SPATIO-TEMPORAL ANALYSIS OF GASOLINE SHORTAGE IN THE TOHOKU REGION AFTER THE GREAT EAST JAPAN EARTHQUAKE

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In this study, we analyzed the actual amount of gasoline transported into the Tohoku region during the first month after the Great East Japan Earthquake. We found that: (1) the amount of gasoline supplied in the Tohoku region during the first two weeks was only \( \frac{1}{3} \) of the normal demand; (2) the shortage of supply in the first two weeks led to a huge “back-log of demand”; (3) it took four weeks for the backlog to be cleared and the lost (suppressed) demand during the period was equivalent to the amount of normal demand for 7 days; (4) the gaps between gasoline supply and demand in the Pacific coast areas were huge, compared with those in the Japan sea coast areas, while the gap in each prefecture of the Tohoku region was gradually reduced over time in the following order: Akita, Aomori, Iwate, Yamagata, and finally, Miyagi prefecture.

Key Words: the Great East Japan Earthquake, gasoline shortage, demand-supply gap, logistics

1. INTRODUCTION

After the Great East Japan Earthquake on March 11, 2011, oil shortages spread over a wide area of the Kanto and Tohoku regions. Obtaining petroleum products became difficult because many service stations had exhausted their gasoline supplies. At stations that still sold gasoline, there were long lines. This situation continued in the Tohoku region for about a month from the occurrence of the earthquake, seriously affecting many daily activities. First, the lack of automotive fuel became a major constraint hindering relief efforts and the delivery of emergency supplies to affected areas on the coast\(^1\). Next, even in the inland area, where the property damage caused by the earthquake was minimal, commuter traffic and recovery efforts were greatly slowed down by the lack of fuel. In particular, it was observed that the level of traffic in the urban area of Sendai,\(^1\) which is the largest economic hub in the Tohoku region, plummeted from the occurrence of the disaster and remained low through early April. This fact implies that the level of social and economic activity across the region, including in the urban Sendai area, was significantly reduced by the fuel shortage. Furthermore, decline in domestic shipping functions due to the fuel shortage, as well as the shortage of petroleum products at corporations, led to supply-chain problems in the manufacturing industry after the disaster.

Other than the oil crisis of the 1970s, Japan had never experienced such a widespread oil shortage. The experience and knowledge gained from this event should be fully utilized to develop precautions against future disasters. Reasonable precautions should be implemented to ensure that this situation is not repeated in case of a large-scale disaster such as continuous earthquakes over the Tokai, Tonankai, and Nankai areas. Precautions could include pre-disaster

\(^1\) In fact, there have been a number of reports from the affected areas and logistics companies on this matter.
measures (e.g., reinforcing facilities that supply oil, building stockpiles of petroleum products, designing a national earthquake disaster support system, etc.) and post-disaster measures (e.g., planning logistical strategies to provide petroleum products in specific disaster situations). Regardless of what measures are planned and considered, it is necessary to comprehensively and quantitatively understand the facts of the past oil shortage — how the situation developed, what measures were implemented, and as a result, what kinds of conditions sequentially unfolded across the broad area in question, and so on.

More than one year after the earthquake, however, the publicly available information to comprehensively illustrate the overall picture of the oil shortage is still far from sufficient. The government and the oil industry have reported the root cause of the oil shortage2: It started when oil refineries in Chiba, Kashima, and Sendai and port facilities in the Tohoku region and on the Pacific coast were struck by the earthquake and the supply function of petroleum products to the Tohoku region stopped. However, since then, almost no information has been released to systematically answer basic questions such as: 1) what measures were implemented, 2) what were the outcomes of those measures, and 3) why the oil shortage lasted nearly a month. In fact, the information that the Ministry of Economy, Trade and Industry (METI) began reporting online one week after the earthquake mostly pertained to the policy outline of overall measures and snippets of individual operations. Even after overcoming the shortage of oil, neither METI nor the Petroleum Association of Japan reported any information or analysis results that would allow comprehensive and quantitative understanding of the situation that arose during the oil shortage2. Furthermore, third-party organizations have been releasing information such as a paper that attributes the main cause of the oil shortage to hoarding by consumers,4) a conclusion that seems to misinterpret the facts5. Thus, there is a dearth of quantitative description or analysis related to the supply side (logistics for delivery of petroleum products).

Perceiving the lack of scrutiny of the supply side, Akamatsu et al.5) conducted an analysis of the three major lines of petroleum products (gasoline, heating oil, and diesel fuel) in the Tohoku region for the month immediately following the earthquake, aiming to quantitatively understand the reality of transporting those products and the overall situation of the supply shortage. Specifically, the study used the statistics on petroleum product sales by prefecture (monthly data) and the amount of petroleum products brought into the ports in the Tohoku region (daily data) to analyze trends in the amount of petroleum products (total of the three major product categories) transported within the Tohoku region and the demand-supply gap during the one-month period after the earthquake. The results reveal that the amount of petroleum products supplied to the Tohoku region was definitely insufficient, suggesting that review of the supply side is necessary to address the oil shortage in the Tohoku region and that the consumption side is secondary.

However, there are some limitations in the analysis conducted by Akamatsu et al.5) First, it analyzed only the total amount of petroleum products without breaking down the quantities into the three product categories. Second, the accuracy of the statistics on the amount of petroleum products brought into the ports in the Tohoku region was not always clear because the statistics were based on data filed by ships that called at the port. Finally, because the analysis of the demand-supply gap for petroleum products was based on aggregated data across the Tohoku region, the situation in smaller areas within the region had not been explored.

This paper, therefore, aims to address these issues to clarify the reality of the petroleum product transportation problem and the gap between demand and supply. To address the first and second problem with the existing analysis, we will use the shipment data (daily data) from refineries, which accurately show the amount of transported petroleum products by category, in addition to the data used by Akamatsu et al.5) We will also analyze the three petroleum product categories separately. In doing so, we will verify the reliability of both sets of data by matching the data on shipment and the amount brought into port in the Tohoku region. In addition, a more detailed analysis will be conducted specifically on gasoline, which is an important petroleum product for consumers in general. To address the third issue, we will develop an estimation model for daily supply by municipality based on the model for transport between oil terminals and service stations to quantitatively demonstrate how the demand-supply gap for petroleum products created by the earthquake widened and then narrowed spatially.

The results of this study confirmed that the conclusion of Akamatsu et al.5) held true for gasoline. The amount of gasoline transported throughout the Tohoku region during the week following the earthquake
was only about one-third of the normal demand. The shortage of incoming gasoline was especially severe in Miyagi, Fukushima, and Iwate Prefectures where port facilities were damaged. The amount of gasoline brought into the Pacific seaboard region from oil terminals along the Sea of Japan was also insufficient. This two-week supply shortage caused the level of cumulative latent demand to substantially exceed the amount of cumulative supply, building up a backlog of demand. Although the amount of gasoline supply per day from the third week after the earthquake onward recovered to a level comparable to the daily demand as a flow variable, it was not at a level that could promptly satisfy the demand backlog, which is a stock variable\(^4\). As a result, it was not until four weeks after the earthquake that the demand backlog cleared. The emergence of the demand backlog that lasted for three weeks resulted in a significant reduction in satisfied demand, diminishing one-week’s worth of demand for gasoline in the entire Tohoku region (in terms of daily demand during the normal time). In other words, it became impossible to conduct social and economic activities corresponding to the amount of lost demand, leading to significant economic losses\(^5\).

In addition, analyzing the development of the demand-supply gap by municipality showed a remarkably large difference in the demand-supply gap between the regions along the Pacific Ocean and the Sea of Japan. Looking at the data by prefecture, it also became evident that the demand-supply gap was large in Miyagi, Iwate, and Yamagata Prefectures (in order of size of gap). Based on the development pattern of the demand-supply gap, the transport from oil terminals in the west to service station in the east and from oil terminals in the north to service stations in the south was insufficient.

The rest of this paper is organized as follows: Chapter 2 explains the data utilized and the subjects analyzed in this paper. Chapter 3 summarizes the damage caused by the Great East Japan Earthquake at petroleum product supply facilities. Chapter 4 presents an overview of the effect of the Great East Japan Earthquake by using the statistics on the sales volume of petroleum products. In Chapter 5, the situation of transportation of petroleum products to the Tohoku region around the time of the earthquake is analyzed by product type using the transport volume data from ships. Chapter 6 uses the statistics on the sales volume and the data on transport volume by ship and railway to analyze the aggregated demand-supply gap for gasoline in the entire Tohoku region after the disaster. In Chapter 7, an estimation model for the volume of gasoline sales by municipality is developed. Chapter 8 analyzes the chronological development of supply and demand conditions for gasoline after the earthquake in each prefecture by using the model developed in Chapter 7. Chapter 9 concludes the paper.

2. DATA AND SCOPE OF ANALYSIS

This chapter offers a brief explanation of the supply flow of petroleum products. Petroleum products are refined from crude oil in a refinery. The supply flow from refinery to retailer generally follows one of two patterns. In the first pattern, tanker trucks deliver products from the refinery directly to service stations and other retailers. In the second pattern, products travel through transport hubs called oil terminals. Most often, tankers ships transport the products from refineries to oil terminals. Railway tank cars are used to reach inland oil terminals. Onward transportation from oil terminals to service stations relies on tanker trucks.

This paper uses data on petroleum product sales and transportation to assess the condition of petroleum product shipment and the demand-supply gap. The petroleum product sales data show the monthly volume of petroleum products sold to consumers by service stations and other retailers, categorized by prefecture. These data are extracted from statistics relating to resources and energy compiled by the METI.\(^6\) The data on transportation of petroleum products comprises three types: (1) shipments brought into the Tohoku region’s ports (“port-entry data”), (2) shipments from refinery ports across Japan (“port-exit data”), and (3) volumes of rail freight entering the Tohoku region (“rail-entry data”). The port-entry data specify the date, time, volume, and port of origin for petroleum products unloaded from oil tankers at ports in the Tohoku region. The port-exit data show the date, time, volume, and destination ports for petroleum products loaded onto tankers at refineries ports across Japan. In addition to that, the port-exit data list shipment volume by category of oil. The rail-entry data (collected in Sasaki\(^7\)) provide the full picture regarding daily total amounts of daily deliveries of petroleum products to the Tohoku region by train.

