Post-Disaster Gasoline Distribution Strategies to Reduce Social-Economic Losses: Lessons from the Great Eastern Japan Earthquake

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Abstract

In the Great East Japan Earthquake on 11th March, 2011, the Tohoku region was faced with serious gasoline shortages for an extended period due to the severe damage on its only oil refinery and the major oil terminals on the Pacific coast by the earthquake and subsequent tsunami. Such gasoline shortages not only hampered relief and restoration efforts, but also dampened socio-economic activities in the entire Tohoku region. In this study, using actual data, we first clarify that the fundamental reason for the gasoline shortage was the failure in adjusting the amount and shipping patterns of gasoline in response to the spatial changes in the production areas caused by the disaster. We then show that the gasoline shortage could have been reduced considerably by some post-disaster gasoline distribution strategies to redirect a certain amount of gasoline into the Tohoku region from other unaffected areas. Finally, we estimate the cost required to execute such a gasoline distribution strategy as well as its economic effect, demonstrating that although the cost is only 300 million yen, the benefit amounts to over 200 billion yen.

Keywords: the Great East Japan Earthquake, gasoline shortage, spatio-temporal analyses, demand-supply gap, gasoline logistics, post-disaster measures

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1. Introduction

After the Great East Japan Earthquake on March 11, 2011, the Tohoku region was faced with serious gasoline shortages for an extended period. Many gas stations ran dry and closed for

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business. A few gas stations that remained operational had waiting lines that extended several kilometers. The gasoline shortages also spread to the region facing the Sea of Japan, where oil terminals were spared from direct earthquake and tsunami damage. This situation continued for over a month, and many gasoline users were unable to obtain enough supply during this time. As a result, relief and restoration efforts were considerably hampered, and socio-economic activities in the entire Tohoku region were dampened. In particular, the gasoline shortages directly reduced labor opportunities, because the percentage of workers who commute by car is high in the Tohoku region. This study clarifies that the extent of the economic loss was tremendous.

Using a quantitative analysis based on the following facts observed in the available data, we demonstrated that the main cause of the gasoline shortages was from the supply-side, especially due to the failure of the gasoline shipping strategy. 1) Gasoline sales in the Tohoku region in March declined approximately 30% compared to the previous year. In particular, March gasoline sales in Miyagi Prefecture located on the Pacific coast declined to half the volume of the previous March. Explaining gasoline shortages of this magnitude caused only by (local and temporary) panic and hoarding behavior is impossible. 2) The only oil refinery in the Tohoku region and the oil terminals on the Pacific coast stopped functioning and became unavailable for an extended period due to the earthquake and subsequent tsunami. As a result, the Tohoku region was forced to rely on gasoline supply shipped from other, unaffected areas. 3) However, the actual amount of gasoline shipped during the first month after the earthquake was insufficient from the standpoint of producing and receiving capacities. Among the port facilities in the Tohoku region, the ones on the coast of the Japan Sea were not directly affected by the earthquake and tsunami; therefore, their capacity to receive shipments must have been restored to normal levels within a few days after the earthquake. Nevertheless, when the amount of gasoline shipped into the ports on the Japan Sea coast from other areas during the first month after the earthquake is compared to the amount shipped in before the earthquake, the increase was approximately only 27×10^3 kL. This is merely a day's worth in terms of idle daily capacity (i.e., the amount of unutilized gasoline production capacity per day) in the unaffected area and only 1.17 days' worth in terms of daily capacity to receive shipments (i.e., the largest amount of gasoline accepted in a day after the earthquake) at the Japan Sea coastal ports. These facts suggest that the gasoline shortages (and subsequent economic loss) became serious and persistent because gasoline was not shipped in large quantities into the Tohoku region from other areas.

It is natural to believe that the reason for unfulfilled regional gasoline shipments lies in the measures executed by the Japanese government after the earthquake, which can be summarized as follows. First, the Japanese government urged consumers to refrain from purchasing nonessential gasoline. However, because the gasoline shortages were caused mainly by reduced supply rather than increased demand as described above, this measure was not a direct solution for gasoline shortages. Second, the Japanese government was entirely focused on addressing the gasoline shortages locally. Specifically, in order to resolve local gasoline shortages in each municipality along the Pacific coast that has been devastated by the tsunami, the government provided meticulous support based on individual requests. However, in terms of support to the whole region, the government only announced that "it would redirect 20×10^3 kL of gasoline *per day* to the Tohoku region from Western Japan" without clarifying the specific method of distribution, which was left to voluntary actions of private companies. In the end, only 27×10^3 kL of gasoline was redirected to Tohoku *per month*, as previously mentioned. Third, the Japanese government regarded the persistent gasoline demand as flow and focused only on the volume of shipments and sales per day, which can be seen from the government reports claiming that gasoline shortages have been resolved. Specifically, the government said that the daily sales volume of gasoline reached 98% of its historical average on the release dated March 25, 2 weeks after the earthquake. However, as described later, this was an overstated claim that could hamper the understanding of the extent of the gasoline shortages and the formulation of related solutions.

In total, the Japanese government was entirely focused on a bottom-up, local and microscopic style of support. However, in order to execute national-scale gasoline shipments in large quantities to a broad area immediately after an earthquake, a top-down approach is essential. First, increasing the supply of gasoline rather than suppress the demand for gasoline should be the top priority. Suppressing demand limits households from engaging in economic activities (e.g., by limiting car commuting) and possibly increases the opportunity loss, especially when increased demand is not the cause of the gasoline shortage. Second, the emphasis should be on global measures rather than on local ones. Specifically, to strengthen the supply system at the macro-level, it is critical to devise concrete solutions that cover the entire affected region rather than responding to individual requests from each municipality. Third, the government should recognize unmet demand as stock and implement measures that consider the characteristics of stock. This is because the unmet demand for gasoline (or at least a portion of it) is stock that carries over to the following day and not flow that is reset daily. In order to carry out the national-scale gasoline shipment by utilizing these types of top-down measures, it is essential: (i) to understand the full extent of the gasoline shortages that occurred after the Great East Japan Earthquake; and (ii) to quantitatively analyze to what extent the gasoline shortages could have been feasibly reduced by such national-scale gasoline shipment.

This study thus examines whether if or not such a national scale gasoline shipment strategy could mitigate the gasoline shortages and consequent economic losses in the Tohoku region. More specifically, we first estimate latent demand for gasoline in each municipality and the capacity to accept inbound shipments at each port, using data on gasoline distributed in the Tohoku region before and after the earthquake. Based on this estimation, we propose feasible gasoline shipment strategies, each of which is to increase the amount of gasoline shipped into the Japan Sea coastal ports (by redirecting supply from other areas) for a certain duration, as soon as these ports resume operating. In order to analyze the gap between gasoline supply and demand under these gasoline shipment strategies, we then propose a method that utilize cumulative curves to represent unmet demand as stock. Subsequently, changes in the demand-supply gap caused by the increases in the amount of gasoline shipped into the Japan Sea coastal ports is quantitatively evaluated, using a model introduced by Akamatsu et al. (2013) that estimates the time-space distribution of unmet demand. Finally, using these results, we estimate the economic effects gained by mitigating the gasoline shortages (i.e., the reduction in the economic losses) and the additional costs required for increased land transportation of gasoline. These estimations clarify that the economic effect reach hundreds of billions of yen, although the additional cost required to transport a large quantity of gasoline overland at an earlier stage is only hundreds of millions of yen.

The remainder of this paper is organized as follows: Section 2 provides an overview of the extent to which the gasoline supply system in the Tohoku region was compromised because of the Great East Japan Earthquake and then describes the data used in the subsequent analysis. Based on this data, Section 3 explains the growth in the size of the gap between the gasoline supply and demand in the Tohoku region after the earthquake. In the next three sections, we estimate the extent to which an appropriate shipping strategy improves the gap between gasoline supply and demand and, in turn, the extent to which an improved demand-supply gap would have reduced the economic loss. Specifically, an estimation model is formulated in Section 4. Section

5 describes the method for analyzing the shipping strategies. Finally, Section 6 estimates the effects and costs of each shipping strategy. Section 7 presents concluding remarks. This study takes the position of fully using existing infrastructure (e.g., the capacity of oil terminals and road networks), because optimizing the contingent operation is necessary to address the situation that arises after a disaster before the long-term implementation of advanced measures, such as increasing gasoline storage facilities and earthquake-proofing key roads, is an option.

2. Background

2.1. Outline of Fuel Transportation in Japan

We briefly explain the supply flow of petroleum products in Japan. First, crude oil is refined in a refinery to create petroleum products. The supply flow from refineries to retailers such as gas stations can be roughly grouped into two patterns. In the first pattern, tanker trucks deliver products directly to gas stations and other retailers from the refinery. In the second pattern, products travel through shipping hubs called oil terminals. In this scenario, the products are transported to oil terminals from refineries mainly using tank ships. However, railroad tankers are used when oil terminals are located inland, and tanker trucks are then used to ship the products from oil terminals to gas stations.

2.2. Damage to Japan's refineries

The locations of refineries in Japan can be divided into five areas, as shown in Figure 1. Among these areas, many refineries are concentrated in western Japan and the Kanto region. In addition, there is only one refinery, Sendai Refinery, in the Tohoku region.

