Evaluating Post-Megadisaster Strategies against Region-Wide Gasoline Shortages in the Aftermath of the Great East Japan Earthquake

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Abstract

In the aftermath of the Great East Japan Earthquake on March 11, 2011, the Tohoku region was faced with serious gasoline shortages for an extended period as a result of severe damage to 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 socioeconomic 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 to adjust the amount and shipping patterns of gasoline in response to the disaster-induced spatial changes in the production areas. We then show that the gasoline shortage could have been reduced considerably by post-disaster gasoline distribution strategies to redirect a certain amount of gasoline into the Tohoku region from other, unaffected areas. We also inferred that a traditional price adjustment policy is not suitable for mitigating socioeconomic losses caused by such large-scale disasters. 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 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-megadisaster 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 were closed for business. The 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 sufficient supply in this period. Consequently, relief and restoration efforts were considerably hampered, and socioeconomic 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 enormous.

Using a quantitative analysis that is based on the following facts observed in the available data, we demonstrate that the main cause of the gasoline shortages was on the supply-side, in particular as a result of the failure of the gasoline shipping strategy. The observed facts are as follows: (1) gasoline sales in the Tohoku region in March declined by approximately 30% compared with 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 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 of time owing to the earthquake and subsequent tsunami. Consequently, the Tohoku region was forced to rely on gasoline shipped from other, unaffected areas; and (3) 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 Sea of Japan 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 that was shipped into the ports on the Sea of Japan coast from other areas during the first month after the earthquake is compared with the amount shipped in before the earthquake, the increase was only approximately 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 Sea of Japan's coastal ports. These facts suggest that the gasoline shortage (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 to the gasoline shortages. Second, the Japanese government was entirely focused on addressing the gasoline shortages locally. Specifically, to resolve local gasoline shortages in each municipality along the Pacific coast that had 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 the voluntary actions of private companies. Ultimately, 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, as evidenced by 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, two 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, 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 suppressing 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 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 to: (i) understand the full extent of the gasoline shortages that occurred after the Great East Japan Earthquake; and (ii) quantitatively analyze the extent to which the gasoline shortages could have been feasibly reduced by such national-scale gasoline shipment.

Some readers might think that such gasoline shortages can be resolved by a price control policy—if there are 100 people demanding gasoline, but the supply is only for one person, then the gasoline shortage can be resolved by raising the gasoline price until the first 99 people resign their demand. Such price controls might be effective for resolving a persistent supply shortage in a regular market. Our analyses, however, show that price control was inappropriate to resolve the gasoline shortages in the 34 weeks following the earthquake for the following three reasons. First, a price control policy merely affects the assignment of a limited amount of gasoline and, therefore, is less effective than the countermeasure of increasing the total supply of gasoline. Second, in the aftermath of a disaster, one can expect neither a decentralized (autonomous) price adjustment mechanism of competitive markets nor a centralized price management to meet the demand and supply of gasoline. Finally, although a perfect price that balances gasoline demand and supply could be found, it would not be acceptable from a humanitarian perspective; that is, most of the social benefit realized by such a high price would be received by the gasoline suppliers rather than by the households in the devastated areas.

Therefore, this study examines whether 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 operations. To analyze the gap between gasoline supply and demand under these gasoline shipment strategies, we then propose a method that utilizes cumulative curves to represent unmet demand as stock. Subsequently, changes in the demandsupply gap caused by 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 timespace 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 reaches hundreds of billions of yen, although the additional cost required to transport large volumes 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 by 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 demandsupply 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) since optimizing the contingent operation is necessary to address the situation that arises after a disaster and 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

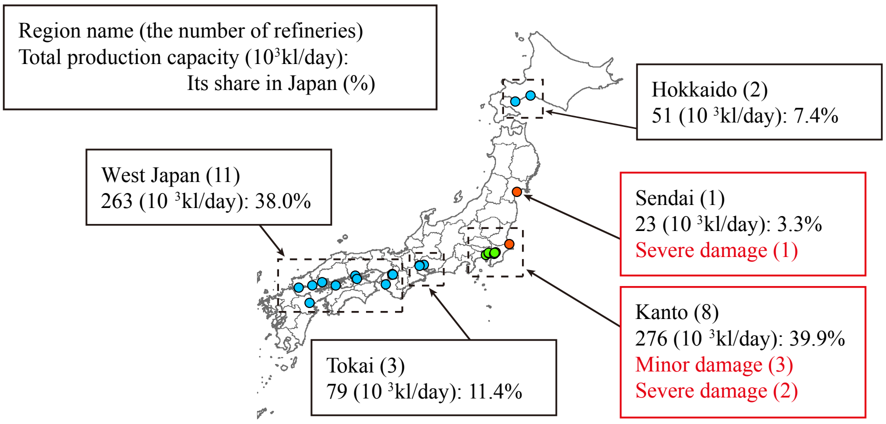


Figure 1: Refineries in Japan and their damage. Blue: no damage, green: minor damage, red: severe damage

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 using mainly 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 suspended for an extended period. Otherwise, throughout Japan, five refineries in the Kanto region suspended their operations owing to the disaster. However, three out of those five sites resumed operations within a few days after the earthquake as 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 operations over a longer period owing to 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

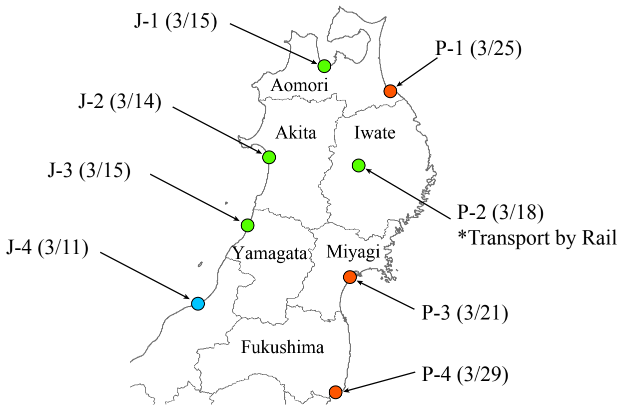


Figure 2: Major oil terminals in the Tohoku region and their resumption dates (month/day). Blue: no damage; green: resumed within a week; red: resumed later.

shortages. Prior to the earthquake, Japan had excess refining capacities owing to the declining demand for petroleum products resulting from energy conservation and alternative energy usage, and the capacity utilization rate had been below 80% in previous years. Thus, Japan would have been able to address the affected refineries and secure petroleum products by increasing the capacity utilization rate at 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 a direct supply of petroleum products by tanker trucks from the Sendai Refinery or receive supplies 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 located inland such as P-5 and P-2, petroleum products are shipped from refineries in other areas by rail. Because direct supply became unavailable in the Tohoku region after the earthquake owing to the damage at Sendai Refinery, all necessary petroleum products had to be transported from refineries in other areas.