Note that the port-entry data and the port-exit data are similar data in the sense that both data show origin-destination shipment pattern of petroleum products’ transportation. Prior to the analysis, we had matched these two port data to specify the amount of daily inbound shipment for each product category, as

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\(4\) Although the daily supply of gasoline recovered faster than those of other petroleum products, the amount was still not enough to meet the demand (including backlog demand).

\(5\) It is estimated that the entire Tohoku region faced economic losses in the order of several hundreds of billions of yen.

\(6\) The data on transportation of petroleum products comprises three types: (1) shipments brought into the Tohoku region’s ports (“port-entry data”), (2) shipments from refinery ports across Japan (“port-exit data”), and (3) volumes of rail freight entering the Tohoku region (“rail-entry data”). The port-entry data specify the date, time, volume, and port of origin for petroleum products unloaded from oil tankers at ports in the Tohoku region. The port-exit data show the date, time, volume, and destination ports for petroleum products loaded onto tankers at refineries ports across Japan. In addition to that, the port-exit data list shipment volume by category of oil. The rail-entry data (collected in Sasaki\(^7\)) provide the full picture regarding daily total amounts of daily deliveries of petroleum products to the Tohoku region by train.

\(7\) The data on transportation of petroleum products comprises three types: (1) shipments brought into the Tohoku region’s ports (“port-entry data”), (2) shipments from refinery ports across Japan (“port-exit data”), and (3) volumes of rail freight entering the Tohoku region (“rail-entry data”). The port-entry data specify the date, time, volume, and port of origin for petroleum products unloaded from oil tankers at ports in the Tohoku region. The port-exit data show the date, time, volume, and destination ports for petroleum products loaded onto tankers at refineries ports across Japan. In addition to that, the port-exit data list shipment volume by category of oil. The rail-entry data (collected in Sasaki\(^7\)) provide the full picture regarding daily total amounts of daily deliveries of petroleum products to the Tohoku region by train.
well as guarantee the reliability of the data. The rail-
entry data were devided by oil category in proportion
to the ratio calculated using the port-entry data.

This paper’s analysis covers three categories of oil
in five Japanese prefectures. The petroleum product
categories analyzed were gasoline, diesel fuel, and
kerosene. These fuels are used for transportation and
household purposes. The regions analyzed were five
prefectures in Tohoku (Aomori, Iwate, Miyagi, Akita,
and Yamagata). Fukushima Prefecture was excluded
from the analysis because many residents relocated as
a result of the nuclear accident, making it impossible
to estimate demand by region in the aftermath of the
earthquake and tsunami. Unless otherwise specified,
therefore, the results presented in this paper are ex-
clusive of Fukushima Prefecture.

3. FACILITIES SUPPLYING PETROLEUM
PRODUCTS

(1) Damage to Japan’s refineries

Japan’s refineries can be broadly grouped into five
geographic areas. As illustrated in Fig. 1, many of the
refineries are concentrated around the Seto Inland Sea
(West Japan) and Tokyo Bay (Kanto). Only one—the
Sendai refinery—is located in the Tohoku region.

The damage sustained by Japan’s oil refineries as
a result of the Great East Japan Earthquake can be
briefly summarized as follows: The Sendai refinery,
the only one in the Tohoku region, was damaged and
operations were suspended for a long time. Elsewhere
in Japan, five refineries in the Kanto area also sus-
pended operations as a result of the damage. Three
of the five sustained only minor damage and resumed
operations within a few days. All told, three refineries
in the Tohoku and Kanto areas, accounting for ap-
proximately 13% of Japan’s total crude capacity, were
forced to suspend operations long term as a result of
disaster damage.

This indicates that long-term loss of refining capac-
ity was limited, and damage to refineries was there-
fore not the fundamental cause of petroleum prod-
ucts shortages. Prior to the earthquake, demand for petroleum products had been declining in Japan as a
result of increasing energy efficiency and conversion
to alternative energy sources. Consequently, in aggre-
gate, operation rate of oil refineries in Japan had been
as low as around 80% for the past few years before the
disaster. Potentially, the damage to some refineries
could have been addressed by ramping up utilization
rates in unaffected refineries to maintain a steady
level of petroleum product output for the country as a
whole. However, because many of the refineries are
located in West Japan, it is easy to imagine how a bot-
tleneck could develop in transporting petroleum prod-
ucts from the refineries to the regions where they were
in short supply. Thus, it can be inferred that the funda-
mental reason for the oil shortage following the Great
East Japan Earthquake was the failure to adjust ship-
ing volumes and transportation patterns in response
to the changed spatial distribution of oil producing re-
gions as a result of disaster damage.

(2) Damage to major oil terminals in Tohoku

Under normal circumstances in Tohoku, petroleum
products are supplied by the Sendai refinery or by re-
fineries in other areas thorough nearby local oil ter-
minals. Fig. 2 depicts the location of major oil ter-
minals in the Tohoku region. Other than those at
Morioka and Koriyama, the terminals are located at
ports that are accessible by tanker. The inland ter-
minals at Morioka and Koriyama receive petroleum
products from refineries by rail. Due to the Sendai re-
finery’s suspension after the disaster, the Tohoku re-
gion was forced to obtain all its petroleum products
from other regions.

The damage sustained by oil terminals as a result

![Refineries in Japan and their damage. Blue: no damage, green: minor damage, red: severe damage.](image1)

![Major oil terminals in Tohoku region and their res-
sumption date. Blue: no damage, green: resumed in the 2nd phase, red: resumed in the 3rd phase.](image2)
of the Great East Japan Earthquake can be outlined as follows: Fig. 2 shows the dates when incoming shipments resumed. As the figure illustrates, almost all oil terminals in the Tohoku region stopped receiving shipments at one point following the disaster. Transportation of petroleum products from Niigata and other regions by tanker truck was the only option during this time. However, due to constraints on the number of tanker trucks and the trucks’ small capacities, the volume transported was likely minimal. Three or four days after the disaster, the oil terminals adjacent to ports on the Japan Sea coast in Aomori, Akita, and Sakata resumed accepting shipments. However, as a result of the tsunami damage, the terminals adjacent to ports on the Pacific coast in Hachinohe, Sendai-Shiogama, and Onahama could not resume normal operations for at least ten days. Thus, during this period, only terminals on the Japan Sea coast could supply petroleum products to the Pacific coast. In summary, the post-earthquake situation at facilities supplying petroleum products in the Tohoku region can be divided into three phases:

**Phase 1** First three days after the earthquake: all oil terminals inoperable;

**Phase 2** Four to ten days after the earthquake: oil terminals on the Pacific coast inoperable as a result of the tsunami damage; terminals on the Japan Sea coast operable;

**Phase 3** Ten days or more after the earthquake: actual production remained impossible because of damage to the Sendai refinery; terminals on the Pacific coast gradually resumed operations.

In addition to the oil terminals depicted in Fig. 2, there were also terminals in the cities of Kesennuma and Kamaishi. However, those terminals handled a very limited amount of products compared to the major terminals and both remained unused for a long period due to damage. They are therefore excluded from this paper’s analysis.

### 4. PETROLEUM PRODUCT SALES IN TOHOKU

Next, the impact of the Great East Japan Earthquake is examined by comparing March 2011 sales of petroleum products by category with March 2010 sales. Focusing on the portion of March sales recorded after the disaster (March 11–31), the results are as shown in Table 1. In the table, [B] denotes estimated sales from March 11–31, 2011, while [A] denotes estimated sales for the same period in 2010. The actual computations used were as follows:

\[ [A] = (21/31) \times [\text{March 2010 sales volume}] \]
\[ [B] = [\text{March 2011 sales volume}] - (10/31) \times [\text{2010 March sales volume}] \]

From Table 1, it can be observed that March sales volumes were down in all five prefectures and for all three categories of oil following the earthquake. Total sales of all petroleum products throughout the Tohoku region had fallen to less than 70% of the previous year’s sales, indicating that the situation in post-disaster Tohoku was extremely serious. Sales in Miyagi Prefecture on the Pacific coast were particularly low, at less than 50% of the previous year’s figure, while Iwate Prefecture’s sales had plummeted to around 60% compared to a year earlier. Even Akita Prefecture, located inland and only slightly damaged by the earthquake, suffered a decline to approximately 70% of previous-year sales. Focusing on the distinctions between the different categories of oil for the Tohoku region as a whole, the post-disaster sales volumes for diesel fuel and heating oil were 60–65% of the previous-year figures, while gasoline remained at 70% of previous-year sales. These figures demonstrate that the declines in gasoline sales volumes were smaller than those for other categories of oil. In Miyagi Prefecture on the Pacific coast, gasoline sales dropped to less than 50% of the previous year’s level, and diesel fuel to around 40%. The severity of the situation cannot be overemphasized.