The damage sustained by oil refineries as a result of the Great East Japan Earthquake can be briefly summarized as follows. First, the Sendai refinery, the only refinery in the Tohoku region, was damaged, and its operation was suspended for an extended period. Otherwise, throughout Japan, five refineries in the Kanto region suspended their operation because of the disaster. However, three out of those five sites resumed their operation within a few days after the earthquake, because their damage was minimal. Ultimately, a total of three refineries in the Tohoku and Kanto regions, accounting for approximately 13% of the total crude oil processing capacity in Japan, were forced to suspend their operation over a long period because of the disaster.

Based on the damage situation previously described, the long-term refinery capacity loss was limited and the refineries affected by the disaster were not the root cause of the petroleum product

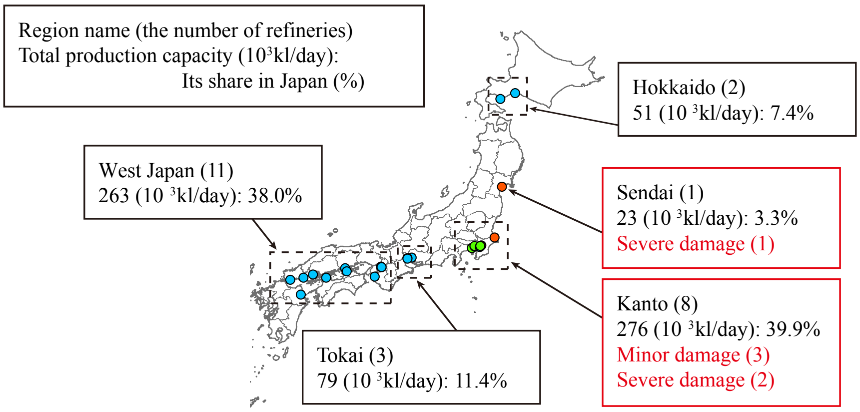

Figure 1: Refineries in Japan and their damage. Blue: no damage, green: minor damage, red: severe damage

shortages. Prior to the earthquake, Japan had excess refining capacities because of declining demand for petroleum products resulting from energy conservation and alternative energy usage, and the capacity utilization rate had been below 80% in the prior years6,7. Thus, Japan would have been able to address the affected refineries and secure petroleum products by increasing the capacity utilization rate at the unaffected refineries. Presumably, the fundamental reason for the oil shortage after the Great East Japan Earthquake was the lack of changes in the amount and shipping patterns of oil in response to the spatial changes in the production areas caused by the disaster.

2.3. Damage to major oil terminals in Tohoku

Under typical circumstances, gas stations and other retailers in the Tohoku region receive direct supply of petroleum products by tanker trucks from Sendai Refinery or receive supply from other areas via oil terminals in the Tohoku region. The locations of the main oil terminals in the Tohoku region are shown in Figure 2. Oil terminals are often located in ports, where they can receive petroleum products from refineries by ship. Regarding oil terminals that are located inland such as P-5 and P-2, petroleum products are shipped from refineries in other areas using railroads. Because direct supply from a refinery became unavailable in the Tohoku region after the earthquake because of the damage at Sendai Refinery, all necessary petroleum products had to be transported from refineries in other areas.

The damage to the oil terminals in the Tohoku region caused by the Great East Japan Earthquake is summarized as follows. Figure 2 shows that according to the date inbound shipments

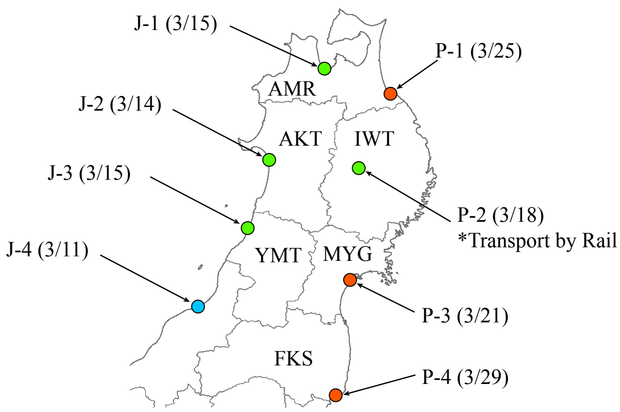

Figure 2: Major oil terminals in Tohoku region and their resumption date. Blue: no damage, green: resumed within a week, red: resumed later. AMR: Aomori, AKT: Akita, IWT: Iwate, YMT: Yamagata, MYG: Miyagi, FKS: Fukushima.

were resumed, every oil terminal except for J-4 in the Tohoku region became temporarily unable to receive petroleum products after the earthquake. During this period, transporting products from Niigata and other areas using tanker trucks was the only option. However, given the capacity constraints and the number of tanker trucks4, assuming they were able to transport a limited amount is natural. Oil terminals J-1, J-2, and J-3, which were adjacent to a Japan Sea coastal port, resumed inbound shipments in 3 to 4 days after the earthquake. Because of the damage, at least 10 days were required to resume inbound shipments for the oil terminals adjacent to ports on the Pacific coast, such as P-1, P-3, and P-4. In other words, there was a period in which the only means of supplying petroleum products to the Pacific coast was to forward them from Japan Sea coastal oil terminals.

2.4. Available Data

In Section 3, we use sales and shipping data on petroleum products to understand the shipping situations and the gap between supply and demand. First, the petroleum product sales data indicate the amount of petroleum products sold each month to consumers at gas stations and other retailers by prefecture, which is a section of the natural resources and energy statistics Ministry of Economy and Industry (2011) compiled by the Ministry of Economy, Trade, and Industry (METI). Next, the petroleum product shipping data indicate detailed origin–destination transportation by ship. This data indicate the date, volume, and classes of petroleum products shipped by oil tankers to the ports in the Tohoku region from refineries in other areas.

In this paper, we define gasoline—a fuel for transportation and general household use—as

Table 1: Sales volume of gasoline in March: Comparison between 2010 and 2011 (10^3kL)

	Aomori	Iwate	Miyagi	Yamagata	Akita	Total
[A] 2010	36	37	81	32	29	214
[B] 2011	33	27	39	28	23	150
[B]/[A](%)	90	72	48	87	82	70

a class of petroleum products for analysis. In addition, we analyze five Tohoku prefectures excluding Fukushima (Aomori, Iwate, Miyagi, Akita, and Yamagata). Fukushima Prefecture is excluded because many people traveled because of the impact of the nuclear accident, and estimating the demand for gasoline in that area after the earthquake is difficult.

3. Demand-Supply Gaps of Gasoline in Tohoku Region after The Earthquake

3.1. Volume of Gasoline Sales in the Tohoku Region

We first examine the impact of the Great East Japan Earthquake by comparing March 2011 sales of gasoline 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. From Table 1, it can be observed that March sales volumes were down in all five prefectures following the earthquake. Total sales of gasoline throughout the Tohoku region had fallen to approximately 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.

In explaining the dramatic decrease in sales volumes, it may be possible 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 suppose 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: Sales volume = Supply volume < 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 3.2 and 3.3.

3.2. *Volume of Gasoline Shipments to the Tohoku Region*

We then examine the pattern of shipments of gasoline from oil refineries nationwide to oil terminals in the Tohoku region following the earthquake by using port outbound and inbound shipment data. In addition, it examines how that pattern changed over time.

3.2.1. *Volume of outbound shipments from ports in other regions*

Table 2 lists the volumes of outbound shipments of gasoline from refineries (ports) in other regions to the Tohoku region within a month before and after the earthquake. The table indicates that the volume and patterns of outbound shipments of gasoline significantly changed after the earthquake. First, shipments of gasoline 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. This can be attributed to the severe damage sustained by oil refineries on the Pacific coast in the Kanto region. 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 to some degree 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 other regions was relatively small. This implies the surprising fact that the press conference convened by METI on March 17, 2011 and the subsequent press release issued by METI were totally inconsistent with the actual situation: the Ministry announced that approximately 20,000 kL per day of gasoline and related products, which covers the majority of the amount required in the Tohoku region, would be shipped to the Tohoku region from oil refineries in Western Japan; however, as Table 2 illustrates, the volumes of gasoline shipped from Western Japan in the month following the earthquake was less than one-tenth of that stated in the government's announcement. This fact apparently indicates that there were coordination failures between METI and the private oil companies that actually undertook the gasoline shipment plan.

Changes in outbound shipment volumes over time can be seen from Figure 3, which shows the weekly volumes of outbound gasoline shipments from the country's oil refineries to oil terminals in the Tohoku region during the five-week period following the earthquake. First, it is evident from Figure 3 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. Only 20% of the normal weekly demand (red dashed line in the figure) was shipped in the

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

	Hokkaido	Kanto	Tokai	West Japan	Others	Total
Before	84	145	7	9	12	257
After	132	53	15	19	1	219
Increase	48	−92	8	10	−11	−38

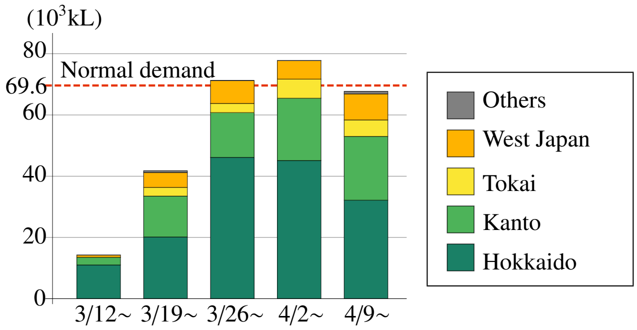

Figure 3: Changes in weekly volume of outbound gasoline shipments from ports in other regions following the earthquake.