The damage to oil terminals in the Tohoku region caused by the Great East Japan Earthquake is summarized as follows. Figure 2 shows that according to the data, inbound shipments were resumed and 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 number of tanker trucks (four), it is assumed they were able to transport a limited amount. Oil terminals J-1, J-2, and J-3, which are adjacent to a Japan Sea coastal port, resumed inbound shipments within 3–4 days following 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 during 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, Trade, and Industry (2011)) compiled by the Ministry of Economy, Trade and Industry (METI). Next, the petroleum product shipping data indicate detailed origindestination 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 a class of petroleum product for analysis. In addition, we analyze five Tohoku prefectures, excluding Fukushima (Aomori, Iwate, Miyagi, Akita, and Yamagata). Fukushima Prefecture is excluded because many people were evacuated owing to the impact of the nuclear accident; thus, estimating the demand for gasoline in that area after the earthquake is difficult.

3. Realized Demand and Supply 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 and [A] denotes estimated sales for the same period in 2010.

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

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 reductions in sales volumes were relatively small in the Akita and Aomori prefectures, which suffered only minor damage to oil terminals and other oil supply facilities. This will be discussed in greater depth in Sections 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 using port outbound and inbound shipment data. In addition, we examine 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 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 Hokkaido, Tokai, and western Japan 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 during 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 first week and approximately 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 is attributable mainly 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 during the first month following the earthquake declined significantly from standard levels from before its incidence.

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

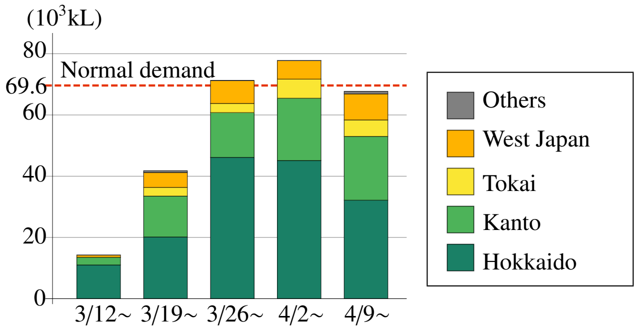


Figure 3: Changes in weekly volume of outbound gasoline shipments from ports in other regions following the earthquake.

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, which had been damaged by the tsunami. In the month before the earthquake, these two ports accounted for approximately half the volume of inbound shipments of gasoline products to the Tohoku region, whereas in the month after the earthquake they accounted for only about one-fifth of the total. Second, the 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 port P-3 (Sendai-Shiogama), where inbound shipments were interrupted for approximately 10 days after the earthquake, shipments of gasoline significantly decreased.

Figure 4 shows the weekly volumes 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 that 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

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

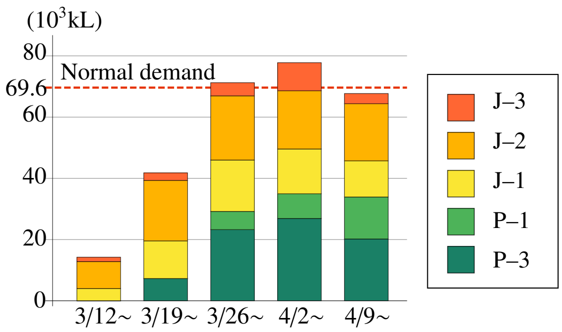


Figure 4: Changes in weekly volume of inbound gasoline shipments to the Tohoku Region following the earthquake.

shipments during the two weeks following the earthquake and, thereby, played 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 Section 4.

4. Reasons for the Prolonged Gasoline Shortage: A Stock-based Analysis

4.1. A Simple Example

Section 3 shows that gasoline supply in the Tohoku region was restored to normal on March 26. However, it took more than one week to resolve the gasoline shortages and households in the Tohoku region (including the authors') suffered severe gasoline shortages until the beginning of April. This stems from the gasoline purchase behavior of households; i.e., each consumer purchased a week's worth of gasoline once per week, rather than a day's worth of gasoline every day. The rest of this subsection presents a simple example for a more detailed explanation.

Suppose 5,000 identical households in a certain area, each of which works every weekday and consumes 2 L gasoline per day and where gasoline is neither supplied nor consumed in the weekend. It is then assumed that 10 kL of gasoline (for 5,000 households) is supplied to this area every day; however, the supply is disrupted for three days (say, from Monday to Wednesday) owing to an earthquake. Let us consider the following two cases according to the gasoline purchase behavior: (a) each household buys 2 L (for one day) gasoline everyday; (b) each household buys 5 L (for five days) gasoline in bulk on the same day of the week (the first 1,000 households purchase every Monday, the second 1,000 households purchase every Tuesday, and so on).

In the former case, there is no time lag between restoration of the gasoline supply and resolution of the shortage: The whole 5,000 households cannot buy gasoline from Monday to Wednesday; thus, the gasoline shortage would be resolved on Thursday, when the gasoline supply is restored.

In the latter case, however, resolution of the gasoline shortage is delayed until four days after the supply is restored as some households should "pent- up" their demand. For the sake of convenience, each group of 1,000 households is labeled as either A, B, C, D, or E, according to the day of the week of gasoline purchase (i.e., households A purchase gasoline every Monday, households B every Tuesday, and so on). On Monday, the first day of gasoline supply disruption, households A cannot purchase gasoline. Each of the remaining households stocks gasoline in their vehicle fuel tank; i.e., households B stock is 2 L (for one day), households C stock is 4 L (for two days), and so on. Table 4 shows the stocks of gasoline for each household each day. On Tuesday, households B run out their stocks and are added to the "wait list" after households A.

Similarly, households C are wait-listed on Wednesday after households A and B. On Thursday, households D are added to the wait list after households C. Since the gasoline supply is restored, 10 kL gasoline (i.e., five days' consumption by 1,000 households) is supplied. We simply suppose that only households A, at the front of the wait list, can purchase gasoline and that each of them purchases 10 L (for five days) in bulk. Households B, C, and D are still wait-listed, and only 2 L (for one day) gasoline is left in each household E's vehicle fuel tank. On Friday, households E are wait-listed after households D, and households B resolve their pent-up gasoline demand. The wait list is gradually reduced on the second Monday and Tuesday, and is completely resolved on the second Thursday and five days after gasoline supply restoration.

Table 4: Dynamics of each household's gasoline stock (kL) in the case that the gasoline shortage necessitates four days to resolve after the restoration of gasoline supply.

	Mon	Tue	Wed	Thu	Fri	Mon	Tue	Wed	Thu
Supply(kL)	0	0	0	10	10	10	10	10	10
A	0	0	0	10	8	6	4	2	10
B	2	0	0	0	10	8	6	4	2
C	4	2	0	0	0	10	8	6	4
D	6	4	2	0	0	0	10	8	6
E	8	6	4	2	0	0	0	10	8
Wait list	A	A,B	A,B,C	B,C,D	C,D,E	D,E	E	-	-

This illustrates that when households purchase gasoline in bulk as a "stock," the pent-up demand gradually accumulates after the disruption of gasoline supply, and gradually resolves after its restoration, causing a delay in the resolution of the shortage. It is necessary, therefore, to use a framework that takes into account the "behavior of gasoline purchase as a stock" and the pent-up demand for analyzing such time lag between the restoration of the gasoline supply and the resolution of the gasoline shortage.