In explaining the dramatic decrease in sales volumes, it is worth considering the possibility that consumer demand for oil declined as a result of damage to cars, the psychological impact of the disaster, or other factors. Yet it is difficult to imagine that these factors alone could have caused such dramatic changes. It would be more natural instead to sup-

### Table 1 Sales volume of oils in March: Comparison between 2010 and 2011 (10^3kl).

<table>
<thead>
<tr>
<th></th>
<th>Aomori</th>
<th>Iwate</th>
<th>Miyagi</th>
<th>Yamagata</th>
<th>Akita</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>G</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[A] 2010</td>
<td>36</td>
<td>37</td>
<td>81</td>
<td>32</td>
<td>29</td>
<td>214</td>
</tr>
<tr>
<td>[B] 2011</td>
<td>33</td>
<td>27</td>
<td>39</td>
<td>28</td>
<td>23</td>
<td>150</td>
</tr>
<tr>
<td>[B]/<a href="%25">A</a></td>
<td>90</td>
<td>72</td>
<td>48</td>
<td>87</td>
<td>82</td>
<td>70</td>
</tr>
<tr>
<td><strong>DF</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[A] 2010</td>
<td>61</td>
<td>40</td>
<td>70</td>
<td>47</td>
<td>37</td>
<td>254</td>
</tr>
<tr>
<td>[B] 2011</td>
<td>46</td>
<td>21</td>
<td>27</td>
<td>37</td>
<td>27</td>
<td>159</td>
</tr>
<tr>
<td>[B]/<a href="%25">A</a></td>
<td>76</td>
<td>54</td>
<td>39</td>
<td>79</td>
<td>73</td>
<td>63</td>
</tr>
<tr>
<td><strong>K</strong></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>[A] 2010</td>
<td>28</td>
<td>28</td>
<td>44</td>
<td>18</td>
<td>18</td>
<td>136</td>
</tr>
<tr>
<td>[B] 2011</td>
<td>20</td>
<td>16</td>
<td>26</td>
<td>15</td>
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<td>56</td>
<td>58</td>
<td>81</td>
<td>59</td>
<td>64</td>
</tr>
</tbody>
</table>

| **Total** |        |       |        |          |       |       |
| [A] 2010 | 125    | 104   | 195    | 97       | 83    | 604   |
| [B] 2011 | 99     | 64    | 92     | 79       | 61    | 395   |
| [B]/[A](%) | 80     | 61    | 47     | 82       | 73    | 65    |

G: gasoline, DF: diesel fuel, K: kerosene

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6 Donations of petroleum products made by a variety of organizations after the earthquake were small compared to the volumes contained in the statistical data for this paper. Donations were therefore omitted from sales volume data in Table 1.

7 In addition, it is reported that wholesale oil prices were fixed...
pose that supplies were insufficient in these regions because of damage to supply facilities, and as a result of the limited supply, the volume of demand expected under normal circumstances failed to materialize. Or, to express it another way:

\[
\text{Sales volume} = \text{Supply volume} \quad < \text{Volume of demand under normal circumstances}
\]

This interpretation is supported by the fact that the drops in sales volumes were relatively small in Akita and Aomori Prefectures, which suffered only minor damage to oil terminals and other oil supply facilities. This will be discussed in more depth in Chapters 5 and 6.

5. VOLUME OF SHIPMENTS OF PETROLEUM PRODUCTS TO THE TOHOKU REGION

This chapter uses port inbound and outbound shipment data to provide insight into the pattern of shipments of petroleum products, by category, from oil refineries to oil terminals in the Tohoku region following the Great East Japan Earthquake. In addition, it examines how that pattern changed over time. Section 5.1 analyzes outbound shipments of petroleum products, by category, from ports in other regions (oil refineries) to the Tohoku region. Section 5.2 analyzes inbound shipments at ports in the Tohoku region (oil terminals). Section 5.3 presents an analysis focused on gasoline. Note that the totals shown in this chapter do not include outbound shipments to the port of Onahama in Fukushima Prefecture or rail shipments to the oil terminal at Morioka.

(1) Volume of outbound shipments from ports in other regions

This section examines the pattern of outbound shipments of petroleum products from oil refineries to oil terminals in the Tohoku region following the earthquake. It also studies changes in outbound shipment volumes over time. Table 2 lists the volumes of outbound shipments to the Tohoku region from each oil refinery port within a month before and after the earthquake. Fig. 3 uses the data in Table 2 to illustrate the difference in volumes before and after the earthquake.

Table 2 and Fig. 3 indicate that the volume of outbound shipments of petroleum products from other regions to the Tohoku region significantly changed after the earthquake. Moreover, they reflect trends in those changes by product category and region. First, shipments of all petroleum products sharply dropped following the earthquake. Second, the volume of outbound shipments from the Kanto region, which accounted for more than half of the outbound shipments before the earthquake, dropped to approximately one-third. Gasoline and kerosene slumped to approximately one-third of the levels prior to the earthquake, and diesel fuel dropped to less than half. This can be attributed to the severe damage sustained by oil refineries on the Pacific coast in the Kanto region. Therefore, the Kanto region also experienced an oil shortage. Third, the volumes of outbound shipments from the Hokkaido, Tokai, and western Japan regions rose after the earthquake. Thus, the decline in outbound shipments from the Kanto region may have been compensated by an increase in outbound shipments from these regions. In particular, there was a marked increase in shipments from the Hokkaido region, whereas the increase from the Tokai and western Japan regions was modest in comparison. This suggests that the press conference convened by METI on March 17, 2011 and the subsequent press release issued by METI were grossly inconsistent with the actual situation. The Ministry announced that approximately 20,000 kl of gasoline and related products would be shipped daily to the Tohoku region from oil refineries in western Japan. This corresponds to approximately 600 (×10^3) kl per month, which implies that the majority of the amount required in the Tohoku region would be shipped from western Japan. However, as Table 2 illustrates, the volumes of all product categories shipped from western Japan in the

<table>
<thead>
<tr>
<th>Product</th>
<th>Hokkaido</th>
<th>Kanto</th>
<th>Tokai</th>
<th>W. Japan</th>
<th>Other</th>
<th>Total</th>
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</thead>
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<tr>
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<td>84</td>
<td>145</td>
<td>7</td>
<td>9</td>
<td>12</td>
<td>257</td>
</tr>
<tr>
<td>After</td>
<td>132</td>
<td>38</td>
<td>25</td>
<td>19</td>
<td>1</td>
<td>239</td>
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<tr>
<td>DF</td>
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<td>137</td>
<td>31</td>
<td>56</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 2: Comparison of outbound shipment volumes from ports in other regions one month before and after the earthquake (10^3 kl).

Fig. 3: Changes in outbound shipment volumes from ports in other regions one month before and after the earthquake.
month following the earthquake was approximately $56 \times 10^3$ (kl), less than one-tenth of that stated in the government’s announcement.

(2) Volume of inbound shipments to ports in the Tohoku region

Table 3 and Fig. 4 compare the volumes of inbound shipments at each oil terminal during the month before and after the earthquake. First, they illustrate that the volume of inbound shipments sharply dropped at ports on the Pacific Ocean that had been damaged by the tsunami (the ports of Hachinohe and Sendai-Shiogama). In the month before the earthquake, these two ports accounted for approximately half of the total. Second, the volume of inbound shipments of petroleum products increased at ports on the Japan Sea (the port of Akita, particularly). However, these increases were insufficient to compensate for the deficit at the ports on the Pacific Ocean. Third, at the port of Sendai-Shiogama, where inbound shipments were interrupted for approximately ten days after the earthquake, shipments of diesel fuel increased, whereas those of gasoline and kerosene significantly decreased. This was likely due to the intensive deliveries of diesel fuel at the port of Sendai-Shiogama following the resumption of inbound shipments on March 21, 2011.

We can further examine the changes in inbound shipments of petroleum products over time using Fig. 5, which shows the cumulative volumes of inbound shipments by category at the major ports of the Tohoku region during the month before and after March 11, 2011, the date of the earthquake. First, the slope of the cumulative curves indicates that the port of Sendai-Shiogama was the largest for inbound shipments of gasoline prior to the earthquake. The volumes of inbound shipments of diesel fuel were significantly greater at the ports of Aomori, Akita, and Hachinohe. Second, the slope of the curve for the cumulative volumes of inbound gasoline shipments greatly increased for the ports of Akita due to the interruption of inbound shipments at the ports of Sendai-Shiogama and Hachinohe following the earthquake. This demonstrates that gasoline was shipped in from ports on the Japan Sea to compensate for the port of Sendai-Shiogama being unusable following the earthquake. A comparatively moderate rising trend is also observed in the volume of inbound shipments of diesel fuel at the port of Akita. These trends progressed toward normalization at the ports of Akita by about April 8, 2011, four weeks after the earthquake. This is illustrated by the slope of the cumulative curve, which approached the level of the month before the earthquake. Third, inbound shipments of gasoline and diesel fuel converged on the port of Sendai-Shiogama once it resumed operations on March 21, 2011. Compared to pre-earthquake levels, the slope for gasoline was largely unchanged, while inbound shipments of diesel fuel significantly increased. This was likely due to the intensive deliveries of diesel fuel at the port of Sendai-Shiogama following its re-opening, with diesel fuel being indispensable for moving relief supplies. On April 11, 2011, apart from the curve for kerosene, and in contrast to the trend for ports on the Japan Sea, the slope of the curve for inbound shipments exceeded that for the month before the earthquake for the port of Sendai-Shiogama. This demonstrates that, in coping with the earthquake, the focal point for inbound shipments of petroleum products shifted from ports on the Japan Sea to those on the Pacific Ocean, primarily Sendai-Shiogama.