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 we have seen in Table 2, the volume of outbound shipments in the first month following the earthquake declined significantly from standard levels before its incidence.

3.2.2. Volume of inbound shipments to ports in the Tohoku region

Table 3 compares the volumes of inbound shipments at each oil terminal in the Tohoku region during the month before and after the earthquake. First, they illustrate that the volume of inbound shipments sharply dropped at ports P-1 and P-3 on the Pacific Ocean that had been damaged by the tsunami. In the month before the earthquake, these two ports accounted for approximately half of the volume of inbound shipments of gasoline products to the Tohoku region, while in the month after the earthquake, they accounted for only about one-fifth of the total. Second, the

Table 3: Comparison of inbound shipment volumes of gasoline to ports in the Tohoku Region one month before and after the earthquake (10^3kL)

	J–1 (Aomori)	J–2 (Akita)	J–3 (Sakata)	P–1 (Hachinohe)	P–3 (Sendai-Shiogama)	Total
Before	52	45	18	54	89	257
After	51	72	19	16	62	219
Increase	−1	27	1	−38	−27	−38

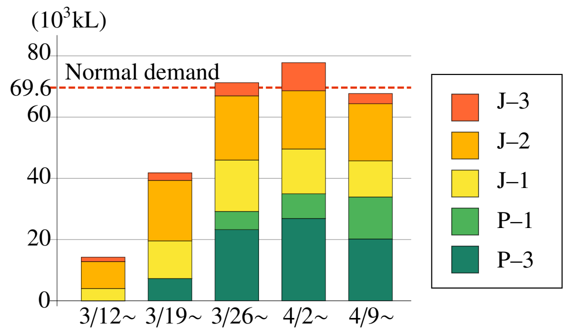

Figure 4: Changes in weekly volume of inbound gasoline shipments to the Tohoku Region following the earthquake.

volume of inbound shipments of gasoline increased at ports J-1, J-2 and J-3 on the Japan Sea. However, these increases were insufficient to compensate for the deficit at the ports on the Pacific Ocean. Third, at the port P-3 (Sendai-Shiogama), where inbound shipments were interrupted for approximately ten days after the earthquake, shipments of gasoline significantly decreased.

Figure 4 shows the weekly volume of inbound gasoline shipments received at oil terminals in the Tohoku region during the five-week period following the earthquake. We see from this figure that the Pacific ports of P-1 and P-3 were barely usable in the two weeks following the earthquake, and only the ports of J-1, J-2 and J-3 on the Sea of Japan were operational. In particular, the port of J-2 (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 P-1 and P-3 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 gasoline to the entire Tohoku region remained insufficient until the Pacific ports of P-1 and P-3 had been fully restored and made operational.

It is worthwhile to note here that care must be exercised when Figure 4 (or Figure 3) is employed to determine when the oil shortage in the Tohoku region was resolved. Figure 4 (or Figure 3) shows 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 this stage, which could not be satisfied in the first and second weeks, had been deferred (i.e., "standby demand" remained). Although supply in the third week following the earthquake could match the demand arising from newly emergent economic flows in that week, the quantities were insufficient to satisfy standby demand. This point will be discussed in detail in the following section 3.3.

3.3. Aggregate Demand–Supply Gap in the Tohoku Region

This section analyzes the volume of gasoline stocks released, the demand–supply gap, and unrealized demand aggregated in the Tohoku region as a whole (by combining sales and transport data for gasoline). This analysis, based on the cumulative curves, demonstrates why oil shortages continued for almost a month after the earthquake.

To analyze the extent to which demand was met throughout the Tohoku region following the earthquake, we define "demand" and "supply" as follows. 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, and its cumulative amount is defined 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 volume of stock releases for the Tohoku region as a whole may be estimated from the following identity:

$$\text{Cumulative sales volume} = \text{cumulative volume of inbound shipments} \quad (1)$$
$$+ \text{ volume of stock releases.} \quad (2)$$

The left-hand side of the equation (i.e., the cumulative sales volume) can be calculated from sales volumes in March following the earthquake (i.e., the sum of the sales volumes per prefecture shown in Table 1). Since the cumulative volume of inbound shipments on the right hand side of the equation also can be calculated from the data for gasoline transported (i.e., the data shown in Figure 4), we obtain the volume of stock releases. This results in stock releases of approximately 14 (10^3) kL for the Tohoku region from the day immediately after the earthquake until March 31,

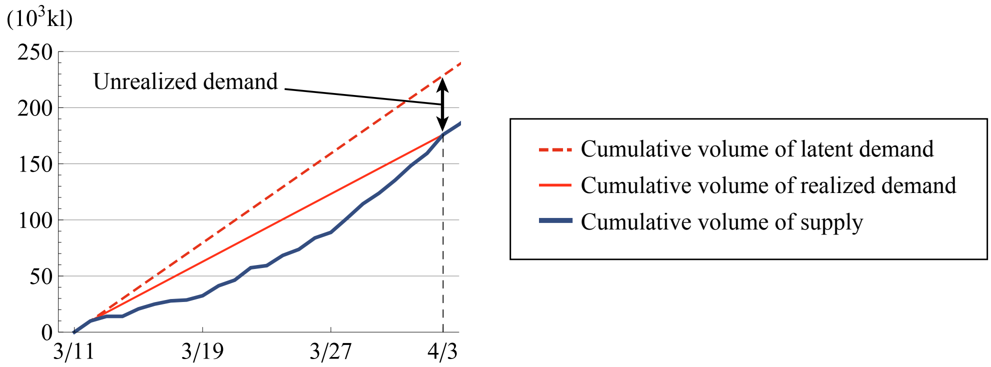

Figure 5: Cumulative demand and unrealized demand for gasoline

2011. Converted to actual sales per day in a normal period (March, 2010), this was approximately 1.4 days' worth of stock releases. Thus, the volume of supply in the Tohoku region was assumed to be the volume of inbound shipments to its oil terminals plus 1.4 days' worth of stock releases in the following analysis.

Based on the estimates of demand and supply thus obtained, we analyze the difference between them ("demand–supply gap"). Figure 5 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 5 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.13). 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 realized demand (solid red line) is included in Figure 5. The assumption, in this case, is that supply shortages were resolved by April 3, 2011 and daily demand was normalized. In this case, the volume of demand prior to the elimination of supply shortages was approximately 66%

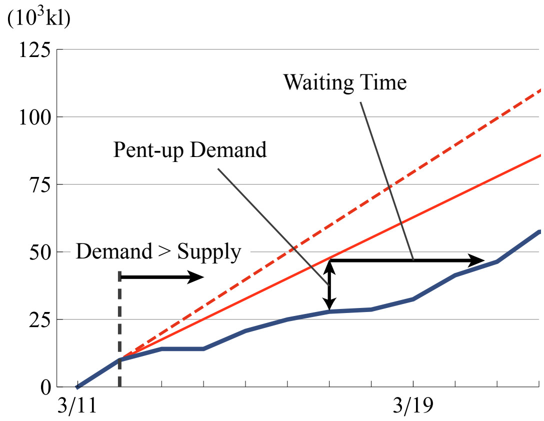

Figure 6: Change in pent-up demand (waiting lines)

of the volume of latent demand, and the difference between the cumulative volumes of realized demand and latent demand is the volume of unrealized demand, which was approximately 64 (10^3kL) when supply shortages are considered to have been resolved (April 3, 2011). Converted to the volume of latent daily demand, this is approximately 6.4 days' worth. 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.

Figure 6 focuses on a part of the period covered in Figure 5 (March 11–20). It examines the gap between the cumulative volumes of demand and supply. Specifically, the vertical distance between the cumulative demand and supply curves represents the volume of pent-up demand (waiting lines), while the horizontal distance indicates the waiting time needed to purchase gasoline. 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 3.2, 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 (Figure 5). This is fundamentally why there were protracted shortages of gasoline throughout the Tohoku region.

As the above analysis demonstrates, the measure essential to relieving the shortage of gasoline in the Tohoku region was to ease supply constraints to the maximum possible degree. 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 gasoline should have been arranged to reduce accumulated pent-up demand once inbound shipments resumed at the port of P-3 (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 gasoline would not have occurred.

It is worthwhile to note the actual measures that were taken by the government and the Petroleum Association of Japan. For more than a month after the earthquake, they pursued public relations activities in the Tohoku region, imploring consumers to refrain from "non-essential and non-urgent purchases of gasoline." As the analysis in this section demonstrates, however, the demand revealed 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 gasoline, instead of providing an adequate level of supply, can be considered as having a high risk of curbing necessary economic activity. That is, this policy aggravated the massive economic loss caused by the inhibition of social and economic activity due to vanishing demand.

4. The Model for Estimating Time-Space Distribution of Demand-Supply Gap

In this section, we provide an overview of the Akamatsu et al. (2013) model, which describes the development of the gap between demand and supply in each municipality at a discrete point in time. This model is composed of two sub-models: an inter-temporal demand dynamics model and a spatial distribution (supply) model. The first model describes how the unmet demand in each municipality changes over each point in time. The second model describes how the gasoline brought into each oil terminal is distributed to each municipality within a given time (i.e., the supply flow to each municipality at a given point in time).