4.2. Cumulative Demand–Supply Analyses

If we apply the above analyses to the Tohoku region after the earthquake, then we have to construct a model that describes households' gasoline purchase behavior as well as collects a sufficiently large and reliable dataset of actual gasoline purchase behavior to calibrate the model. However, to the authors' best knowledge, there is neither a model nor dataset available for the case of the Great East Japan Earthquake. In this section, therefore, we propose a framework that utilizes cumulative demand–supply curves to capture the aggregated pent-up demand of each specific area in the Tohoku region from a macroscopic viewpoint. In this framework, given

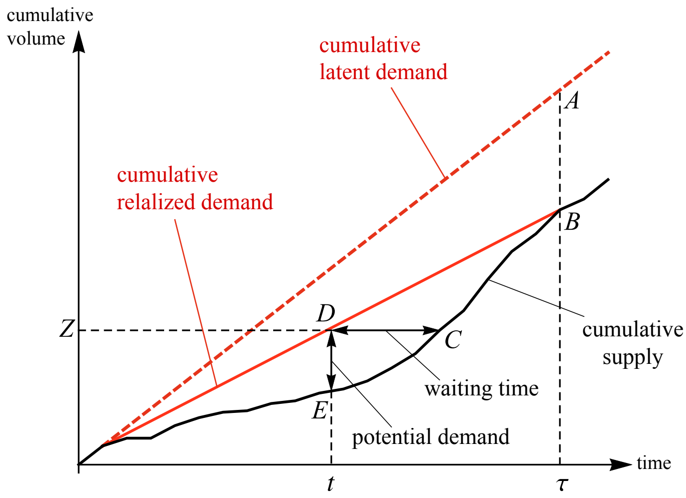


Figure 5: Cumulative curves of the latent demand, the revealed demand and the supply of gasoline.

the latent demand—the amount consumed when supply is adequate—and the actual sales in the target area of each day after the earthquake, we obtain the total unrealized demand and the total waiting time for purchasing gasoline. These values can be used to evaluate the economic impact of prolonged gasoline shortages in the Tohoku region as fully explained in Section 6.

Figure 5 shows the cumulative curves in the proposed framework, where the horizontal axis is time (days after the earthquake) and the vertical axis is cumulative amounts of the gasoline demand and supply. The red dashed line indicates the cumulative latent demand that would possibly be realized in the target area by the date if the earthquake did not occur. The black solid line is the cumulative supply actually realized in the target area by post- earthquake date. Although it seems natural to suppose that the gasoline shortage is resolved when the cumulative supply reaches the cumulative latent demand, it is observed that the gasoline shortage is resolved before these curves are met; that is, gasoline demand-supply became normal around April 3, when the cumulative supply is only 70% of the same date in the previous year. This implies that some households would "give up" their demand if they had a long wait while the rest would remain wait-listed. In other words, a portion of the latent demand is unrealized and the only remaining is realized. We depict the cumulative realized demand by a solid line as shown in Figure 5. The apparent gasoline shortage is resolved when the cumulative gasoline sales reaches to the cumulative realized demand (τ in Figure 5). The total unrealized demand due to the prolonged gasoline shortage represented as a difference between the cumulative latent demand

and cumulative realized demand at that time (AB in Figure 5).

The pent-up demand as well as the waiting time for purchasing gasoline can be evaluated by the difference of the cumulative realized demand and the cumulative supply: the amount of pent-up demand at time t is indicated as a difference of the cumulative realized demand and the cumulative supply at time t (DE in Figure 5); the waiting time of a household, who demands th Zth kL of gasoline, is depicted as the difference of the cumulative curves corresponding to Z (DC in Figure 5). Thus, the total waiting time caused by the gasoline shortage can be evaluated as the area between the cumulative realized demand and the cumulative supply curves.

4.3. Reasons for the Prolonged Gasoline Shortage in the Tohoku Region

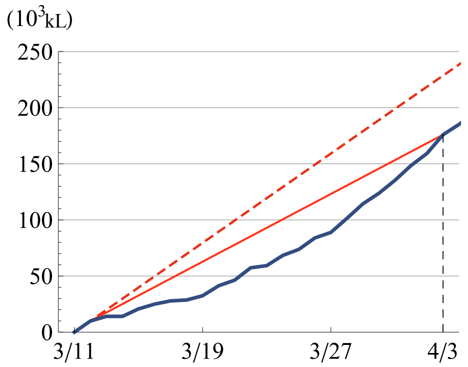
This section demonstrates why gasoline shortages continued for almost a month after the earthquakeffff using the cumulative curves introduced in the previous section. To obtain the cumulative curves from the available data, we assume that (i) the latent demand at each day equals the daily sales volume in the same month of the previous year; (ii) the supply at each day equals to the total volume of inbound shipments (by ship/rail) to oil terminals plus the volume of stock releases[1]; and (iii) the gasoline shortages were resolved by April 3, 2011 and daily demand was normalized.

Figure 6 shows that the cumulative latent demand (red dashed line), the cumulative realized demand (red solid line), and the cumulative supply (solid blue line) of gasoline in the Tohoku region after the earthquake. We can observe that, even if the volume of daily supply (the slope of the cumulative supply) matched or exceeded that of daily demand (the slope of the latent/realized demand), pent-up demand (the difference between the cumulative realized demand and cumulative supply) would not instantly disappear. In fact, as we have seen in Section 3.2, the volume of

[1]The volume of stock releases for the Tohoku region as a whole may be estimated from the following identity:

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

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, 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. We also assume 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.



Note: Even though around 3/26 the slope of cumulative volume of supply proximately equals that of ative latent demand, pent-up demand still exists at that point.

Figure 6: Cumulative demand and unrealized demand for gasoline

daily supply did meet that of daily demand around March 26, 2011; however, a further week was required to resolve the pent-up demand that had accumulated through supply shortages until that point (Figure 6).

Accordingly, we summarize the reason for the prolonged gasoline shortages in Tohoku region after the earthquake as follows: (i) the supply shortage in the two weeks after the earthquake caused a massive accumulation of pent-up demand; (ii) although the daily supply is restored to the standard daily demand at March 26, a further week was required to resolve demand and the cumulative supply met the cumulative realized demand.

It is worthwhile to note the actual measures undertaken 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 demonstrate, 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.

5. Proposed Strategies

5.1. Limitations of Pricing Policy

In this article, we evaluate the negative impacts of the prolonged gasoline shortages on socio-economic activities in the Tohoku region using the total unrealized demand as well as the total waiting time. As shown in Section 4.3, these mainly stem from the supply shortage (or, equivalently, the excess demand) of gasoline in the first two weeks after the earthquake. From the traditional economic viewpoint, such demandsupply mismatches as well as their consequential socio-economic losses seem to be mitigated by price adjustments in the gasoline market. This section, however, shows that such price adjustments fundamentally resolve neither the total unrealized demand nor the total waiting time and, thus, necessitate some other countermeasures to increase the gasoline supply.f

It is obvious that the total unrealized demand cannot be resolved without increases in the gasoline supply because it is the difference between the cumulative latent demand and the cumulative revealed demand (i.e., the cumulative supply) at April 3, when the gasoline demand and supply became normal.

