all transportation companies in Iwate Prefecture as well as data on individual requests from evacuation shelters (obtained from the Tohoku University logistics research team) in the three-week period following the earthquake.

(2) Changes in supply systems

With services restored on the Tohoku Expressway and National Highway 4 on March 12, the government considered creating a primary consolidation center along these routes. The government selected the location of this center on the basis of the following criteria: transportation convenience, sufficient space within facilities, sufficient size to allow direct entry of large trucks into the facility, and the ability to accommodate the use of forklifts and other equipment. In discussions between Iwate Prefecture and the Iwate Prefecture Truckers Association, it was determined that the Iwate Prefecture Industrial Culture Center “Apio”, located in Takisawa-mura, Iwate-gun near Morioka City which is the prefectoral capital, met these requirements, and thus the center was recognized as a primary consolidation center; operations began on March 14. The location of Apio is shown in Fig.3.

On March 15, 15 routes of general road running east to west, connecting the Tohoku Expressway with the coast, was re-opened to traffic. Intensive restoration efforts including bridge repairs began after this re-opening, with the Namitabashi on National Highway 45 in Otsuchi becoming operational on March 17, and most general roads open for traffic by March 20. Recovery efforts in Rikuzentakata lagged somewhat, but a temporary road for the Numata overpass connecting the consolidation center with evacuation centers was eventually completed and the Kawaharagawa bridge was repaired on March 25.

(3) Trends in transported food quantities

Trends in transported food quantity for the seven towns listed above from March 12 to April 1 are shown in Fig.4.

Transported food quantities in many towns increased on March 14, when the Apio center was opened, and at around March 20, when most roads were open to traffic. In addition, food quantities increased dramatically on March 25 in Rikuzentakata, when a transportation network was finally in place. Thus, there appears to be a connection between the quantity of food transported and the presence of a functioning supply system.

(4) Trend in food-related supply-demand gaps

Supply-demand gaps were calculated by estimating the daily per capita food demand according to the
number of evacuees in evacuation centers in each town, and by comparing this quantity to the quantity of food supplied.

In this case, the quantity of food supplied is the sum of the transported quantities and inventory (leftovers from the previous day), or is simply the transported quantities where there is no inventory from the previous day. If it is assumed that only rice balls needed to be consumed on the same day that they were transported, the food quantities supplied on day $t$ are expressed by equations (1)-(4).

$$S_t = Z_{t-1} + x_t^a + x_t^b$$  \hspace{1cm} (1)  

If $D_t < x_t^a$, then $Z_t = S_t - x_t^a$  \hspace{1cm} (2)  

If $x_t^a \leq D_t < S_t$, then $Z_t = S_t - D_t$  \hspace{1cm} (3)  

If $S_t \leq D_t$, then $Z_t = 0$  \hspace{1cm} (4)

Here, subscript $t$ denotes day. $S$, $D$, and $Z$ represent the supply quantity, demand quantity, and inventory quantity, respectively, per day (per capita and per day). In addition, $x^a$ and $x^b$ are the transported amounts of rice balls and other food items per day (per capita and per day), respectively.

Fig. 5 shows the trends in the supply-demand gaps (i.e., supply quantities minus demand quantities) for food items in the seven municipalities from March 12 to April 1.

In Otsuchi, Yamada, and Iwayizumi, where food demand was relatively low, overall supply exceeded demand after March 15, when the Apio center was operational and the Tohoku Expressway and other general roads along the coast became passable. On the other hand, Rikuzentakata, which had many refugees, experienced multiple food shortages from March 11 until March 24. Only after bridges became passable on March 25 did supply begin to exceed demand. Thus, it is clear that upgrades to supply systems, including the opening of transport routes, are critical toward ensuring a sufficient supply of food.

3. REGIONAL ECONOMETRIC MODEL

(1) Impact of long-term transportation network disruptions on the regional economy

Disruptions to transportation networks caused by the Great East Japan Earthquake were resolved relatively quickly in Iwate Prefecture, with the exception of railways along the Pacific coast. We formulated a regional econometric model to analyze the impact of hypothetical long-term disruptions to transportation networks as a means of validating the importance of a rapid recovery.