Setting the day of the earthquake (March 11) as $t = 0$ and the point in time when the gasoline demand and supply returned to normal as T, we consider a set of discrete periods in increments of 1 day, such that $T := \{1, 2, \cdots, \mathrm{T}\}$. The set of oil terminals (the origin) and the set of municipalities (the destination) within the analysis areas are represented by O and D, respectively.

Within this framework, the inter-temporal dynamics of unmet demand across time is written as the following difference equation, where the unmet demand at the end of time $t \in T$ in municipality $j \in D$ is expressed as $X_j(t)$:

$$X_j(t) = (1 - \beta\Delta t)X_j(t-1) + \left\{r_j(t) - s_j(t)\right\}\Delta t, \quad t = 1, 2, \cdots, \mathrm{T}. \quad X_j(0) = 0. \tag{3}$$

Here, $r_j(t)$ is latent demand for gasoline per unit of time, and $s_j(t)$ is the amount of gasoline supplied per unit of time. β is a constant that represents the reduction rate of unmet demand for each point in time, called the disappearance rate. In equation (3), $\{r_j(t) : t \in T\}$ is a model input, and β is a parameter, which are separately estimated using the method described in the next section. $\{s_j(t) : t \in T\}$ is an endogenous variable determined using the spatial distribution (supply) model described later.

The spatial distribution (supply) model describes the allocation of the gasoline brought into each oil terminal in the Tohoku region to each municipality (i.e., the supply flow in each municipality in a given time). The amount of gasoline brought into oil terminal $i \in O$ per unit of time as of time $t \in T$ (i.e., the amount gasoline available to be supplied) is denoted by $p_i(t)$. Revealed gasoline demand per unit of time in municipality $j \in D$ at time t is denoted as $q_i(t)$ and defined as the sum of: a) the unmet demand at the beginning of time t (i.e., the unmet demand at time $t-1$ minus the reduced demand) converted into the unit of flow and b) the latent demand flow that surfaces in a given time:

$$q_j(t) := \frac{1 - \beta\Delta t}{\Delta t} X_j(t-1) + r_j(t)$$

The cost required to transport one unit of gasoline from oil terminal $i \in O$ to municipality $j \in D$ is denoted as a constant $c_{i,j}$, and the amount of gasoline transported per unit of time between this origin and destination pair in time $t \in T$ is denoted as $x_{i,j}(t)$. We assume that the amount of transported gasoline $\boldsymbol{x}(t) := \{x_{i,j}(t) : (i, j) \in O \times D\}$ and the unmet demand at the end of the period $\boldsymbol{X}(t) := \{X_j(t) : j \in D\}$ are determined to minimize the total shipping costs while smoothing the disparity in the demand-supply gap among municipalities. This is formulated as the following convex programming problem:

$$[\text{P}] \quad \min_{\boldsymbol{x}(t)} \left\{ \sum_{i,j} c_{i,j} x_{i,j}(t) + \theta f[\boldsymbol{x}(t), \boldsymbol{X}(t)] \,\middle|\, \begin{array}{ll} \sum_{j \in D} x_{i,j}(t) = p_i(t) & \forall i \in O, \\ \sum_{i \in O} x_{i,j}(t) \leq q_j(t) & \forall j \in D, \\ x_{i,j}(t) \geq 0 & \forall (i,j) \in O \times D \end{array} \right\}$$

The first term of the objective function in this problem represents the total shipping cost. In the second term, $f[\boldsymbol{x}(t), \boldsymbol{X}(t)]$ is a convex function representing the smoothness of the demand-supply at time t. The given constant θ, which represents the importance of smoothing the function, is called the smoothing parameter. The first constraint condition is that the amount of gasoline shipped from each oil terminal matches the amount of gasoline supply, and the second constraint condition is that the amount of gasoline transported to each municipality does not exceed the demand. Using the gasoline shipping flow $\boldsymbol{x}(t)$ at time t, the gasoline supply flow to municipality j in a given time can be written as follows:

$$s_j(t) := \sum_{i \in O} x_{i,j}(t)$$

The relationship between these two sub-models is summarized in Figure 7. The figure shows how unmet demand in municipality $j \in D$ are determined during the period between $t-1$ and t. First, we assume that the unmet demand $X_j(t-1)$ at the end of time $t-1$ is a given condition. Furthermore, $(1 - \beta\Delta t)X_j(t-1)$ is demand carried over to the beginning of time t, which is added to the new latent demand in time t, $r_j(t)\Delta t$, as the revealed demand in time t, denoted as $q(t)\Delta t$. The gasoline supply flow (sales) to each municipality in time t, $\boldsymbol{s}(t) := \{s_j(t) : j \in D\}$, is determined based on the spatial distribution (supply) model that includes the revealed demand flow $\boldsymbol{q}(t) := \{q_j(t) : j \in D\}$ and shipped-in gasoline flow $\boldsymbol{p}(t) := \{p_i(t) : i \in O\}$ as given conditions. Finally, revealed demand minus the amount of gasoline supply obtained during time t (i.e., resolved demand), $s_j(t)\Delta t$, becomes unmet demand $X_j(t)$ at the end of time t.

Using the described model and calculating the sequences $(\boldsymbol{q}(0), \boldsymbol{s}(0)), (\boldsymbol{q}(1), \boldsymbol{s}(1)), \cdots, (\boldsymbol{q}(\text{T}), \boldsymbol{s}(\text{T}))$ for the revealed demand for gasoline and the supply flow in each municipality, a cumulative chart of gasoline supply and demand in each municipality can be created. First, the sequences of revealed demand and supply flow can be solved using the following steps.

Step 0 : Set the unmet demand in all municipalities $j \in D$ on the day of the earthquake as $X_j(0) = 0$. Set the time as $t := 1$.

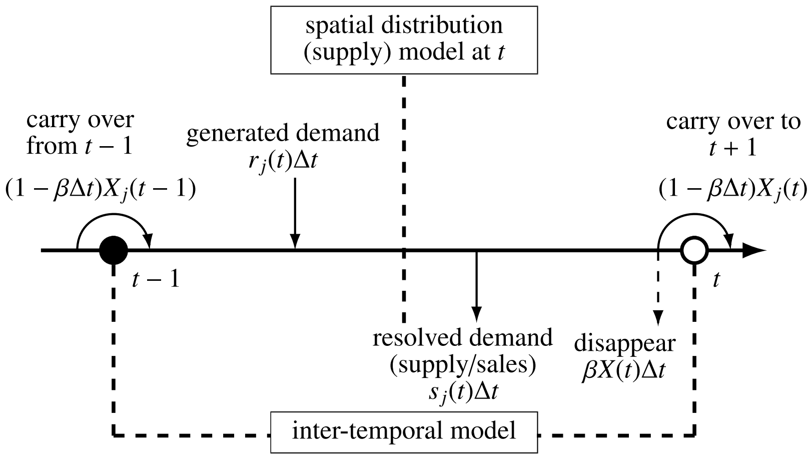

Figure 7: Relationship between the inter-temporal demand dynamics and the spatial distribution model

Step 1 : Using $X_j(t-1)$, that is, the unmet demand at the end of time $t-1$, and $r_j(t)$, that is, the new latent demand in time t, as given conditions, set the revealed demand flow in time t as

$$q_j(t) := \frac{1-\beta\Delta t}{\Delta t} X_j(t-1) + r_j(t)$$

Step 2 : Using revealed demand $\boldsymbol{q}(t)$ in each municipality, the volume of supply $\boldsymbol{p}(t)$ at each oil terminal, and the cost of transportation $\{c_{i,j}\}$ as given conditions, solve the problem [P] for transported gasoline flow $\boldsymbol{x}(t)$.

Step 3 : Define the gasoline sales flow in municipality j in time t as

$$s_j(t) := \sum_{i \in O} x_{i,j}(t)$$

and the unmet demand at the end of time t as $X_j(t) := \left\{q_j(t) - s_j(t)\right\} \Delta t$.

Step 4 : Terminate if $t = \mathrm{T}$. Otherwise, return to Step 1 and set the time to $t := t+1$. Using the sequences of latent demand flow $r_j(t)$, revealed demand flow $q_j(t)$, and supply flow $s_j(t)$ for municipality $j \in D$, each of cumulative latent demand $R_j(t)$, cumulative revealed demand $Q_j(t)$, and cumulative supply $S_j(t)$ can be solved as follows:

$$R_j(t) := \sum_{\tau=0}^{t} r_j(\tau)\Delta t, \qquad Q_j(t) := \sum_{\tau=0}^{t} q_j(\tau)\Delta t, \qquad S_j(t) := \sum_{\tau=0}^{t} s_j(\tau)\Delta t$$

5. Procedures for Analyzing Distribution Strategies

In this section, we describe the procedure for using the model from the previous section to analyze the change in the demand-supply gap in each municipality under a given shipping strategy. Section 5.1 shows the procedure for estimating the extent of the gasoline shortages that occurred after the Great East Earthquake as a base case. From the facts found in the base case analyses, Section 5.2 proposed two feasible national-scale gasoline shipment strategies as well as procedures to analyze to what extent the gasoline shortages could have been reduced.