Then, the total waiting time might be mitigated by price adjustments theoretically, though its implementation could be extremely difficult. What is even worse, most of the social benefits from the price adjustment would be received by the gasoline suppliers rather than the households in the devastated areas, which might make it socially unacceptable. This can be explained as below.

First, it is unnatural to suppose that the gasoline market maintains normal functions of " autonomous " price adjustment in the devastated area after the disaster. It is also hard to expect rational behavior for each household since each household had only local and restrictive knowledge on the gasoline market. After the earthquake, the transportation network as well as the information network was fragmented in the Tohoku region, thus, no common information was available regarding which service station (SS) was open, how much gasoline was supplied, and so on. Most households did not know how many SSs were open around them and where they were located. Even if one could have a list of open SSs, some might to be beyond a vehicle's fuel limit. In such circumstances, it seems impractical to expect an appropriate pricing—no matter whether a centralized control by the local government of an autonomous distributed adjustment among SSs—as well as efficient gasoline assignment. In fact, it is reported that oil wholesalers left the gasoline price in the Tohoku region unchanged after the earthquake primarily because they did not have sufficient information about gasoline markets.

Second, even if the gasoline market could be perfectly competitive after the disaster, where each household acts rationally and a perfect price balances demand and supply, most social benefits in the market are received by the gasoline suppliers instead of households in the devastated areas. This necessitates a social scheme that justifies such an inequality from a humanitarian perspective.

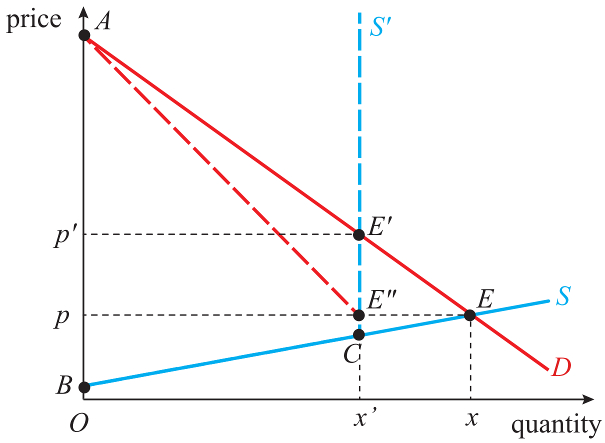


Figure 7: Social surplus before/after the earthquake

Suppose that each SS charges a daily “perfect price” that balances gasoline demand and supply (say, five times the normal price). In this case, the pent- up demand would completely disappear and the gasoline shortage would be resolved immediately after the gasoline supply was restored. However, the social benefits brought by such high prices is mainly received by the gasoline suppliers and results in significant decreases in consumer surplus as shown in Figure 7. In Figure 7, the normal gasoline demand, the normal gasoline supply, and the market equilibrium are represented by D, S, and E, respectively, and p and x are the corresponding equilibrium price and quantity, respectively. Suppose the maximum gasoline supply is limited to x' due to the disaster and the supply curve is changed to S'. When the gasoline price is adjusted via market competition, the equilibrium shifts from E to E' while the equilibrium price shifts from p to p'. The social benefit decreases from ABE to $ABCE'$, the latter of which consists of the consumers' surplus $Ap'E'$ and the producers' surplus $BCE'p'$.

We then analyze the social benefit if the gasoline price is maintained at p, where potential demand here (i.e., the number of households with positive reservation price) is x but the maximum supply is $x' < x$. Although the gasoline assignment cannot be determined uniquely in such a case, we assume that the gasoline is assigned to x' households uniformly randomly chosen from x households. In this case, the consumers' surplus, the producers' surplus and the social surplus are respectively represented by ApE'', $BCE''p$, and $ABCE''$. We can observe that the surpluses with and without the price adjustment satisfy

$$\begin{array}{ll} \text{social surplus} & ABCE' \geq ABCE'' \\ \text{consumers' surplus} & ApE' \leq ApE'' \\ \text{producers' surplus} & BCE'p' \geq BCE''p. \end{array}$$

That is, the price adjustment via market competition could achieve the larger social surplus because the increase in the producers' surplus $p'pE''E'$ is larger than the decrease in the consumers' surplus $AE''E'$. It should be noted that most of the consumers' surplus is received by households in the devastated areas while most of the producers' surplus is received by the oil sellers, who have markets outside of the devastated area.

These facts imply the following. First, a price adjustment cannot be justified unless there is a social scheme that transfers the producers' surplus to the customers (i.e., the households in the devastated area). To the best of the authors' knowledge, no such social scheme has been developed. Even if it exists, it is difficult to implement after a disaster. Second, the fixed price seems reasonable from a humanitarian viewpoint, although it might pay a relatively small producers' surplus for mitigating the socio-economic losses (reductions in consumers' surplus) in the devastated areas.

Accordingly, gasoline shortages and their consequent socio-economic losses cannot be mitigated by price adjustments; thus, some other countermeasures that increase the gasoline supply, as shown in the following sections, are inevitable.

5.2. Proposed Gasoline Distribution Strategies

As shown in the previous section, the gasoline shortage as well as the subsequent socio-economic losses could not be mitigated without increasing the gasoline supply following the Great East Japan Earthquake. This section first summarizes the daily inbound shipments of gasoline into the Tohoku region after the earthquake from the data used in Section **??**, where the weekly inbound shipments into the Tohoku region are analyzed. From the facts found in the daily inbound volume analyses, we then propose two gasoline distribution strategies as national-scale countermeasures for gasoline shortages.

Let $t = 0, 1, 2, \cdots$ be an index of date, where $t = 0$ is the day of the earthquake (March 11). The daily volume of gasoline shipped into the Japan Sea coastal ports (J-1, J-2, and J-3) after the disaster is 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, four days after the earthquake (point A in the figure); and (3) 8,653 kL, or 2.55 times the normal volume of gasoline (i.e., the average volume in the month prior to the earthquake) was brought into the region on March 22, one week after the date inbound shipments were resumed (point B in the figure). Based on these facts, the following are assumed in our analysis: it was possible to successively ship a total of 8,653 kL gasoline (equivalent to the amount of gasoline shipped into the three Japan Sea coastal ports on March 22, $t = 11$) into the three Japan Sea coastal ports after March 15 ($t = 4$) and allocate it to the municipalities in the Tohoku region.