(3) Volume of inbound and outbound gasoline shipments

This section focuses exclusively on gasoline and examines changes in the volume of shipments over time as illustrated in Fig. 6 and Fig. 7. Fig. 6 shows the weekly volumes of outbound gasoline shipments from the country’s oil refineries to oil terminals in the Tohoku region. Fig. 7 shows the weekly volume of inbound gasoline shipments received at oil terminals in the Tohoku region. Both figures cover the five-week

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Comparison of inbound shipment volumes to ports in the Tohoku region one month before and after the earthquake ($10^3$ kl).</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Aomori</td>
</tr>
<tr>
<td>G</td>
<td></td>
</tr>
<tr>
<td>Before</td>
<td>52</td>
</tr>
<tr>
<td>After</td>
<td>51</td>
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<tr>
<td>DF</td>
<td></td>
</tr>
<tr>
<td>Before</td>
<td>44</td>
</tr>
<tr>
<td>After</td>
<td>36</td>
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<tr>
<td>K</td>
<td></td>
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<tr>
<td>Before</td>
<td>64</td>
</tr>
<tr>
<td>After</td>
<td>56</td>
</tr>
<tr>
<td>Total</td>
<td>160</td>
</tr>
</tbody>
</table>

Fig. 4 Changes in inbound shipment volumes to ports in the Tohoku region one month before and after the earthquake.
First, it is evident from Fig. 6 that the volume of outbound shipments was particularly low in the two weeks following the earthquake compared with normal demand for gasoline in the Tohoku region. About 20% of the normal weekly demand\(^9\) (red dashed line in the figure) was shipped in the first week and about 60% in the second week. Second, the volume of shipments recovered to levels exceeding normal demand in the third and fourth weeks following the earthquake. This recovery from the disaster in the third and fourth weeks was mainly attributable to increased shipments from the Hokkaido region. There were also shipments from the West Japan region from the second week following the disaster, but their contributions were modest compared with the increase from the Hokkaido region. Third, the volume of shipments from the Kanto region witnessed continuous growth. However, as shown in Table 2 and Fig. 3, the volume of outbound shipments in the first month following the earthquake declined significantly from standard levels before its incidence.

\(^8\) See Table A1 and Fig. A1 in the Appendix for the pattern of OD (origin/destination) shipment volumes for gasoline from oil refineries (origin) to oil terminals (destination) and changes before and after the earthquake.

\(^9\) Calculated using statistics,\(^6\) the volume of gasoline sales in March 2010.

Fig. 7 shows that the Pacific ports of Hachinohe and Sendai-Shiogama were barely usable in the two weeks following the earthquake, and only the ports of Akita, Aomori, and Sakata on the Sea of Japan were operational. In particular, the port of Akita accounted for approximately half the volume of inbound shipments in the two weeks following the earthquake, playing a central role in the matter. However, the increase in inbound shipment volumes at these ports in the Sea of Japan was insufficient when considering the Tohoku region as a whole, and there was a clear lack of supply. As the ports of Sendai-Shiogama and Hachinohe on the Pacific Ocean side were restored during the second to fourth weeks, inbound shipment volumes there gradually increased. This enabled the receipt of supplies corresponding to normal demand levels. Ultimately, however, the supply of petroleum products to the entire Tohoku region remained insufficient until the Pacific ports of Sendai-Shiogama and Hachinohe had been fully restored and made operational.

Care must be exercised when employing Fig. 6 and Fig. 7 to determine when the oil shortage in the Tohoku region was resolved. Fig. 6 and Fig. 7 show that outbound shipment volumes increased from the third week after the earthquake and, at a glance, give the impression that the oil shortage had been resolved. However, it should be noted that consumer demand at
The daily sales volume in the same month of the previous year is considered as the standard for daily consumption (i.e., the amount consumed when supply is adequate). This is referred to as latent daily demand, or cumulatively as cumulative latent demand.

We then define supply as the volume of inbound shipments (by ship/rail) to oil terminals plus the volume of stock releases. The latter must be taken into account as inventories are considered to have been released at service stations and oil terminals in the Tohoku region following the earthquake to cover shortages in supply from inbound shipments from other regions.

The volume of stock releases is unclear for individual oil terminals and service stations. However, for the Tohoku region as a whole, it can be derived from the following equation, which should have applied during the studied period:

\[
\text{Cumulative sales volume} = \text{cumulative volume of inbound shipments} + \text{volume of stock releases}
\]

This results in stock releases of approximately \(14 \times 10^3\) kl for the Tohoku region as a whole. Converted to actual sales per day in a normal period (March, 2010), this was approximately 1.4 days’ worth of stock releases (see Figure 8). In the following, the volume of supply in the Tohoku region has been calculated as the volume of inbound shipments to its oil terminals plus 1.4 days’ worth of stock releases.

6. AGGREGATE DEMAND–SUPPLY GAP IN THE TOHOKU REGION

This chapter analyzes the volume of gasoline stocks released, the demand–supply gap, and unrealized demand in the Tohoku region by combining sales and transport data for petroleum products. This analysis, based on the cumulative figures, demonstrates why oil shortages continued for almost a month after the earthquake.

(1) Estimated demand and supply in the Tohoku region

This section defines and estimates demand and supply to analyze the extent to which demand was met throughout the Tohoku region following the earthquake.

The volume of supplies is unclear for individual oil terminals and service stations. However, for the Tohoku region as a whole, it can be derived from the following equation, which should have applied during the studied period:

\[
\text{Cumulative sales volume} = \text{cumulative volume of inbound shipments} + \text{volume of stock releases}
\]

Thus, the volume of stock releases from immediately after the earthquake until March 31, 2011 may be estimated by calculating the cumulative sales volume on the left-hand side of the equation from sales volumes in March following the earthquake (i.e., the sum of the sales volumes per prefecture shown in Table 1) and the cumulative volume of inbound shipments on the right hand side of the equation from data for petroleum products transported. This results in stock releases of approximately \(14 \times 10^3\) kl for the Tohoku region as a whole. Converted to actual sales per day in a normal period (March, 2010), this was approximately 1.4 days’ worth of stock releases (see Figure 8). In the following, the volume of supply in the Tohoku region has been calculated as the volume of inbound shipments to its oil terminals plus 1.4 days’ worth of stock releases.

(2) The aggregate demand–supply gap in the Tohoku region

This section analyzes the difference between demand and supply (demand–supply gap) as estimated in the previous section. Figure 8 portrays the cumulative volumes of latent demand (red dashed line), inbound shipments (blue dotted line), and supply (solid blue line: cumulative volume of inbound shipments + 1.4 days’ worth of stock). This figure assumes that, in the two days following the earthquake, inventories were supplied according to the latent demand, and that supply was equal to the volume of inbound shipments once stocks had been depleted. Figure 8 demonstrates that the cumulative curve for latent demand continually remained above that for supply, implying that the
supply would have continued to be insufficient if the latent demand had been fulfilled. However, in reality, waiting lines at service stations and depleted inventories were resolved by about mid-April 2011 at the latest. This suggests that consumers resigned themselves to not obtaining a portion of the latent demand. This paper defines this demand that was abandoned by consumers as unrealized demand.

Considering the existence of unrealized demand, the volume of consumer demand that was fulfilled would have been less than the cumulative volume of latent demand. The cumulative volume of demand (solid red line) is included in Fig. 9. The assumption, in this case, is that supply shortages were resolved by March 31, 2011 and daily demand was normalized.

In this case, the volume of demand prior to the elimination of supply shortages was approximately 66% of the volume of latent demand, and the difference between the cumulative volumes of demand and latent demand is the volume of unrealized demand, which was approximately 64 \times 10^3 \text{ kl} when supply shortages are considered to have been resolved (March 31, 2011). Converted to the volume of latent daily demand, this is approximately 6.4 days’ worth of stock releases. This implies that a massive economic loss was sustained as a result of the Great East Japan Earthquake, which eliminated social and economic activities corresponding to as much as 6.4 days’ worth of demand in gasoline terms.

Fig. 10 focuses on a part of the period covered in Fig. 9 (March 11–20). It examines the gap between the cumulative volumes of demand and supply. The trend in pent-up demand (waiting lines) for petroleum products can be identified from the gap between the two cumulative curves shown in the figure. Specifically, the vertical distance between the cumulative demand and supply curves represents the volume of pent-up demand, while the horizontal distance indicates the waiting time needed to purchase petroleum products. The waiting lines that formed at individual service stations can be described as a manifestation of this aggregate pent-up demand. It should be noted that even if the volume of daily supply (a flow variable) matched or exceeded that of daily demand, pent-up demand (a stock variable) would not instantly disappear. In fact, as we have seen in Section 5.3, the volume of daily supply did meet that of daily demand around March 26, 2011, but a further week was required to resolve the pent-up demand that had accumulated through supply shortages until that point (Fig. 9). This is fundamentally why there were protracted shortages of petroleum products throughout the Tohoku region.

As the above analysis demonstrates, the measure essential to relieving the shortage of petroleum products in the Tohoku region was to ease supply constraints to the maximum possible degree. Nevertheless, additional measures should have been implemented. First, adequate land transportation from the Japan Sea to the Pacific Ocean should have been organized immediately after the earthquake to avoid generating pent-up demand. Next, a more aggressive supply of petroleum products should have been arranged to reduce accumulated pent-up demand once inbound
shipments resumed at the port of Sendai-Shiogama on March 21, 2011. Specifically, the volume of daily supply should have been consistently higher than that of normal daily demand. If such a plan had been executed, pent-up demand could have been resolved sooner and a protracted shortage of petroleum products would not have occurred.  

However, the volume of supply was not adequately generated considering the level of pent-up demand. Instead, measures were taken to restrain demand. For more than a month after the earthquake, the government and the Petroleum Association of Japan pursued public relations activities in the Tohoku region, imploring consumers to refrain from “non-essential and non-urgent purchases of petroleum products.” As the analysis in this section demonstrates, the demand created in the Tohoku region following the earthquake represented standard demand that had been greatly suppressed through supply constraints. Thus, most of the actual demand in the Tohoku region following the earthquake was not for “non-essential and non-urgent purchases.” Therefore, the public relations activities calling for restraint in demand of petroleum products can be considered as having a high risk of curbing necessary economic activity. Therefore, the conclusion is that this policy aggravated the fundamental problem in relation to the Great East Japan Earthquake, namely the massive economic loss caused by the inhibition of social and economic activity due to vanishing demand. To effectively resolve the problem, a policy of mitigating the overwhelming initial supply shortages and promptly addressing the accumulated pent-up demand was required.