(2) Formulation of the model

In accordance with the flow diagram in Fig. 6, the model is formulated. Outlines of the sub-models are shown below. For each sub-model, the superscript $t$ denotes the period.

a) Production

Gross regional product is expressed with the private capital stock in operation, the number of workers considering average working hours, and transportation accessibility of firms.

$$X_t = f(ROW_t \cdot KP_t, LHR_t \cdot NW_t, ACCF_t)$$  \hspace{1cm} (5)

Here, $X$ is production, $ROW$ is index expressing the rate of capital utilization, $KP$ is private capital stock, $LHR$ is the index that expresses average working hours, $NW$ is the number of workers and $ACCF$ is transportation accessibility of firms.

b) Private capital stock

Private capital stock in the current period is defined as private capital stock in the previous period, less depreciation, plus private capital investment in the current period.
\[ KP_i = (1 - ROD)KP_{i-1} + IP_i \]  \hfill (6)

Here, \( ROD \) is the rate of depletion of capital stock and \( IP \) is private capital investment.

c) Number of workers

Assuming that increase in the labor demand is basically decided by the economic climate, increase in the number of workers from the previous period can be expressed with the gross regional product.

\[ NW_i - NW_{i-1} = f(GRP_i) \]  \hfill (7)

Here, \( GRP \) is the realized gross regional product.

d) Private consumption expenditure

Private consumption expenditure is formulated as a per-person function considering the effect of population change in the future. Private consumption expenditure per person can be explained by household disposable income per person and transportation accessibility of households.

\[ \frac{CP_i}{POP_i} = f\left( \frac{YH_i}{POP_i}, ACCH_i \right) \]  \hfill (8)

Here, \( CP \) is private consumption expenditure, \( POP \) is population, \( YH \) is household disposable income and \( ACCH \) is transportation accessibility of households.

e) Household disposable income

Household disposable income after taxes have been deducted from the household income can be explained by the realized gross regional product.

\[ YH_i = f(GRP_i) \]  \hfill (9)

f) Private capital investment

The private capital investment is explained by gross regional product and private capital stock in the previous period, considering the acceleration process and the stock adjustment process.

\[ IP_i = f(GRP_i, KP_{i-1}) \]  \hfill (10)

g) Export

Export consists of shipment to other regions within Japan and export to foreign countries, but mostly it is shipment within the nation. Therefore, export is explained by the gross domestic product.

\[ E_i = f(GDP_i) \]  \hfill (11)

Here, \( E \) is export. \( GDP \) is gross domestic product.

h) Import

Import is expressed with final regional demand (in other words, the sum of private consumption expenditure, private housing investment, private capital investment, government expenditure and public investment) in addition to import in the previous period.

\[ M_i = f(M_{i-1}, FD_i) \]  \hfill (12)

Here, \( M \) is import and \( FD \) is final regional demand.

i) Gross regional expenditure

Gross regional expenditure is defined as the sum of private consumption expenditure, private capital and housing investments, government consumption expenditure, public investment, inventory increase, and net export (export minus import).

\[ GRE_i = CP_i + IP_i + IHP_i + CG_i + IG_i + Z_i + (E_i - M_i) \]  \hfill (13)
Here, $\text{GRE}$ is gross regional expenditure, $\text{CG}$ is government consumption expenditure, $\text{IG}$ is public investment, $Z$ is inventory increase, $E$ is export, and $M$ is import.

**j) The realized gross regional product**

It is assumed that the gross regional product is realized as the average of potential productivity and gross regional demand. Here, for potential productivity, in the production function of equation (5), the rate of capital utilization $\text{ROW}$ is set at 100%. Gross regional demand is made equal to gross regional expenditure.

$$\text{GRP}_t = \text{Average}(\hat{X}_t, \hat{\text{GRE}}_t)$$  \hspace{1cm} (14)

Here, $\text{GRP}$ is the realized gross regional product, $\hat{X}$ is potential productivity and $\hat{\text{GRE}}$ is gross regional demand.