5.1. Base Case

The actual state of gasoline allocation under the shipping strategy that was executed is used as the base case. This base case is derived as follows: First, we estimate the dataset and parameters required as the model inputs. This procedure can be written as follows: 1) Estimate the transportation cost per unit of gasoline $c_{i,j}$ based on the shortest distance from each oil terminal to each municipality measured using a Geographical Information System (GIS). 2) Estimate $r_j(t)$, the demand flow in each municipality in time t, based on pre-earthquake monthly sales volume by prefecture between March and April 2010. 3) Estimate $p_i(t)$, the volume of supply in each oil terminal during time t, based on the daily volume of gasoline brought into each port between March and April 2011. 4) Estimate the disappearance rate as $\beta = 0.106$ based on the date when the gasoline shortages throughout the Tohoku region were considered resolved (April 3, according to Akamatsu et al. (2013). 5) Estimate the smoothing parameter as $\theta = 20.56$ to minimize the disparity between the monthly sales in March 2011 by prefecture, Z_k, and the sales volume $S_k := \sum_{t\in\tau}\sum_{j\in D_k} s_j(t)$ in each prefecture $k \in K$ during the corresponding time period τ. Here, K is the set of prefectures in the Tohoku region and D_k is the set of municipalities in prefecture k.

Next, use the model inputs $\{c_{ij}\}$, $\{r_j(t)\}$, $\{p_i(t)\}$ and the model parameters β and θ obtained thus far and assign them to the model from the previous section in order to calculate the cumulative revealed demand $\{Q_j(t)\}$ and the cumulative supply $\{S_j(t)\}$ in each municipality.

Using these, calculate the demand-supply gap in each municipality at each point in time or $\left\{S_j(t)\middle/Q_j(t)\right\}$, the ratio of cumulative supply to cumulative revealed demand up to each point in time.

5.2. Distribution Strategies

The daily volume of gasoline shipped into the Japan Sea coastal ports (J1, J2, and J3) estimated in the base case is tabulated and shown in Figure 8. In this figure, the following three points are observed: 1) The volume of gasoline shipped into the ports on the coast of the Japan Sea largely varies by day, 2) the shipments resumed on March 15, 4 days after the earthquake (point A in the figure), and 3) 23,314 (kL), or 1.93 times the normal volume of gasoline (i.e., the average volume in the month prior to the earthquake) was brought into the region at that time. Based on these facts, the following are assumed in our analysis: It was possible to successively ship a total of 23,314 (kL) gasoline (equivalent to the amount of gasoline shipped into the three Japan Sea coastal ports on March 15, when $t = 4$) into the three Japan Sea coastal ports after March 15 ($t = 4$) and allocate it to the municipalities in the Tohoku region.

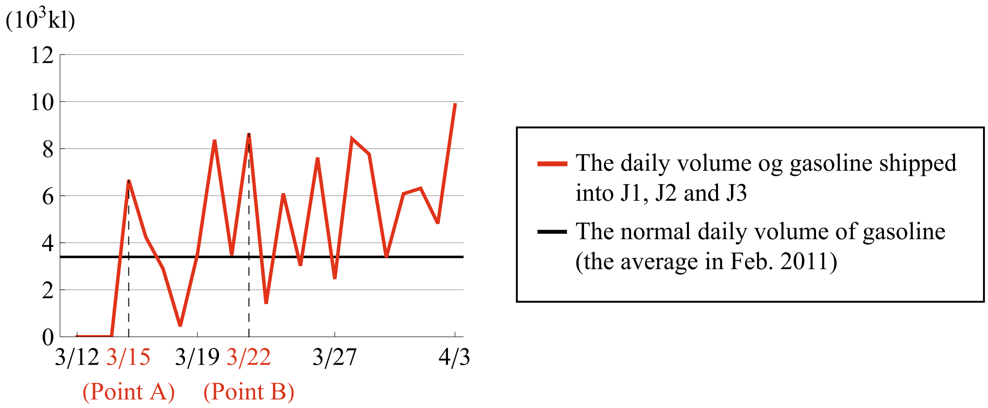

Figure 8: The ship-in volume of J1, J2 and J3 after the earthquake

The validity of this assumption is supported by the following three observations: First, the daily capacity for accepting shipments at these three ports is larger than the amount brought in on March 15. Second, the lead-time at oil terminals is sufficiently short for the terminals to accept in succession the amount shipped into these three ports on March 15. Finally, as mentioned in Section 1, the refinery capacity in the areas not directly affected by the earthquake including western Japan was sufficient. On the basis of this assumption, we propose the two following strategies for eliminating the gasoline shortages at an early stage:

Proposed Strategies

Strategy S (short): Assuming the same amount of gasoline as that brought in on March 15

($t = 4$) and successively shipping it to the three Japan Sea coastal ports daily for 7 days from March 15 ($t = 4$) to March 22 ($t = 11; \mathcal{T}_S := \{4, 5, \cdots, 11\}$).

Strategy L (long): Assuming the same amount of gasoline as that brought in on March 15 ($t = 4$) and successively shipping it into the three Japan Sea coastal ports daily for the 14 days from March 15 ($t = 4$) to March 29 ($t = 18; \mathcal{T}_L := \{4, 5, \cdots, 18\}$).

In the following discussion, $\mathcal{T}_S$ and $\mathcal{T}_L$ are referred to as the operational period. We estimate the demand-supply gap under Strategies S and L using the procedure used in the base case. In doing so, the values used in the base case are identical for the disappearance rate β, smoothing parameter θ, and the amount shipped to each port $\{p_i(t)\}$ during the non-operational period. For the amount shipped into the three Japan Sea coastal ports $O_J = \{J1, J2, J3\}$ during the operational period, the amount shipped into those ports on March 15, $\{p_i(t = 11) : i \in O_J\}$, is used.

6. Analyses of Distribution Strategies

In this section, we estimate the economic effect as well as the additional shipping cost required under the proposed distribution strategies —Strategies S and L—, following the procedure described in the previous section. The economic effects are defined as the economic loss that can be reduced in comparison to the base case under the strategies. First, in Section 6.1, the effect of each distribution strategy on the demand-supply gap for the entire Tohoku region is analyzed. Next, in Section 6.2, the change in the demand-supply gap in each municipality created by each distribution strategy is quantified and the total necessary shipping time is calculated. While the former is used and latter is converged, the economic effect of each strategy and the additional cost of shipping is estimated in Section 6.3. Here, we demonstrate that the cost is only in hundreds of million yen, while the economic effect is in the order of hundreds of billion yen.

6.1. Changes in the Aggregated Demand-Supply Gap in the Entire Tohoku Region

Using the method described in Section 3.3, the effects of the distribution strategies S and L on the demand-supply gap for the entire Tohoku region are analyzed. Figure 9 shows the cumulative curves of gasoline demand and supply for the entire Tohoku region for the base case and for the cases achieved using Strategies S and L. The red dotted line, red solid line, and blue solid line in each diagram indicate cumulative latent demand $R(t) := \sum_{j \in D} R_j(t)$, cumulative revealed demand $Q(t) := \sum_{j \in D} Q_j(t)$, and cumulative supply $S(t) := \sum_{j \in D} S_j(t)$, respectively.

Figure 9 reveal the effect of Strategies S and L on improving gasoline shortage from the following three viewpoints: (1) reduced pent-up demand in each point in time, (2) early elimination of the demand-supply gap, and (3) reduced unrealized demand. First, we compare the pent-up demand $X(t) = R(t) - S(t)$ under each strategy to that in the base case. Figure 9 shows that a distribution strategy can further reduce pent-up demand at all points in time in comparison to the base case. Secondly, this difference has a significant impact on time τ, the point at which the gasoline shortages are resolved; $Q(\tau) = S(\tau)$. Specifically, although the gasoline shortages continued until April 3 in the base case and until April 2 under Strategy S, Strategy L reduces the time required to resolve gasoline shortages to March 27. Lastly, in order to evaluate the economic effects of such reduced pent-up demand and early resolution of the gasoline shortages, we compare $U(\tau) = R(\tau) - Q(\tau)$, that is, unrealized demand through the end of the analysis period. In the base case, 53,803 (kL) of gasoline demand disappeared. In contrast, the unrealized demand under Strategies S and L are 26,954 (kL) and 15,605 (kL), respectively. In other words, we can see that unrealized demand can be reduced from one-half to one-third by implementing either Strategy S or Strategy L.

Table 4: The volume of unrealized demand and the date when supply shortage are resolved

	Base Case	Strategy-S	Strategy-L
The volume of unrealized demand	53,803 (kL) (5.4 days)	26,954 (kL) (2.7 days)	15,605 (kL) (1.6 days)
The date of supply shortage resolved	4/3	4/2	3/27

6.2. Time-Space Distribution of Gasoline Shortage under Each Strategies

In this section, we analyze how the distribution strategies change the demand-supply gap by municipality and then determine the total shipping time required to execute the distribution.