7. ESTIMATION MODEL FOR SUPPLY AND DEMAND BY MUNICIPALITY

As we have seen so far, although oil terminals along the Sea of Japan were restored soon after the earthquake, those on the Pacific Ocean coast remained defective for long because of damage caused by the tsunami. For this reason, one would suspect that even within the Tohoku region, the timing of actual resolution of the supply shortage was largely different between the Sea of Japan side and the Pacific Ocean side. Thus, this chapter will construct a model that estimates the amount of gasoline supplied from oil terminals to each municipality in the Tohoku region. Chapter 8 will analyze how the demand-supply gap developed in each prefecture and each municipality.

We should note here that the purpose of the chapter is to estimate the spatio-temporal distribution of the demand-supply gaps in the Tohoku region using limited data. We do not intend to examine any hypotheses about the oil suppliers’ behavior after the earthquake.

(1) Estimation model for sales volume by municipality

The estimation model for sales volume by municipality further consists of two models. The first one is a gasoline allocation model that determines the amount of gasoline transported from each oil terminal to each municipality in a given time from the day after the earthquake. The second model is a dynamic model of demand and supply stock that describes the amount of available gasoline at each oil terminal and the development of potential demand in each municipality across time.

a) Framework of the model

Setting the day of the earthquake as \( t = 0 \) and considering the set of discrete time \( t = 0, 1, \cdots \), where the duration is one day, the set of indices from \( t = 1 \) to an appropriate time \( T > 1 \) is defined as \( T := \{1, \cdots, T\} \). The oil terminal set and the municipality set (the origin and the destination of gasoline allocation) are represented by \( O \) and \( D \), respectively. The amount of gasoline supplied per day from oil terminal \( i \in O \) in time \( t \in T \) (i.e., the amount of gasoline transported to oil terminal \( i \) in time \( t \)) will be called the rate of supply, represented by \( w_i(t) \). The demand for newly generated gasoline at municipality \( j \in D \) per day in time \( t \in T \) will be called the rate of potential demand, represented by \( r_j(t) \). Here, the rate of supply \( [w_i(t)] \) and the rate of potential demand \( [r_j(t)] \) in the estimation model for sales volume by municipality are given conditions called model inputs. The method for determining these model inputs is described in Section 8.1.

b) Dynamic model for potential demand and supply stock

The amount of gasoline in stock (i.e., available for supply) at oil terminal \( i \in O \) at the end of any time \( t \in T \) will be called supply stock, represented by \( X^S_i(t) \). The initial value of supply stock is set as \( X^S_i(0) = 0 \). The amount of gasoline supplied from oil terminal \( i \in O \) between the beginning and the end of time \( t \) is defined as the sum of inventory at the end of the previous time step and the amount of supply generated during this time step:

\[
p_i(t) := X^S_i(t - 1) + w_i(t) \Delta t. \tag{1}
\]

We assume that gasoline available for supply will be allocated to municipalities based on demand; gasoline.
will be stocked at the oil terminal only when there is a surplus. We assume this to be true no matter how gasoline is allocated among municipalities.

The amount of gasoline transported from oil terminal \(i \in O\) to municipality \(j \in D\) per unit of time during the complete period of time \(t\) will be called the rate of transport, represented by \(x_{i,j}(t)\). When the rate of transport \(x(t) := x_{i,j}(t) : (i, j) \in O \times D\) is provided, the dynamics of supply stock can be expressed as the following formula:

\[
X^S_j(t) = X^S_j(t-1) + \left( w_i(t) - \sum_{j \in D} x_{i,j}(t) \right) \Delta t
= p_i(t) - \sum_{j \in D} x_{i,j}(t) \Delta t. \tag{2}
\]

The amount of gasoline still in demand (unmet demand) in municipality \(j \in D\) at the end of time \(t \in T\) will be called the potential demand stock, expressed by \(X^D_j(t)\). The initial value of the potential demand stock is set as \(X^D_j = 0\). As we have seen in Chapter 6, consumers were forced to forgo some of their unmet demand for three to four weeks following the earthquake. In other words, this unmet demand disappeared. To express this, we assume that, of the potential demand stock at the end of time \(t - 1\), only \((1 - \beta \Delta t)X^D_j(t - 1)\) will remain at the beginning of time \(t\). Here, \(\beta \in (0, 1/\Delta t)\) is a given constant, representing the rate of demand that will disappear during the period between the end of time \(t - 1\) and the beginning of time \(t\). In what follows, \(\beta\) is called the rate of disappearance. The amount of actual demand for gasoline in municipality \(j \in D\) between the beginning and the end of time \(t\) is defined as the sum of the potential demand stock carried over from the previous time step and the newly generated potential demand at this time step. This can be represented as:

\[
q_j(t) := (1 - \beta \Delta t)X^D_j(t - 1) + r_j(t) \Delta t. \tag{3}
\]

By doing so, the dynamics of the potential demand stock will be expressed by the following formula:

\[
X^D_j(t) = (1 - \beta \Delta t)X^D_j(t - 1) + \left( r_j(t) - \sum_{i \in O} x_{i,j}(t) \right) \Delta t
= q_j(t) - \sum_{i \in O} x_{i,j}(t) \Delta t. \tag{4}
\]

c) Gasoline allocation model (basic model)

A model that determines gasoline allocation \(y(t) := (x(t), X^S(t), X^D(t))\) is considered, where the amount of gasoline supply \(\{p_i(t) : i \in O\}\) and the amount of potential demand \(\{q_j(t) : j \in D\}\) at each time \(t \in T\) are given. Here, \(x(t) := \{x_{i,j}(t) : (i, j) \in O \times D\}\), \(X^S(t) := \{X^S_i(t) : i \in O\}\) and \(X^D(t) := \{X^D_j(t) : j \in D\}\) vectorially represent the rate of transport at time \(t\), the supply stock at the beginning of time \(t\), and the potential demand stock at the beginning of time \(t\), respectively. This section develops a formula for the scenario in which shipping planners aim only to minimize the total cost (i.e., the sum of shipping costs and inventory costs) as a basic model of gasoline allocation. This model will be expanded later in Section 7.2 to a framework that conducts the allocation such that the unmet demand \(\{X^D_j(t)\}\) will not become too skewed across municipalities. Thus, the framework will take fairness into consideration.

The allocation \(y(t) := (x(t), X^S(t), X^D(t))\) under the gasoline allocation model is assumed to be feasible when the following three conditions are met:

1. The sum of the total gasoline transported into each municipality and the (unmet) potential demand stock at the end of the time period equals the amount of actual demand in the given municipality:

\[
\sum_{i \in O} x_{i,j}(t) \Delta t + X^D_j(t) = q_j(t), \quad \forall j \in D. \tag{5}
\]

2. The sum of the total gasoline transported from each oil terminal and the supply stock at the end of the time period equals the amount of supply at the given oil terminal:

\[
\sum_{j \in D} x_{i,j}(t) \Delta t + X^S_i(t) = p_i(t), \quad \forall i \in O. \tag{6}
\]
[3] The amounts of supply stock at each oil terminal, the potential demand stock in each municipality, and the transported amount between each link are not negative:

\[ X_i^O(t) \geq 0, \quad \forall i \in O, \quad (7) \]

\[ X_j^D(t) \geq 0, \quad \forall j \in D, \quad (8) \]

\[ x_{ij}(t) \geq 0, \quad \forall (i, j) \in O \times D, \forall t \in T. \quad (9) \]

Shipping planners seek the option to minimize the total shipping cost within a range of feasible gasoline allocation \( y(t) \) in each time \( t \in T \). This is formulated as follows:

\[
\min_{y(t)} \sum_{i \in O} \sum_{j \in D} c_{i,j}(t)x_{i,j}(t) + \sum_{i \in O} C_i X_i^O(t),
\]

s.t. (5), (6) and (8)

(10)

Here, \( c_{i,j} \) is the time it takes from oil terminal \( i \in O \) to municipality \( j \in D \). \( C_i \), which is a given constant that represents the inventory cost for excess gasoline at oil terminal \( i \in O \), and is assumed to satisfy \( C_i > \max_j \{c_{i,j}\} \).

d) The amount of gasoline sales by municipality

The amount of gasoline sales by municipality can be estimated by combining the two models: the dynamic model of potential demand and supply stock and the gasoline allocation model, which have been described so far. Specifically, the rate of transport \( x(t) \) can be determined when the rate of supply \( \{w_i(t)\} \), the rate of potential demand \( \{q_j(t)\} \), and the rate of disappearance \( \beta \) are provided. In doing so, the amount of gasoline transported into each municipality \( j \in D \) per unit of time (which also equals sales amount per unit of time) at time \( t \) is called the rate of sales, expressed as \( s_j(t) := \sum_{i \in O} x_{i,j}(t) \).

(2) Expansion to a framework that considers inter-regional transfer

The basic model described in the previous section is a reasonable representation of gasoline allocation under normal circumstances. During the post-earthquake period, however, shipping planners seem to have allocated gasoline with the aim of reducing imbalances in the demand-supply gap between the municipalities covering more areas rather than simply minimizing costs as Akamatsu et al.\(^3\) reported: it is observed that considerable amount of gasoline was transferred from oil terminals on the Sea of Japan side—such as Akita and Aomori—to municipalities on the Pacific Ocean side, which are not usually included in the supply area. Therefore, to create a framework that considers such inter-regional transfer, this section develops two models, namely target demand model and entropy model, as an expansion of the basic model. The former reduces the imbalance in the demand-supply gap between municipalities by uniformly setting the allocation amount to each municipality, while the latter represents the imbalance in the demand-supply gap by adding a term that represents the degree of skew of the unmet demand \( \{X_j^D(t)\} \) to the objective function.

a) The target demand model

In the target demand model, it is assumed that shipping planners allocate gasoline not to meet the actual demand \( q_j(t) \) from municipality \( j \in D \) at time \( t \in T \), but to meet the target demand \( n(t)q_j(t) \), which is derived by multiplying the actual demand by a constant coefficient \( n(t) \in (0, 1) \). This assumption represents the desire of shipping planners to allocate gasoline to as many areas as possible, that is, even if this requires suppressing allocations to some areas. Here, \( n(t) \) is called the target demand coefficient. It is expressed by the following piecewise linear function for time \( t \):

\[
n(t) = \min \left\{ n_0 + \frac{1 - n_0}{r_e}(t-1), 1 \right\}. \quad (10)\]

Here, \( n_0 \) and \( r_e \) are parameters that represent the initial target demand coefficient as of the day after the earthquake \( t = 1 \) and the time when the adjusted allocation that uses the target demand is terminated and the normal allocation resumed. Formula (10) represents this natural transition in which the target demand is small immediately after the earthquake, but gradually returns to normal over time.