**k) Transportation accessibility**

Transportation accessibility of firms and households for the whole object area are expressed with equations (15) and (16) using the shares of transportation modes for firms and households, respectively. Transportation accessibility for the whole object area for each transportation mode is calculated as the weighted average of accessibility for small region $r$ in the object area by population of region $r$ as expressed by equation (17). Transportation accessibility for region $r$ is defined as the reciprocation of the weighted average of generalized time from region $r$ to other regions all over the country by population of regions of destination as expressed by equation (18).

$$\text{ACCF}_t = RF_t \text{ACC}^{\text{RD}}_t + (1 - RF_t) \text{ACC}^{\text{RL}}_t$$  \hspace{1cm} (15)

$$\text{ACCH}_t = RH_t \text{ACC}^{\text{RD}}_t + (1 - RH_t) \text{ACC}^{\text{RL}}_t$$  \hspace{1cm} (16)

$$\text{ACC}^M_t = \frac{\sum_r (\text{POP}_{r,s} \cdot \text{ACC}^M_{r,s})}{\sum_r \text{POP}_{r,s}}$$  \hspace{1cm} (17)

$$\text{ACC}^M_{r,s} = \frac{\sum_s \left( \text{POP}_{r,s} \left( T^{M}_{r,s} + TC^{M}_{r,s} W_{r,s} \right) \right)}{\sum_s \text{POP}_{r,s}}$$  \hspace{1cm} (18)

Here, $\text{ACCF}$ and $\text{ACCH}$ are transportation accessibility of firms and households in the object area (Iwate Prefecture), respectively. $\text{ACC}^{\text{RD}}$ and $\text{ACC}^{\text{RL}}$ are transportation accessibility of road transport and rail transport in the object area, respectively. $RF$ and $RH$ indicate the modal share of road transport for firms and household, respectively. $M$ means transportation mode ($\text{RD}$ or $\text{RL}$). Subscripts $r$ and $s$ represent regions in the object area and all over the country except the object area, respectively. $T$ is travel time between regions and $TC$ is travel cost between regions, while $w$ is the value of time.

**3) Parameter estimation**

For equations (5) to (12), after specifying the function format, estimations are made by OLS using time-series data from 1996 to 2009. The economic data used for the estimation are basically real values from “the Annual Report on Prefectural Economic Accounting” (Economic and Social Research Institute, Cabinet Office of Japan). Transportation accessibilities are calculated with equations (15)-(18) using travel time and cost data in each year from five major cities in Iwate Prefecture (Morioka, Miyako, Hanamaki, Ichinoseki, and Kamaishi: $r$ in equation (17) and (18)) to major cities across Japan (Sapporo, Aomori, Akita, Yamagata, Sendai, Ishinomaki, Fukukawa, Fukushima, Koriyama, Shira-kawa, Aizuwakamatsu, Iwaki, Haranomachi, Niigata, Mito, Utsunomiya, Maebashi, Tokyo, Nagoya, Osaka and other major cities in Iwate Prefecture: $s$ in equation (18)). Travel times and travel costs using roads in each year are calculated through the Navitime software assuming that general roads such as national highways were used before expressways opened. Travel times and travel costs using railways are determined through the Navitime and Ekisupaato software assuming that conventional lines were used before the Shinkansen Lines opened. As for the modal share, the modal shares of road transport for firms and households in equations (15) and (16) are set based on data in 2000 from “Inter-Regional Travel Survey in Japan” and “Inter-Regional Freight Transport Survey in Japan” (Ministry of Land, Infrastructure, Transport and Tourism, respectively). As for population in equations (17) and (18), living area data or prefectural data are used for the northern part of Japan including the Tohoku area, and regional data are used for Tokyo (South Kanto region), Nagoya (Chubu region) and Osaka (the western part of Japan).

In addition to the explanatory variables shown in the equations, a fixed period dummy variable ($\text{DUM} = 0$ or 1) is used as a variable in many functions for estimation. While the $t$ values and the Durbin-Watson ratio (D.W.) are kept above a certain level (basically absolute values of $t$ values >1.0 and 1.0 <D.W. <3.0), the function format with the highest value of the coefficient of determination is used for each function. Actually, estimations were conducted for equations (5)’-(12)’ shown below.
The results of the estimations for equations (5)'-(12)' are shown in Table 1. In the table, the figure in parentheses indicates the t value for each parameter; ** indicates significance at 5% level; and * indicates significance at 20% level.

Using the estimated functions, the final test that compares the estimated data and the actual data of economic variables from 1997 to 2009 is conducted. Fig.7 shows the results of the final test for gross regional product (GRP) in Iwate Prefecture. From the figure, it is clear that estimated and actual GRP show similar trends and the model can simulate the economic situation in the past.