First, we analyze the development of the time-space distribution of the demand-supply gap by using Figures 10 and 11. These maps of municipalities are color-coded based on the supply rate $S_j(t) \big/ Q_j(t)$ at a given time. A higher supply rate indicates a smaller demand-supply gap. Figure 10 compares the demand-supply gap at three points in time in the first 10 days after the earthquake (i.e., March 15, 18, and 22) under Strategies S and L to the demand-supply gap in the base case. Because the amount of gasoline brought in is the same for Strategies S and L during this period, the distribution of the demand-supply gap also matches. The results of the

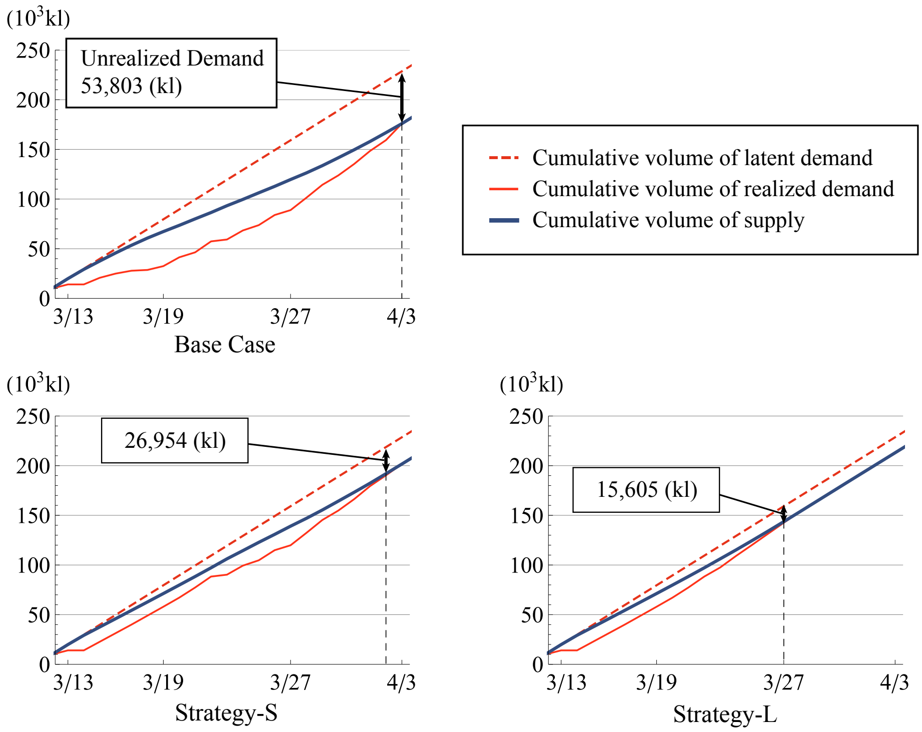

Figure 9: Cumulative latent demand, revealed demand and supply for gasoline under each strategies

base case indicate that (1) there were large scale gasoline shortages in the Pacific Ocean side and (2) although there were gasoline shortages in the regions by the Japan Sea, they were not as serious as those on the Pacific coast. Furthermore, we can see that the proposed strategies S and L- considerably reduced the demand-supply gap in areas on both coasts of the Pacific Ocean and the Japan Sea. Specifically, we see that the demand-supply gap is gradually eliminated eastward as the gasoline brought into the ports on the coast of the Japan Sea is transported longer distances over time.

Figure 11 shows the demand-supply gap at three points in time in the subsequent 10 days (i.e., March 25, March 29, and April 1). The results of the base case show that gasoline was not sufficiently distributed to many municipalities on the Pacific coast as of April 1, 3 weeks after the earthquake. The same is true under Strategy S: There are some municipalities on the Pacific coast where the gasoline is not sufficiently distributed even as of April 1. In contrast, under Strategy L, gasoline is promptly supplied to all municipalities, and the shortages are completely resolved as of March 29.

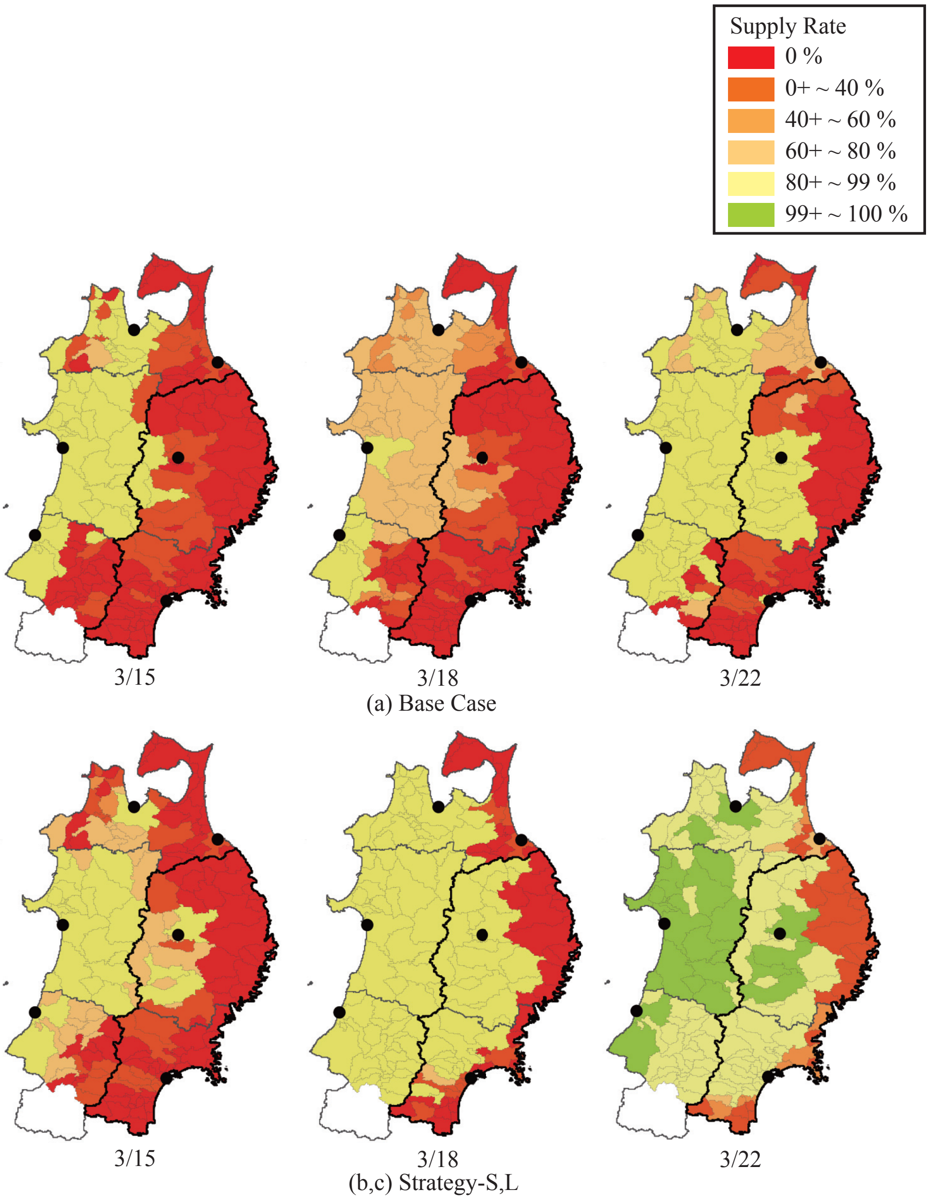

Figure 10: Spatial distribution of demand-supply gap per municipality (3/15, 3/18, 3/22)