Of the three conditions ([1], [2], and [3]) that characterize the allowable range of the basic model, only [1] is modified to define the allowable range under the target demand model as follows:

\[ [1'] \text{The sum of the total gasoline transported into each municipality and the (unmet) potential demand stock at the end of the time equals the amount of target demand in the given municipality:} \]

\[
\sum_{i \in O} x_{i,j}(t)\Delta t + X_j^D(t) = n(t)q_j(t), \quad \forall j \in D. \quad (11)\]

The target demand model is formulated as the linear programming problem that determines the allocation to minimize the total cost within the allowable range, which has been revised as shown previously. The formulation is as follows:

\[
\min_{y(t)} \sum_{i \in O} \sum_{j \in D} c_{i,j}(t)x_{i,j}(t) + \sum_{i \in O} C_i X_i^O(t), \quad (TD)\]

s.t. (11), (6) and (8).

In what follows, the set of an initial target demand coefficient and the time when allocations return to normal, \( (n_0, r_e) \), will be called the target demand parameters.

b) The entropy model

Under the entropy model, it is assumed that shipping planners allocate gasoline in a way that the ratio of unmet potential demand stock at the end of time
step to the actual demand at time \( t \), or \( \frac{x_{j}^{(t)}}{q_{j}(t)} \), will not be disproportionate across the municipalities. Specifically, the degree of skew (unevenness) is expressed by the following entropy weighted by the potential demand stock:

\[
\mathcal{H}(X^{D}(t)) := -\sum_{j \in D} q_{j}(t) \left( \frac{X^{D}(t)}{q_{j}(t)} \right) \ln \left( \frac{X^{D}(t)}{q_{j}(t)} \right) = -\sum_{j \in D} X^{D}_{j}(t) \ln X^{D}_{j}(t) + \sum_{j \in D} X^{D}_{j}(t) \ln q_{j}(t).
\]  

(12)

The entropy \( \mathcal{H}(X^{D}(t)) \) will be positive as long as the ratio of unmet demand \( \frac{x_{j}^{(t)}}{q_{j}(t)} \) is more than 0 but less than 1, and becomes smaller as the ratio of unmet demand becomes skewed among municipalities with large actual demand.

The entropy model calculates a feasible gasoline allocation such that \( y(t) \) minimizes the nonlinear weighted sum of the total transportation cost and the entropy (with inverted sign) at time \( t \in T \). This is formulated as follows:

\[
\min_{y(t)} \sum_{i \in O} \sum_{j \in D} c_{i,j}(t)x_{i,j}(t) + \sum_{i \in O} C_{i} X_{i}^{2}(t) - \theta \mathcal{H}(X^{D}(t)), \quad \text{s.t. } (5), (6) \text{ and } (8).
\]

(EP)

Here, \( \theta > 0 \) is a given constant that represents the weight of unevenness towards the total transportation cost. It is called the smoothing coefficient.

As a note, while the above target demand model is a linear programming problem, the entropy model is a convex programming problem. The dimensions of variables are at most \( O(D \times D) \) in both, and the solutions can be obtained quickly using the existing solver.

Hereafter, the target demand parameters when using the target demand model as gasoline allocation model, \( (n_{0}, r^{*}) \), and the smoothing coefficient when using the entropy model, \( \theta \), are called allocation parameters. Together, they are expressed as \( (n_{0}, r^{*} | \theta) \).

(3) Parameter estimation method

This section describes the method for estimating the rate of disappearance \( \beta \), a parameter of the estimation model for sales volume by municipality, as well as the allocation parameters \( (n_{0}, r^{*} | \theta) \). Specifically, the rate of disappearance \( \beta \) is first calculated (separately from gasoline allocation) on the basis of the observations regarding the aggregated potential demand stock for the entire Tohoku region \( \sum_{j} X_{j}^{D}(t) \). Next, using this rate of disappearance \( \beta \) as a given condition, the gasoline allocation parameter(s) (i.e., either the target demand coefficient parameters \( (n_{0}, r^{*}) \) or the smoothing coefficient \( \theta \)) will be estimated based on the actual gasoline sales in each prefecture.

a) Estimation of the rate of disappearance \( \beta \)

As the best estimated value for the rate of disappearance \( \beta \), this study uses the value obtained at the time when the aggregated potential demand stock for the entire Tohoku region first disappears becomes closest to the actual observed time when the demand-supply gap is resolved. This estimation can be done separately from the gasoline allocation model. First, the total potential demand stock for the entire Tohoku region at the end of any given time \( t \in T \) is defined as \( X^{D}(t) := \sum_{j \in D} X_{j}^{D}(t) \). This dynamic is assumed to behave according to the following formula:

\[
X^{D}(t) = \left( 1 - \beta \Delta t \right) X^{D}(t - 1) + \sum_{j \in D} \left( r_{j}(t) - w_{j}(t) \right) \Delta t, \quad X^{D}(0) = 0. \tag{13}
\]

Further, the solution process of Formula (13) for the rate of disappearance \( \beta \) is expressed as \( \{X^{D}(t; \beta)\} \). Next, the time when the actual resolution of the demand-supply gap for the entire Tohoku region was observed is defined as \( \tau^{*} \) (the specific value will be described later). In addition, a value that will satisfy the following conditions will be selected as the best estimated value of the rate of disappearance \( \beta^{*} \).

\[
\beta^{*} = \arg \max_{\beta \in [0, 1]} \left\{ \beta : \left| \frac{X^{D}(t; \beta)}{X^{D}(t; \beta) = 0} \right| \right\} \quad t = \tau^{*} - 1, \quad \Delta t > 0.
\]

(14)

b) Estimation of the initial target demand coefficient \( n_{0} \) and the \( \theta \)

When the rate of disappearance \( \beta^{*} \) (therefore, the dynamics of potential demand stock under this rate of disappearance \( \beta^{*} \)) calculated in the previous section was used as a given condition, the sales volume by municipality (aggregated by prefecture) estimated by the model and the actual sales by prefecture can estimate parameters for the gasoline allocation model.

Let us assume that the actual sales \( Z_{k}(\tau) \) of each prefecture \( k \in K \) through certain time \( \tau \in T \) are being observed now. Next, using the rate of sales \( s_{j}(t) = \sum_{i \in O} X_{i,j}(t) \), we can define the amount of gasoline to be sold in municipality \( j \in D \) between time \( t = 1 \) and the end of any given time \( \tau \in T \) (cumulative sales volume) as:

\[
S_{j}(\tau) = \sum_{i=1}^{\tau} s_{j}(\tau) \Delta t, \quad \forall k \in K. \tag{15}
\]

Next, we represent the set of prefectures for analysis as \( K \) and the set of municipalities included in prefecture \( k \in K \) as \( D_{k} \). At this instance, the cumulative sales volume through the end of any given time \( \tau \in T \) in prefecture \( k \in K \) is expressed as \( S_{k}(\tau) := \sum_{j \in D_{k}} S_{j}(\tau) \).
Section 8.2 estimates the rate of disappearance (the rate of potential demand, etc.) based on available model inputs (e.g., the rate of gasoline supply, allocation parameters, etc.). This equation is formulated as follows:

\[ (n_0^*, r^*) = \arg \min_{(n_0, r^*) \in [0.1]} \sum_{k \in K} \left( S_k(r^*; n_0, r^*) - Z_k(r^*) \right)^2. \]  

When using the entropy model as the gasoline allocation model, the equation to calculate the best estimated value for the smoothing coefficient \( \theta \) is formulated as follows:

\[ \theta^* = \arg \min_{\theta \in [0, \infty)} \sum_{k \in K} \left( S_k(r^*; \theta) - Z_k(r^*) \right)^2. \]

### 8. ESTIMATION OF DEMAND-SUPPLY GAP BY MUNICIPALITY

In this chapter, we estimate the demand-supply gap by municipality through the estimation model for sales volume by municipality and the parameter estimation method described in the previous section. First, Section 8.1 describes the method of calculating model inputs (e.g., the rate of gasoline supply, the rate of potential demand, etc.) based on available data. Thereafter, by using those model inputs, Section 8.2 estimates the rate of disappearance \( \beta \) and allocation parameters \( (n_0, r^* | \theta) \). Based on the parameters estimated this way, Sections 8.3 and 8.4 analyze the demand-supply gap by municipality as well as the aggregation of those gaps by prefecture.