<table>
<thead>
<tr>
<th></th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>d'</th>
<th>D.W.</th>
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<td>5.5954</td>
<td>0.4018**</td>
<td>0.7475**</td>
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<td>-2.9436</td>
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<tr>
<td>(6)'</td>
<td>0.9580**</td>
<td>(317.0920)</td>
<td>-0.0182**</td>
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<td>2.31090</td>
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<tr>
<td>(7)'</td>
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<td>(-3.6498)</td>
<td>-6.281.5**</td>
<td>-5.1919</td>
<td>1.37666</td>
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<tr>
<td>(8)'</td>
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<td>(-3.3859)</td>
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<tr>
<td>(9)'</td>
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</table>

Note: For (5)', (9)' and (12'), DUM=1 (2008-2009), 0 (other years).

For (7), DUM=1 (2002, 2004, 2006 and 2009), 0 (other years).

For (10)', DUM=1 (1998-1999), 0 (other years), DUM2=1 (2002-2003), 0 (other years).

For (11)', DUM=1 (2009-1), 0 (other years).

\[
\ln \left( \frac{X_t}{LHR_t \cdot NW_t} \right) = a + b \ln \left( \frac{ROW_t \cdot KP_t}{LHR_t \cdot NW_t} \right) + c \ln \left( ACF_t \right) + d DUM_t
\]

\[
T \left( KP_t - IP_t \right) = b KP_t \quad \quad \quad (6)'
\]

\[
NW_t - NW_{t-1} = a + b GRP_t + c DUM_t
\]

\[
CP_t = a + b YH_t + c ACCH_t + d DUM_t
\]

\[
YH_t = a + b GRP_t + c DUM_t
\]

\[
IP_t = a + b GRP_t + c KP_{t-1}
\]

\[
+ d DUM_t + d' DUM_2
\]

\[
E_t = a + b GDP_t + d DUM_t
\]

\[
M_t = a + b M_{t-1} + c FD_t + d DUM_t
\]
(4) Simulation of the impact of the Great East Japan Earthquake

Using the model, the impact of the Great East Japan Earthquake on Iwate Prefecture’s regional economy is simulated for 10 years after the earthquake (2010-2022).

Fig.8 shows the results of three simulations: 1) a no earthquake case (“No earthquake” in Fig.8); 2) a case considering damage only to transportation facilities, which is assumed to continue for ten years (“Continuing transport network disruption” in Fig.8); and 3) a case considering actual damage to production equipment (private capital stock), humans (labor supply) and transport facilities as well as the recovery efforts that are conducted or planned after the earthquake (“All damage and reconstruction demand” in Fig.8).

To estimate reconstruction demand, we allocated Iwate Prefecture’s (announced) total reconstruction costs equally across the reconstruction plan periods (2012-2019), and assumed that this was the annual increase in public investment in each year. For recovery from the various types of damage, we set private capital utilization and average work hours to pre-earthquake levels in the final year of the planned reconstruction period.

The results of our simulation show that the impact of the long-term transportation network disruptions on the gross regional product (differences between “No earthquake” and “Continuing transport network disruption” in Fig.8) is as large as the impact of actual damage on production equipment, etc. and reconstruction-related demand (differences between “No earthquake” and “All damage and reconstruction demand” in Fig.8). This is not a real case for the Great East Japan Earthquake. However, the results indicate the possibility of a serious impact on the regional economy when transport facility damage is sustained over a long period.

4. CONCLUSION

Focusing on Iwate Prefecture, which experienced significant damage to its transportation network because of the Great East Japan Earthquake, this paper analyzed the impact of transportation network disruptions on the distribution of goods during the three weeks following the earthquake, developed a regional econometric model that can analyze the time-series impact of transportation network disruptions, reconstruction demand, etc. on the regional economy, and conducted the simulation analyses. The results of the analyses indicate that the opening of transport routes is critical toward ensuring a sufficient supply of food in the short term and the impact of the long-term transportation network disruptions on the gross regional product is as large as the impact of the actual damage on reconstruction-related demand. These results seem to suggest the importance of a rapid recovery of the transportation network.

Topics for future research are as follows:
- Formulation of a regional econometric model that considers changes in the parameters for each function after the disaster and the repayment of reconstruction debt.
- Examination of disaster-resistant transportation networks using the model developed in this paper.

ACKNOWLEDGMENT: In this paper, we used the data that were collected or calculated by Mr. Takahiro IJIMA, Mr. Nariaki UMEMOTO, Mr. Takuro YANO and Ms. Chisato SUGA who are former students of the Chiba Institute of Technology. We wish to express our gratitude to them.

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