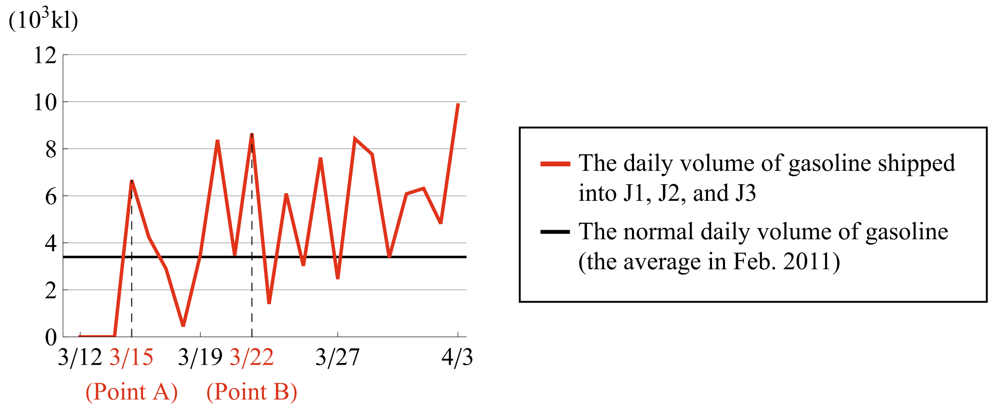


Figure 8: Inbound volumes of J1, J2, and J3 after the earthquake.

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 22. Second, the lead-time at oil terminals is sufficiently short for the terminals to accept, in succession, the amounts shipped into these three ports on March 22. 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 following two strategies for eliminating gasoline shortages at an early stage.

Proposed Strategies

Strategy S (short): Assuming the same amount of gasoline as that brought in on March 22 ($t = 11$), which is successively shipped to the three Japan Sea coastal ports daily for seven days from March 15 ($t = 4$) to March 22 ($t = 11$). Let $\mathcal{T}_S := \{4, 5, \cdots, 11\}$ be referred to the operational period of Strategy S.

Strategy L (long):

Assuming the same amount of gasoline as that brought in on March 22, which is successively shipped to the three Japan Sea coastal ports daily for the 14 days from March 15 ($t = 4$) to March 29 ($t = 18$). Let $\mathcal{T}_L := \{4, 5, \cdots, 18\}$ be referred to the operational period of Strategy L.

5.3. Procedures for Analyzing Distribution Strategies

This section summarizes the procedures for analyzing the above two proposed distribution strategies. First, we estimate the extent of the gasoline shortages that occurred after the Great East Earthquake as a base case. Let $\mathcal{I}$ be the set of oil terminals where the gasoline is produced and $\mathcal{J}$ be the set of municipalities where the gasoline is consumed. Let $\mathcal{K}$ be the set of the target prefectures in the Tohoku region (i.e., Miyagi, Iwate, Aomori, Akita, and Yamagata) and $\mathcal{J}_k$ be the set of municipalities in prefecture . We denote the set of target dates by $t = 01, 2, \cdots, \mathrm{T}$, setting $t = 0$ as March 11, the day of the earthquake, and T as April 3, the day the gasoline shortage is considered to be resolved. The base case is then derived as follows.[2]

Step 1 Estimate the model inputs from the data.

(i) Estimate the latent gasoline demand flow (i.e., daily volumes) of each municipality $\{r_j(t) : j \in \mathcal{J}\}$ for each date $t = 1, \cdots, \mathrm{T}$ based on pre-earthquake monthly sales volume by prefecture between March and April 2010.

(ii) Estimate the gasoline supply flow of each oil terminal $\{p_i(t) : i \in \mathcal{I}\}$ for each target day $t = 1, 2, \cdots, \mathrm{T}$ based on the daily volume of gasoline brought into each port between March and April 2011.

(iii) Estimate the transportation cost per unit of gasoline from each pair of municipality and oil terminal $\{c_{i,j} : (i, j) \in \mathcal{I} \times \mathcal{J}\}$ based on the shortest distance from each oil

[2]For details of the model, see (Akamatsu et al., 2013).

terminal to each municipality as measured using a Geographical Information System (GIS).

(iv) Let $R_j(t) = \sum_{\iota=1}^{t} r_j(\iota)\Delta t$ and $P_i(t) = \sum_{\iota=1}^{t} p_i(\iota)\Delta t$ be the cumulative latent demand of municipality j and the cumulative supply of oil terminal i at t, respectively.

Step 2 Estimate the revealed gasoline demand flow $\{q_j(t)\}$ and the sales flow $\{s_j(t)\}$ of each municipality, using the model that is shown in **??**. The model parameters estimated

(i) to minimize the disparity between the monthly sales in March 2011 by prefecture, Z_k, and the sales volume $S_k := \sum_{t\in\tau}\sum_{j\in\mathcal{J}_k} s_j(t)$ in each prefecture $k \in K$ during the corresponding time periods τ.

(ii) subject to the constraint that the gasoline shortage in the Tohoku region is resolved at T, i.e., $\sum_j Q_j(\mathrm{T}) = \sum_j S_j(\mathrm{T})$ and $\sum_j Q_j(t) < \sum_j S_j(t)$ for any $t < \mathrm{T}$, where $Q_j(t) = \sum_{\iota=1}^{t} q_j(t)\Delta t$ and $S_j(t) = \sum_{\iota=1}^{t} s_j(t)$.

(iii) taking into account transportation costs from each oil terminal to each municipality: municipalities closer to an oil terminal tend to receive much more gasolines compared with distant ones.

Step 3 Based on the cumulative latent demand $\{R_j(t)\}$ the cumulative revealed demand $\{Q_j(t)\}$ and the cumulative sales $\{S_j(t)\}$ calculate the pent-up demand $\{X_j(t)\}$ and the total unrealized demand $\{U_j(\mathrm{T})\}$:

$$X_j(t) = Q_j(t) - S_j(t), \qquad U_j(\mathrm{T}) = R_j(\mathrm{T}) - Q_j(\mathrm{T}).$$

We then estimate the gasoline shortages under the proposed strategies, Strategy S and Strategy L, using a similar procedure as that used in the base case. In doing so, the amount shipped to each port during the non-operational period $\{p_i(t) : t \notin \mathcal{T}_S \text{ or } \mathcal{T}_L\}$ in Step 1, and the values used in the base case are identical for the model parameters, in Step 2. 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.

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.

In the following discussion, $\mathcal{T}_S$ and $\mathcal{T}_L$ are referred to as the operational periods. 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 effects as well as the additional shipping cost required under the proposed distribution strategies S and L following the procedure described in the previous section. Economic effects are defined as the economic loss that can be reduced in comparison with 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 converged, the economic effects of each strategy and the additional cost of shipping are estimated in Section 6.3. Here, we demonstrate that the cost is only in the hundreds of million yen, whereas 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 4, 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 reveals the effects of Strategies S and L on improving the 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 with the base case. Second, this difference has a significant impact on time τ, the point at which the gasoline shortage was 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, 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, 54×10^3 kL of gasoline demand disappeared. In contrast, the unrealized demand under Strategies S and L are 27×10^3 kL and 16×10^3 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.