---

**Fig. 12** Parameter estimation model.

The purpose of this section is to calculate the allocation parameters \( (n_0, r^* | \theta) \) by which the cumulative sales volume by prefecture \( \{S_k(t) : k \in K\} \) obtained best explains the actual sales observed for each prefecture \( \{Z_k(t) : k \in K\} \). Specifically, when selecting the target demand model as the gasoline allocation model, the cumulative sales volume corresponding to the target demand coefficient parameters \( (n_0, r^*) \) is defined as \( \{S_k(r^*; n_0, r^*) : k \in K\} \). Then, the set of cumulative sales volume and actual sales in the same time period \( (n_0, r^*) \) that minimizes the residual sum of squares with \( Z_k(\tau) \) are selected as the best estimated values. This equation is formulated as follows:

\[ (n_0^*, r^*) = \arg \min_{(n_0, r^*) \in [0.1]} \sum_{k \in K} \left( S_k(r^*; n_0, r^*) - Z_k(r^*) \right)^2. \]

We obtain \( S_k(r^*; n_0, r^*) \) by the following equation that minimizes the residual sum of squares with \( Z_k(\tau) \) as the best estimated value for the smoothing parameter \( \theta \):

\[ \theta^* = \arg \min_{\theta \in [0, \infty)} \sum_{k \in K} \left( S_k(r^*; \theta) - Z_k(r^*) \right)^2. \]

---

**11** Sendai City was broken down to five wards of Aoba, Miyagino, Wakabashishi, Taihaku, and Izumi.
by \( N_j \), and the population by prefecture is expressed as \( N_k := \sum_{i \in B_k} N_j \).

In what follows, we will describe the method for using these data to determine 1) the time \( r^* \) when the demand-supply gap was resolved throughout the Tohoku region, which was used to estimate the rate of disappearance, 2) the actual sales \( \{Z_k(t^*)\} \) for each prefecture, which was used to estimate allocation parameters, 3) the rate of supply \( \{w_i(t)\} \) at each oil terminal, which was an input for the estimation model for sales volume by municipality, and 4) the rate of potential demand \( \{r_j(t)\} \) in each municipality.

a) Time when the demand-supply gap was resolved throughout the Tohoku region

In this analysis, April 4, 2011 (\( r^* = 25 \)) was considered as the time when the demand-supply gap was resolved throughout the Tohoku region. It was based on the following two observations found in a report:\(^3\) on waiting lines at gasoline stations:

- Lines were formed every day until April 3;
- Except in some areas that suffered damage from the tsunami, lines had temporarily cleared as of April 4.

This time period was also determined comprehensively from the results of a sensitivity analysis employing a model involving the time of resolution.

b) Actual sales by prefecture and the analysis period

In this analysis, the period between March 12 (\( t = 1 \)), the day after the earthquake, and March 31 (\( t = 20 \)) was selected as the period for comparison of actual sales by prefecture with cumulative sales volume. Here, upon estimating actual sales \( Z_k(t^*) \) in prefecture \( k \), the following two assumptions were set in place: a) actual daily gasoline sales were equal to actual monthly sales divided by the number of days in the given month, and b) the actual sales of oil from March 1 to the day of the earthquake, March 11, were equal to the actual sales in the same period in 2010. Based on these assumptions, the best estimated value for the actual sales \( Z_k \) in prefecture \( k \) was calculated as follows:

\[
Z_k(20) = Z_k^{2011,3} \frac{11}{31} Z_k^{2010,3}, \quad \forall k \in K.
\] (18)

c) Rate of supply at each oil terminal

For the harbor-type oil terminals (i.e., Aomori, Hachinohe, Akita, Sakata, and Sendai-Shiogama), the amount of oil transported daily into a given oil terminal in a given time \( w_i^{2010}(t) \) is used without modifications as the rate of supply \( w_i(t) \) at oil terminal \( i \in O \) at time \( t \in T \):

\[
w_i(t) = w_i^{2010}(t), \quad \forall i \in O, \forall t \in T.
\] (19)

The rate of supply at the Morioka oil terminal was calculated based on Sakasai’s data on the annual amount transported by railway to Iwate Prefecture in normal times (fiscal year 2010), the actual amount of gasoline transported into Morioka by railway after the earthquake (between March 18 and April 19, 2011), and the actual operation of diverted trains (length of freight train per day).

Thus, the amount of cumulative supply at the terminal \( i \) between the initial time \( t = 1 \) to the end of any given time \( \tau \in T \) is expressed as follows:

\[
W_i(\tau) = \sum_{t=1}^{\tau} w_i(t), \quad \forall i \in O, \forall \tau \in T. \quad (20)
\]

d) Rate of potential demand in each municipality

The rate of potential demand \( r_j(t) \) in municipality \( j \) as of time \( t \) is estimated in the following way. First, the actual gasoline sales at prefecture \( k \in K \) in March and April 2010 (i.e., the year prior to the earthquake) converted into daily sales (prorated by the number of days in the month) are defined as \( z_k^{2010,3} = Z_k^{2010,3} / 30 \) and \( z_k^{2010,4} = Z_k^{2010,4} / 31 \). Next, each municipality \( j \in D_k \) included in the given prefecture apportioned based on the population of the given municipality (i.e., multiplied by \( N_j/N_k \)) is used for the rate of gross potential demand at the time corresponding to each given month:

\[
r_j(t) = \begin{cases} 
 z_k^{2010,3} N_j/N_k & t = 1, \ldots, 20, \\
 z_k^{2010,4} N_j/N_k & t = 21, \ldots, 35, \\
 \end{cases} \quad \forall j \in D_k, \forall k \in K. \quad (21)
\]

Note that the sum of actual sales estimated for the applicable period, \( \sum_{k \in K} Z_k(20) \), is greater than the sum of cumulative supply during the same period (i.e., March 12, 2011 to March 31, 2011), \( \sum_{i \in O} W_i(20) \). Presumably, this gap \( \sum_{k \in K} Z_k(20) - \sum_{i \in O} W_i(20) \) is the sales volume of gasoline already in stock at gas stations and oil terminals on March 11, 2011; that is, the day when the earthquake occurred. It is probably reasonable to think that after the earthquake, these inventories were sold and consumed within the municipality where those gas stations are located. Since there were no data on the amount of inventory each municipality had, this analysis used the total amount of inventory \( \delta \) apportioned based on the population of each municipality \( j \in J \) as the initial gasoline inventory in the given municipality:

\[
\delta_j = \left( \sum_{k \in K} Z_k(20) - \sum_{i \in O} W_i(20) \right) \frac{N_j}{N}, \quad \forall j \in J. \quad (22)
\]

where \( N := \sum_{k \in K} N_k \) is the total population in the Tohoku region.

We assume that municipality \( j \in D \) first consumes this (estimated) initial inventory \( \delta_j \) starting at the beginning of time \( t = 1 \), the day after the earthquake, and subsequently consumes gasoline allocated from oil terminals once the initial inventory runs out. To
put it differently, the demand for gasoline is offset by the amount of inventory consumption until the inventory is exhausted. If we define the time when the inventory is depleted in municipality \( j \in D \) as \( \{ \tau_j^* : \delta_j \in (\hat{R}_j(\tau^*_j - 1), \hat{R}_j(\tau^*_j)] \} \), then the rate of (net) potential demand after offsetting the amount of inventory consumption will be calculated as:

\[
 r_j(t) = \begin{cases} 
 0 & 1 \leq t \leq \tau_j^*, \\
 \hat{R}_j(\tau^*_j) - \delta_j & t = \tau_j^*, \\
 \hat{r}_j(t) & \tau_j^* < t.
\end{cases} 
\]

(2) Results of parameter estimation

First, by assigning the time when the demand-supply gap throughout the Tohoku region was resolved, \( \tau^* = 25 \) (as given in Section 8.1 a)) to the estimation model for the rate of disappearance (14), the best estimated value was calculated as \( \beta^* = 0.130 \).

Next, solving the allocation parameter estimation models (16) and (17) by using the rate of disappearance \( \beta^* \) and the actual sales by prefecture \( Z_k(20) \) (which is given in Section 8.1 b)) led to the best estimated values \( (n^*_0, r^*_a) = (0.16, 23) \) and \( \theta^* = 44.0 \).

Table 4 shows the estimated cumulative sales volume and actual sales by prefecture calculated under each model. The last row in Table 4 shows the deviation of the estimated cumulative sales from the actual sales for all prefectures (discrepancy rate: \( \sum_k |S_k - Z_k|/\sum_k Z_k \)). This table indicates that the target demand model fits actual sales better than the entropy model. In particular, the entropy model resulted in overestimating the sales volume in Miyagi Prefecture and Akita Prefecture, while underestimating the sales volume in Yamagata Prefecture. It appears that the model overestimated the amount of gasoline transferred from the Sea of Japan side to the Pacific Ocean side.

Because the above-described model parameters were estimated based on limited data, it would be too simplistic to systematically judge the quality of these models. Therefore, the spatiotemporal analyses of demand-supply gap in the following sections will use the target demand model and entropy model according to the purpose of each analysis. Specifically, the target demand model — the one with a smaller discrepancy rate — is first used in the time-series analysis of the demand-supply gap tabulated by prefecture in Section 8.3. However, when looking at the municipality level, a spatial unit smaller than a prefecture, the target demand model sometimes results in extremely skewed allocations. For example, although the demand-supply gap is completely resolved in one of its neighboring towns, a certain town does not receive any gasoline allocation \(^\text{12}\). This is because this model does not explicitly consider the disparities of demand-supply gap among municipalities. This type of skewed allocation is not only non-intuitive, but is also inconsistent with word-of-mouth information such as “gogo.gs” discussed later. Therefore, the spatial distribution analysis on the demand-supply gap at the municipality level in Section 8.4 will use the results obtained by the entropy model, which have less skewed demand-supply gaps among municipalities.