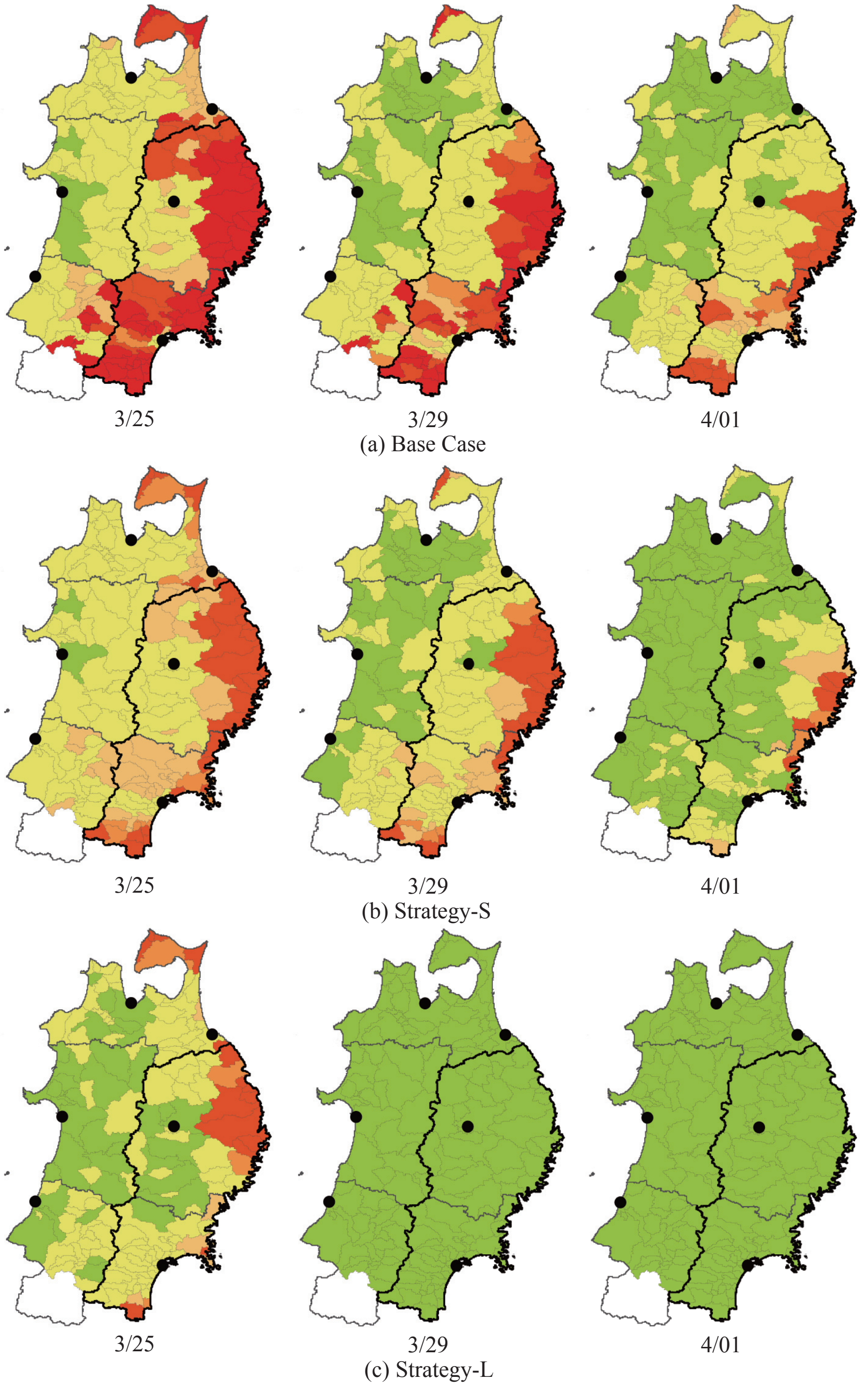

Figure 11: Spatial distribution of demand-supply gap per municipality (3/25, 3/29, 4/1)

Next, Figure 12 examines differences in the effect of national scale gasoline shipment on the elimination of the demand-supply gap between prefectures on the Pacific coast (Iwate and Miyagi) and those on the Japan Sea coast (Aomori, Akita and Yamagata). In the base case, enormous pent-up demand was accumulated in the areas on the Pacific coast, because almost no gasoline was supplied for 1 week after the earthquake. In contrast, although there was a temporary increase in the pent-up demand, it did not significantly accumulate in the areas on the coast of the Japan Sea. Comparing these cumulative curves to the ones under the proposed strategies, we can see that the three effects mentioned in Section 6.1—– (1) reduced pent-up demand, (2) early elimination of the demand-supply gap, and (3) reduced unrealized demand —– are evident in the areas on the Pacific coast.

Figure 13 shows the spatial distribution of unrealized demand by municipality—which has a particularly close relationship with economic loss. Here, the prefectures on the Pacific coast (Iwate and Miyagi) are enclosed with the thick black line. In the base case, the unrealized demand on the Pacific coast 43.5 (10^3kL) is extremely high, which is 81% of the unrealized demand in Tohoku region, 53.9 (10^3kL). This unrealized demand on the Pacific coast is reduced to 21 (10^3kL) under Strategy S and to 12 (10^3kL) under Strategy L, which are one-half and one-fourth of the base case, respectively.

Lastly, the total shipping time required to implement the distribution strategies is calculated. The cumulative total shipping time to accomplish the allocation pattern $\{x_{i,j}(\tau) : \tau \in [0, t]\}$ through time $t \in T$ is defined by the following equation:

$$\Phi(t) = \sum_{\tau=0}^{t} \sum_{i,j} c_{i,j} x_{i,j}(\tau)$$

The total cumulative shipping time in the base case as well as that under each distribution strategy is shown in Figure 14. Clearly, it increases as the amount of gasoline distributed (i.e., the amount of gasoline brought into the ports). Section 6.3 translates the amount of unrealized demand and the total shipping time into yen to conduct cost-benefit analyses on the distribution strategies.

6.3. Cost-Benefit Analyses of Gasoline Distribution Strategies

In this section, we estimate the economic effects gained through the gasoline distribution strategies (i.e., the amount of reduction in the economic loss) and the cost of those strategies. Note that, this analysis doesn't intend to discuss accuracy of the estimation or the novelty and

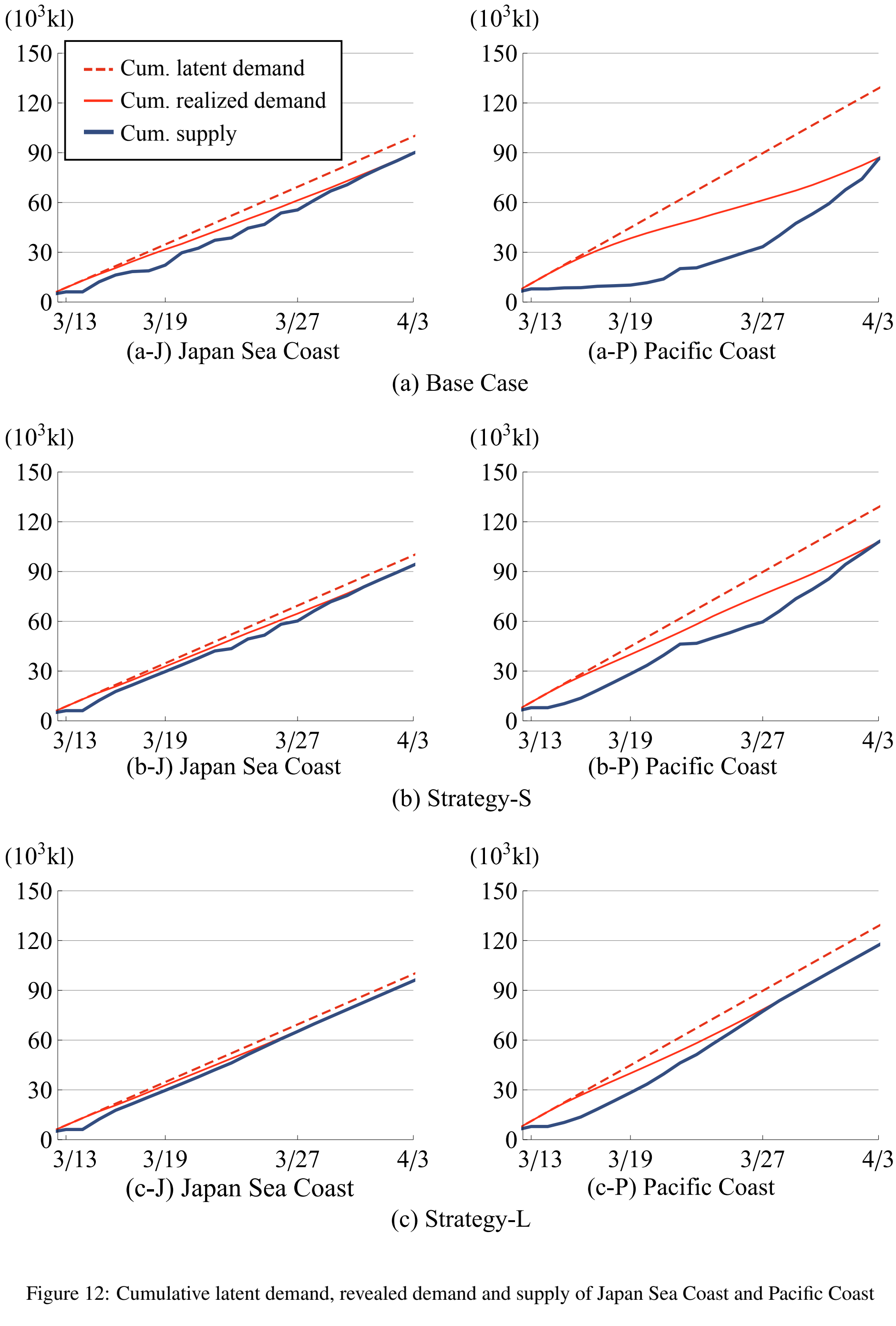

Figure 12: Cumulative latent demand, revealed demand and supply of Japan Sea Coast and Pacific Coast