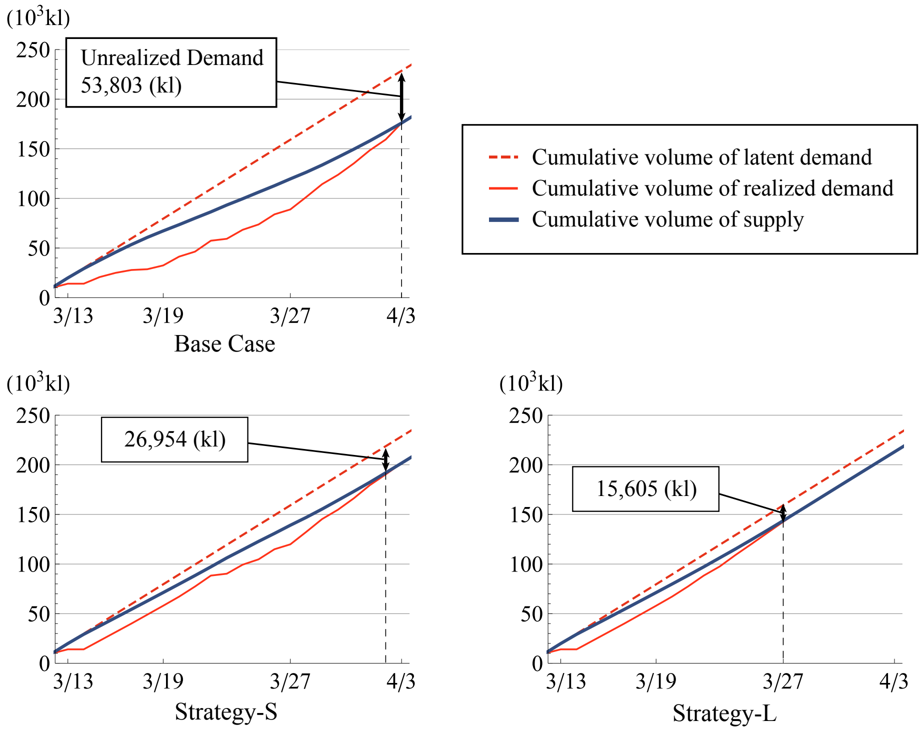


Figure 9: Cumulative latent demand, revealed demand, and supply for gasoline under each strategy.

6.2. Time–Space Distribution of Gasoline Shortage under Each Strategy

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

Table 5: Volume of unrealized demand and the date when supply shortage is resolved under the base case and Strategies S and L.

	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

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 during 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 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 the Pacific and Japan Sea coasts. Specifically, we see that the demand-supply gap is gradually eliminated eastward as the gasoline brought into the ports on the Sea of Japan 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, three 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.

Next, Figure 12 examines differences in the effect of national-scale gasoline shipments 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 one week following the earthquake. In contrast, although there was a temporary increase in pent-up demand, it did not significantly accumulate in the areas

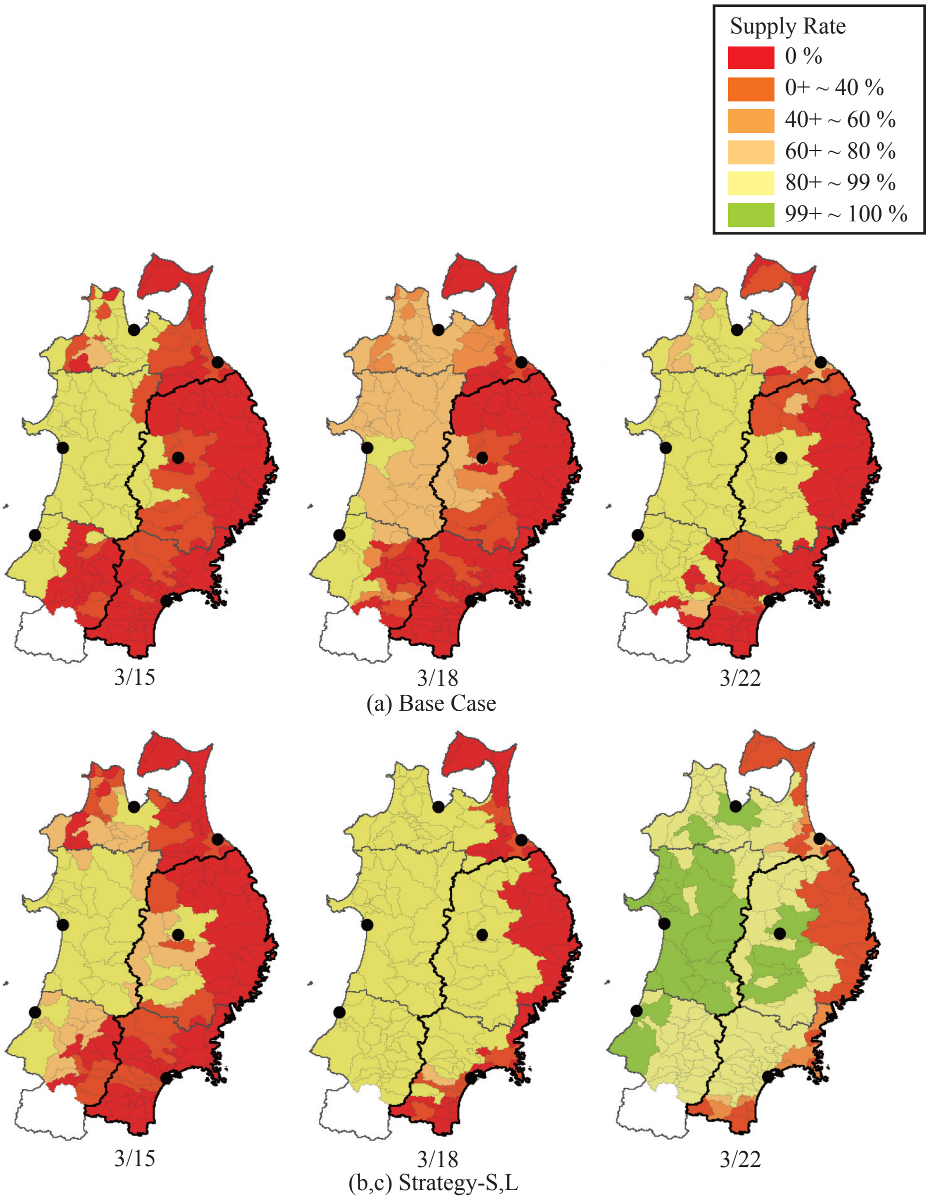


Figure 10: Spatial distribution of demandsupply gap by municipality (3/15, 3/18, 3/22) for (a) the base case and (b and c) Strategies S and L.