(3) Changes in demand-supply gap per prefecture

This section uses cumulative charts of potential demand, actual demand, and sales volume of each municipality to analyze the changes in the demand-supply gap over a period of time. First, the cumulative potential demand in municipality \( j \in D \) between time \( t = 1 \) and the end of time \( \tau \in T \) is expressed as follows:

\[
 R_j(\tau) = \sum_{i=1}^{\tau} r_j(i) \Delta t, \quad \forall \tau \in T, \forall j \in D \tag{24}
\]

When the rate of disappearance \( \beta \) is given, the demand that disappeared (i.e., disappeared cumulative demand) from time \( t = 1 \) to the end of time \( \tau \in T \) in municipality \( j \in D \) will be expressed as:

\[
 E_j(\tau) := \beta \sum_{i=1}^{\tau} X_j^D(t-1) \Delta t, \quad \forall \tau \in T, \forall j \in D \tag{25}
\]

The difference between the cumulative potential demand \( R_j(\tau) \) through time \( \tau \in T \) in municipality \( j \in D \) and the disappeared cumulative demand \( E_j(\tau) \) during the same time period is called “cumulative actual demand in the given municipality” (i.e., through the point of time \( \tau \)) and is shown as follows:

\[
 Q_j(\tau) = R_j(\tau) - E_j(\tau) = \sum_{i=1}^{\tau} \left[ r_j(t) - \beta X_j^D(t-1) \right] \Delta t \tag{26}
\]

\(^{12}\) Refer to Fig. A2 listed in the Appendix for the detailed allocation results at the municipality level calculated by the target demand model.
The demand-supply gap in municipality $j \in D$ at time $t$ is then expressed by the difference between the cumulative actual demand and cumulative sales volume, or $Q_j(t) - S_j(t)$.

The cumulative potential demand, cumulative actual demand, and cumulative sales volume by municipality obtained this way are aggregated for each prefecture $k \in K$ and shown in Fig. 13. It has to be noted that the entropy model used April 4 ($\beta = 0.130$) as the date when cleared backlog demand was used for estimating the sales volume. The dotted line, thick solid line, and thin solid line in each chart indicate the cumulative amount of potential demand, actual demand, and sales volume, respectively. Using cumulative charts allows visualization of the backlog demand (the difference between actual demand and sales volume) and the demand that disappeared owing to gasoline shortage (the difference between potential demand and actual demand) in each prefecture at each point of time. The following two points can be seen from Fig. 13. First, there are regional differences in terms of the time when the demand-supply gap was resolved. While the gap was resolved within about two weeks after the earthquake in Aomori and Akita on the Sea of Japan side, it was not resolved until the third week in Miyagi and Iwate on the Pacific Ocean side and in Yamagata, which has only the smaller oil terminals. Second, the demand that disappeared (the difference between the potential and actual demand) increases as the demand-supply gap increases. In particular, the sales volume was overwhelmingly insufficient relative to the demand in Miyagi Prefecture, indicating a serious disappearance of the demand (i.e., inhibited economic activity). Lastly, even in Akita and Aomori, where the queueing demand cleared relatively quickly, the amount of supply was not at a level that could have covered the demand in the same period in the previous year, and disappearing demand could be observed. This discrepancy was probably because some of the gasoline transported from the ports of Akita and Aomori were transferred to Iwate, Miyagi, and Yamagata to an extent that could not cause disruption.

(4) Spatial distribution of the demand-supply gap per municipality

The spatial distribution of the demand-supply gap calculated per municipality and its trend are shown in Fig. 14. This figure shows six separate time points,
$t = 4, 7, 11, 14, 18, 21$, by color-coding each municipality based on the rate of supply (cumulative sales per unit cumulative actual demand), or $S_j(t)/Q_j(t)$, at each given time. A greater rate of supply indicates a smaller demand-supply gap. First of all, this figure demonstrates that the demand-supply gap in the areas along the Pacific Ocean was not resolved easily. In particular, gasoline was not distributed sufficiently even three weeks after the earthquake (i.e., when the demand-supply gap was basically resolved in most areas) in some of the coastal areas in Miyagi and Iwate. Secondly, we can see that the demand-supply gap was greater in the eastern and southern regions compared to the western and northern regions, respectively, at any given point of time. Both these results are consistent with the information posted on the word-of-mouth website “gogo.gs” as shown in Fig. 15.

It is possible that since the shipping planners could not secure a supply route to the Pacific Ocean side in the early stages after the earthquake, the above-described spatially skewed demand-supply gap of gasoline was caused. While the supply systems were restored gradually from the oil terminals on the Sea of Japan side (the west and north sides), land transportation to the Pacific Ocean side (the east and south sides) was limited. Presumably, it led backlog demand to accumulate, causing the prolonged gasoline shortages in these areas$^{13}$. To improve the gasoline shortage in the Pacific Ocean, there arose the need for preparatory and emergency measures that would guarantee the supply capacity by enabling the transfer of gasoline, immediately after the disaster, from the west to the east and the north to the south.

$^{13}$ We have already seen in Chapter 6 that the gasoline demand comparable to 6.4 days under normal circumstances and its corresponding social and economic activities were lost owing to this prolonged shortage of gasoline.
9. CONCLUSION

This paper reviewed the conditions of supply facilities of petroleum products during regular operations and immediately after the Great East Japan Earthquake and then quantitatively assessed the supply system to the Tohoku region at the time of the disaster by using data on petroleum product shipments and sales. The results confirmed that the oil shortage in the Tohoku region at the time of the Great East Japan Earthquake was due to insufficient supply. Furthermore, the analysis that utilized a gasoline allocation model demonstrated that the shortage in the Tohoku region was spatially skewed by area; in particular, the oil shortage in Miyagi Prefecture persisted until the four weeks after the earthquake.

As to tasks that lie ahead, the first would be to review logistical strategies that could improve the supply situation in light of the supply facility constraints observed during this disaster. Then, as measures for large-scale disasters in the future, it is also important to consider conducting an analysis that combines the post-disaster transport logistics strategy (including stockpiling facilities for petroleum products) and facility reinforcement plan with designing systems such as the government aid scheme for oil companies operating at the time of disaster.
ACKNOWLEDGEMENTS: We are deeply grateful to the Tohoku Regional Bureau of Ministry of Land, Infrastructure, Transport and Tourism (MLIT) and port managers of Aomori, Hachinohe, Akita, Sakata and Sendai-Shiogama, for making the port inbound shipment data available. For the port outbound data, we would like to thank the Hokkaido Regional Development Bureau and the Regional Bureaus of Kanto, Chubu, Kinki, Chugoku and Shikoku of MLIT, port managers of Muroran, Tomakomai, Chiba, Kawasaki, Yokohama, Nagoya, Yokkaichi, Wakayama-Shimotsu, Sakai-Izumikita, Imabari, Sakaide, Mizushima, Iwakuni, Tokuyama-Shimomatsu and Ube, as well as JX Nippon Oil & Energy, Idemitsu Kosan Co. Ltd., Kyokuto Petroleum Industries, Ltd., COSMO Oil Co. Ltd., Seibu Oil Co. Ltd., Taiyo Oil Company, Limited., Toa Oil Co. Ltd., Tonen General Sekiyu K. K., and Fuji Oil Co. Ltd.. We appreciate the comments on appropriate use of data offered by the Transport Research and Statistics Office of MLIT. Our deepest gratitude goes to Makoto Mizutani (Deputy Head of Reconstruction Agency) and Hajime Inamura (Professor at Tohoku Institute of Technology) for their invaluable support in collecting port inbound and outbound data. We also thank Takuya Maruyama (Associate Professor at Kumamoto University) and Ryo Inoue (Associate Professor at Tohoku University) for generously helping us with the GIS aspect of the present research.

APPENDIX

Table A1 shows the origin-destination (OD) pattern of gasoline shipment one month before and after the earthquake. The origins are areas of refineries as shown in Fig. 1 (Hokkaido, Kanto, Tokai and West Japan) and the destinations are oil terminal ports in the Tohoku region (Aomori, Hachinohe, Akita, Sakata, and Sendai-Shiogama). Fig. A1 illustrates changes in share as a percentage of total gasoline shipments to Tohoku between one month before and after the earthquake.

Fig. A2 shows the spatial distribution of the demand-supply gap calculated by the target demand model. We can observe less intuitive distributions, particularly at \( t = 14, 18, 21 \), in which areas at 98+ ~ 100% and 0% in the rate of supply lay side-by-side.

![Fig. A2](image-url) 

### Table A1

<table>
<thead>
<tr>
<th>Origin</th>
<th>Aomori</th>
<th>Hachinohe</th>
<th>Akita</th>
<th>Sakata</th>
<th>Sendai-Shiogama</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hokkaido</td>
<td>before</td>
<td>21.7</td>
<td>17.6</td>
<td>26.6</td>
<td>13.9</td>
<td>4.4</td>
</tr>
<tr>
<td></td>
<td>after</td>
<td>25</td>
<td>9.3</td>
<td>45.8</td>
<td>18</td>
<td>33.6</td>
</tr>
<tr>
<td>Kanto</td>
<td>before</td>
<td>22.6</td>
<td>30.0</td>
<td>15.4</td>
<td>1.7</td>
<td>74.9</td>
</tr>
<tr>
<td></td>
<td>after</td>
<td>19.7</td>
<td>2.6</td>
<td>10.1</td>
<td>0.0</td>
<td>20.2</td>
</tr>
<tr>
<td>Tokai</td>
<td>before</td>
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<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>after</td>
<td>1.7</td>
<td>4.5</td>
<td>0.0</td>
<td>0.0</td>
<td>8.3</td>
</tr>
<tr>
<td>W. Japan</td>
<td>before</td>
<td>3.7</td>
<td>0.0</td>
<td>2.8</td>
<td>0.0</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>after</td>
<td>3.4</td>
<td>0.0</td>
<td>15.6</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Others</td>
<td>before</td>
<td>3.8</td>
<td>6.2</td>
<td>0.0</td>
<td>2.4</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>after</td>
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<td>0.0</td>
<td>0.0</td>
<td>0.6</td>
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</tr>
<tr>
<td>Total</td>
<td>before</td>
<td>51.8</td>
<td>53.8</td>
<td>44.8</td>
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<td>89</td>
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<tr>
<td></td>
<td>after</td>
<td>50.6</td>
<td>16.4</td>
<td>71.5</td>
<td>18.6</td>
<td>62.1</td>
</tr>
</tbody>
</table>

![Table A1](image-url)
Fig. A2 Spatial distribution of demand-supply gap per municipality (estimated by the target demand model).
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