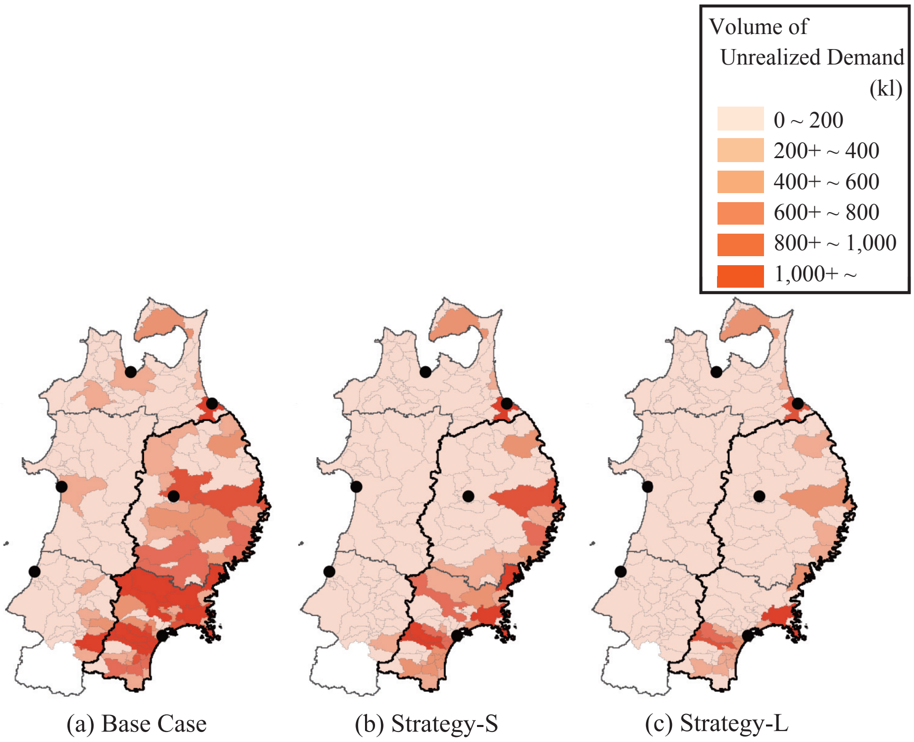

Figure 13: Spatial distribution of unrealized demand

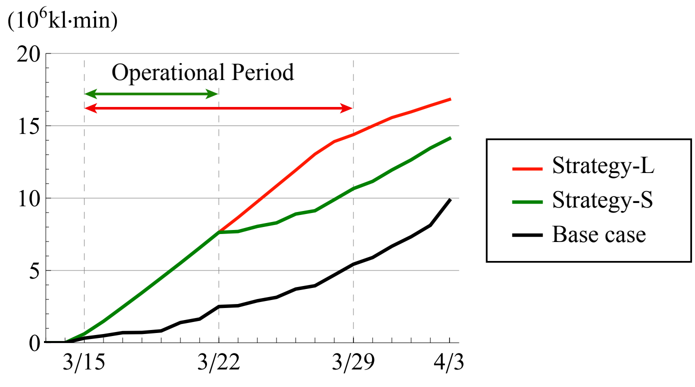

Figure 14: Cumulative shipping time

versatility of the method itself, but to understand the practical order of the economic loss and shipping cost based solely on the available data.

We estimate the economic loss caused by the gasoline shortages from two perspectives, namely the macro and micro perspectives. First, the macroscopic economic loss is defined as a production opportunity loss due to the disappearance of demand, and it is estimated using the unrealized demand calculated in the previous section and the gross regional product (GRP) of the Tohoku region. We assume that the aggregate production function of Tohoku region is linearly homogeneous to its gasoline consumption. In this case, the reduced economic loss from the gasoline shortage amount corresponding to the unrealized demand is calculated using the following equation:

$$\begin{array}{l}\text{Macroscopic Economic}\\\text{Loss (JPY)}\end{array} = \frac{\text{GRP of Tohoku Region (JPY/year)} \times \text{Unrealized Demand (kL)}}{\text{Gasoline Consumption of Tohoku Region (kL/year)}} \quad (4)$$

Because some economic activities do not require gasoline consumption, this estimated amount can be regarded as the upper bound of the actual economic loss.

Next, we define microscopic economic loss as the value of commuting and conducting business that is lost while waiting to purchase gasoline. This can be estimated using the following equation, which uses the pent-up demand calculated in the previous section and the average amount of gasoline purchased by consumers per once.

$$\begin{aligned}\begin{array}{l}\text{Microscopic Economic}\\\text{Loss (JPY)}\end{array} &= \frac{\begin{array}{l}\text{Value of Time}\\\text{(JPY/day} \times \text{person)}\end{array} \times \begin{array}{l}\text{Sum. Pent-up Demand}\\\text{(kL} \times \text{day)}\end{array}}{\text{Gasoline Purchase Per Once (kL/person)}} \\ &= \text{Value of Time (JPY/day} \times \text{person)} \\ &\qquad \times \text{Total Number of Waiting Days (day} \times \text{person)}\end{aligned} \quad (5)$$

Here, the sum of pent-up demand is the area between the cumulative demand and supply curves in Figure 9, which is calculated using the following equation:

$$\sum_{t=0}^{\mathrm{T}} X(t)$$

The total number of waiting days for purchasing gasoline is defined as dividing the sum of pent-up demand divided by the average amount of gasoline purchased per once. In this study, we

[0] Value of time is assumed 3,573 (JPY/day × person), derived from dividing 2010 GRP of Tohoku Region (JPY/year) by 2010 Employed Population (person) and the number of Week Days (day).

assume that the amount of average gasoline purchased is 50 L. Because commuting and conducting business by using gasoline are only some of the economic activities, the economic loss defined in Equation (5) can be considered the lower limit of the actual economic loss. Therefore, the actual economic loss probably lies between the estimated macroscopic (4) and microscopic economic losses (5).

Table 6.3 shows the values of the microscopic and macroscopic economic losses. In the base case and the proposed strategies, the lower bounds are approximately 80% of the upper bound, which seems to be reasonable. Under the base case, the estimated economic loss caused by the gasoline shortages is approximately 290 (lower) to 360 (upper) billion yen [1]. By comparing this and the economic losses of the proposed strategies, we can derive the economic effects of the proposed strategies: that of Strategy S is 145 to 180 billion yen; and that of Strategy L is 206 to 256 billion yen.

Table 5: Economic loss and costs of gasoline distribution strategies

	Base Case	Strategy-S	Strategy-L
Volume of unrealized demand (kL)	53,803	26,954	15,605
Macroscopic economic loss -upper bound- (billion JPY)	-360	-180	-104
Upper economic effect of strategy (billion JPY)	–	+180	+256
Sum. pent up demand (kL × day)	507,580	254,283	147,219
Microscopic economic loss -lower bound- (billion JPY)	-290	-145	-86
Lower economic effect of strategy (billion JPY)	–	+145	+206
Total shipping time for the perood of 3/12 ∼ 4/3 (million kL × min)	9.84	14.12	16.82
Additional shipping cost (billion JPY)	-0.46	-0.65	-0.78
Additional cost for executing strategy (billion JPY)	–	-0.20	-0.32

Lastly, we estimate the additional shipping costs required to execute the strategies and compare the economic effects gained by those strategies. In this paper, we converted the shipping time calculated in Section 6.2 into JPY by assuming that it would cost 200,000 yen to charter an

[1] This range correspond to 3.52 to 4.36 billion dollars (derived by the exchange rate of Feb. 2011, (JPY/USD) 82.498)

average-sized (i.e., 18 kL capacity) tanker truck in Japan for 1 day (8 hours). According to the results showed in Table 6.3, the additional cost for executing Strategies S and L are 0.20 million yen and 0.32 million yen, respectively. As shown in Table 6.3, the benefit-to-cost ratio is far larger than 1. Thus we can conclude that the distribution strategies S and L yield tremendous economic effects relative to the additional required cost.

Table 6: Cost-benefit analyses of each strategies

	Strategy-S	Strategy-L
Economic Effect of strategy (billion JPY)	+145 ~ +180	+206 ~ +256
Cost of Strategy (billion JPY)	-0.20	-0.32

7. Concluding Remarks

In this study, we demonstrated that the long-term regional gasoline shortages occurred after the Great East Japan Earthquake, and that consequent economic loss could have been reduced by an appropriate gasoline distribution strategy. Specifically, we first estimated the time-space distribution of gasoline shortages and demonstrated that the loss of gasoline demand after the Great East Japan Earthquake caused economic losses of approximately 300 billion yen. Second, we demonstrated that this economic loss could have been reduced considerably if the amount of gasoline shipped into the three Japan Sea coastal ports, which were not directly affected by the earthquake and tsunami, had been increased. Specifically, we showed that the economic loss could have been reduced to one-third of the original value if 2.6 times the normal amount of gasoline had been shipped into these three ports successively for a period of 2 weeks after these ports resumed accepting shipments. In addition, we estimated the cost required to execute such a gasoline distribution strategy as well as its economic effect, demonstrating that although the cost is only 300 million yen, the benefit amounts to over 200 billion yen.

Based on the results of this study, we can derive the following policy implications: The loss caused by prolonged gasoline shortages that hamper economic activities is enormous, and quickly resolving such a situation is critical. Therefore, when a catastrophic disaster strikes, it is necessary for the government to promptly predict whether a regional gasoline shortage will occur. Then, when a gasoline shortage is expected, the maximum amount of gasoline that can be accepted to available ports should be shipped as quickly as possible over a certain period (e.g., 1 to 2 weeks).

In order to execute these shipments, the following measures are likely necessary. First, the government should collect and tabulate data on the gasoline demand trend (actual sales) by municipality on a regular basis in preparation for large-scale disasters. Second, once an earthquake occurs, the government should assess the capacity for supplying gasoline within the affected areas, compare it to the gasoline demand, and determine whether there a regional gasoline shortage will exist. Third, when it is determined that a gasoline shortage will occur (i.e., the supply capacity will become insufficient), the government should systematically collect and compile information and formulate specific strategies to ship gasoline from other areas. Finally, the government should secure funds before a disaster occurs and organize a scheme to reimburse private companies that pay the additional expenses necessary to implement the strategy.

In many regional cities in the world, the percentage of workers who commute by car is high as with the Tohoku region that was affected by this disaster. For these regional cities, gasoline is another utility—similar to electricity, gas, and water—required to support socio-economic activities. We demonstrated that it is crucial to specify pre- and post-disaster measures that achieve the appropriate distribution of these goods after a disaster, for a successful *socio-economic activity continuation plan* (SACP).

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