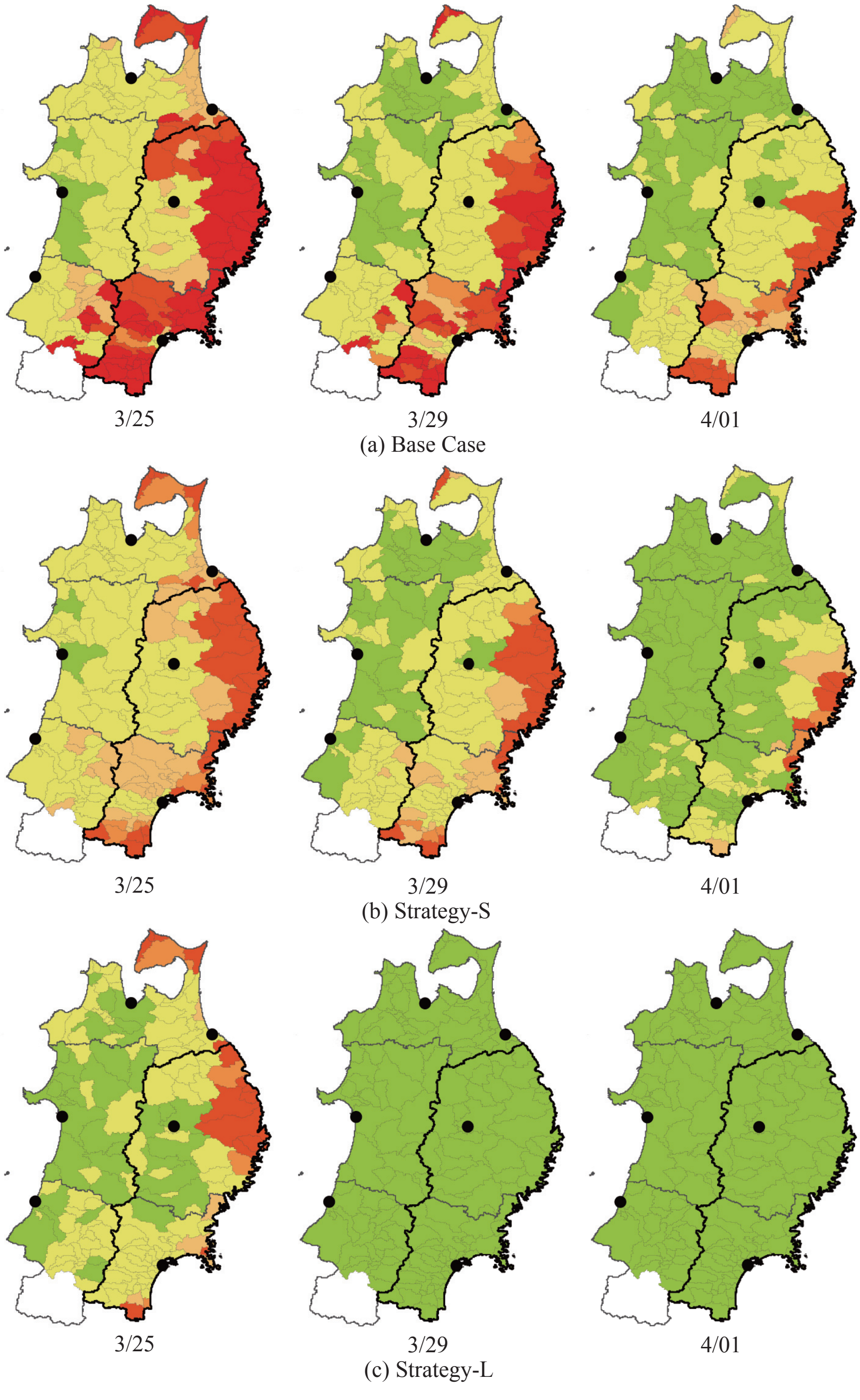


Figure 11: Spatial distribution of demandsupply gap by municipality (3/25, 3/29, 4/1) for (a) the base case, (b) Strategy S, and (c) Strategy L.

on the coast of the Japan Sea. Comparing these cumulative curves with 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 (44 $\times 10^3$kL) is extremely high—81% of the unrealized demand in Tohoku region, 54 $\times 10^3$kL. This unrealized demand on the Pacific coast is reduced to 21 $\times 10^3$kL under Strategy S and to 12 $\times 10^3$kL 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 whith 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 using two new methods, each of which uses (a) total unrealized demand and (b) total waiting time, respectively. It should be noted that these analyses DO NOT intend to discuss the accuracy of the estimation or the novelty and versatility of the method itself, but rather to understand the practical order of the economic losses and shipping cost based solely on the available data.

We first estimate production opportunity losses in the Tohoku region due to reductions in gasoline supply (i.e., disappearance of gasoline demand that is meant to be realized) using the total unrealized demand and macroeconomic indicators (gross regional product, GRP) and the

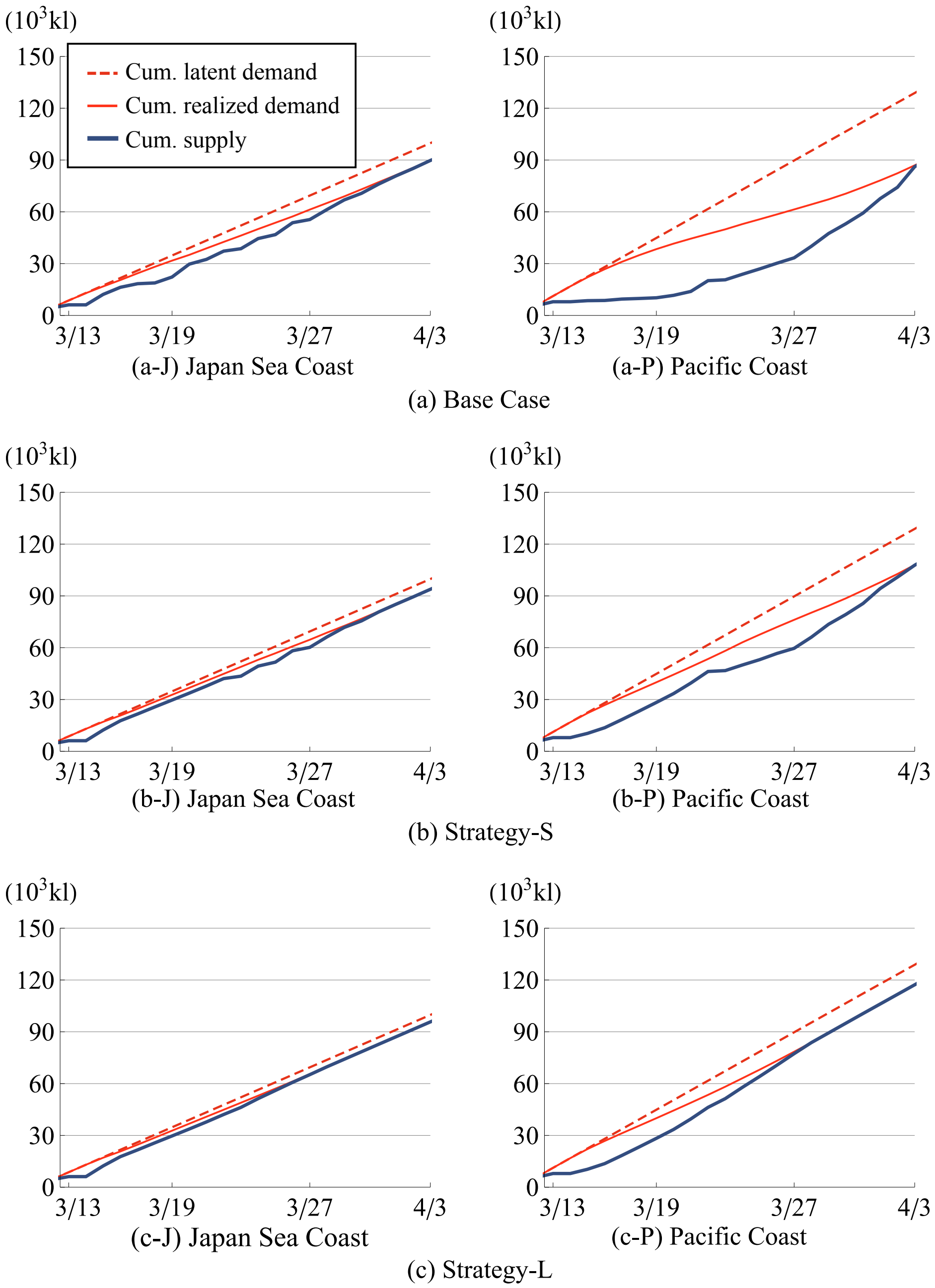


Figure 12: Cumulative latent demand, revealed demand and supply of Japan Sea Coast and Pacific Coast for (a) the base case, (b) Strategy S, and (c) Strategy L.

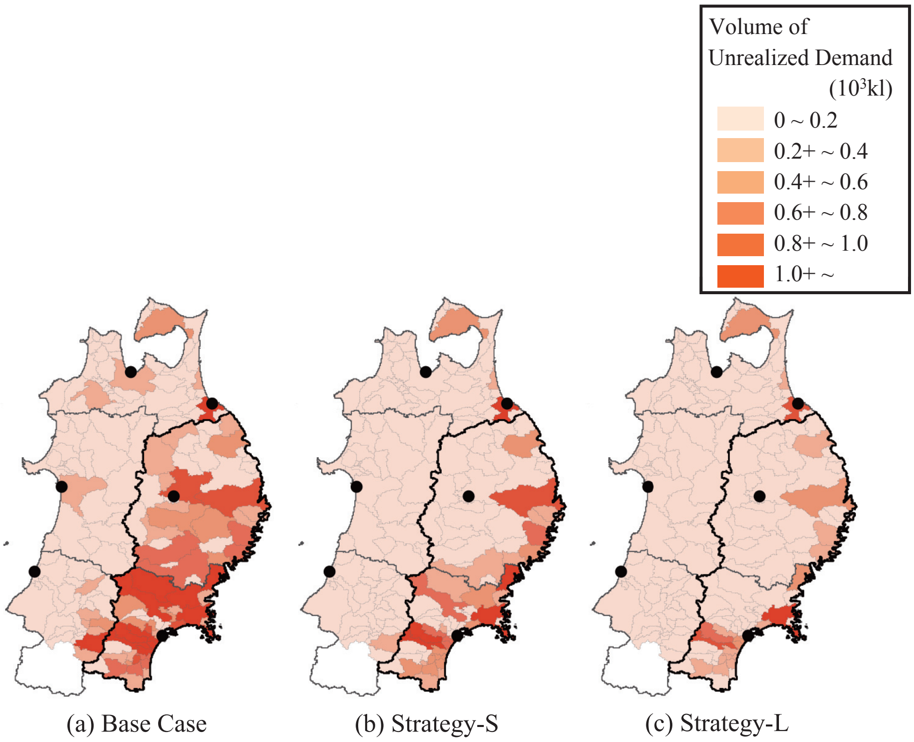


Figure 13: Spatial distribution of unrealized demand for (a) the base case, (b) Strategy S, and (c) Strategy L.

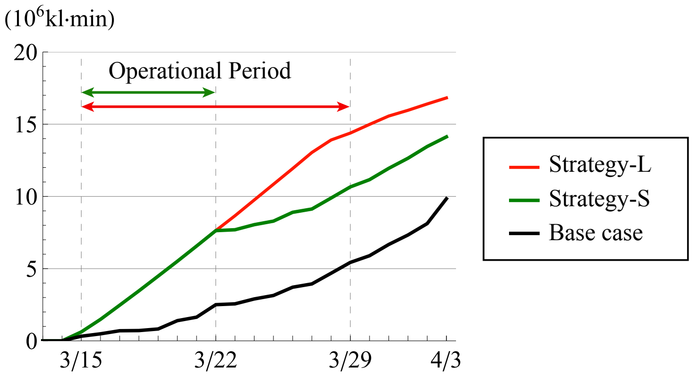


Figure 14: Cumulative shipping times

gasoline consumption of the Tohoku region. To do so, we assume here that the aggregate production function of the Tohoku region is linearly homogeneous to its gasoline consumption. In this case, the amount of production opportunity losses can be estimated using the following equation:

$$\begin{array}{l}\text{Macroscopic Economic} \\ \text{Loss (JPY)}\end{array} = \frac{\text{GRP of Tohoku Region (JPY/year)} \times \text{Unrealized Demand kL}}{\text{Gasoline Consumption of Tohoku Region (kL/year)}} \quad (3)$$

Since the socio-economic loss defined in Eq. (3) is estimated using macroeconomic indicators, we simply refer it to as "macroscopic economic loss."

We then estimate the opportunity losses of households awaiting gasoline purchase using the total waiting time and principles of microeconomic behavior of consumers. This can be estimated from the following equation[3]:

$$\begin{aligned}\begin{array}{l}\text{Microscopic Economic} \\ \text{Loss (JPY)}\end{array} &= \frac{\begin{array}{c}\text{Value of Time} \\ \text{(JPY/day} \times \text{person)}\end{array} \times \begin{array}{c}\text{Sum. Pent-up Demand} \\ \text{(kL} \times \text{day)}\end{array}}{\text{Gasoline Purchase Per Once (kL/person)}} \\ &= \text{Value of Time (JPY/day} \times \text{person)} \\ &\qquad \times \text{Total Number of Waiting Days (day} \times \text{person).}\end{aligned} \quad (4)$$

In Eq. (4), we measure the total waiting time, which is originally calculated in units of gasoline consumption (i.e., kL) from the cumulative curves, in units of population by dividing it by the amount of average gasoline purchased per once of each household, which is assumed to be 50 L. Since the socio-economic loss defined in Eq. (4) is estimated based on parameters of microeconomic behavior, we refer it to as "microscopic economic loss."

The macroscopic economic loss in Eq. (3) and the microscopic economic loss in Eq. (4)can be regarded as the upper and the lower bounds of actual socio-economic losses, respectively. First, since there are some industries that do not consume gasoline for production, the socio-economic loss estimated by Eq. (3) can be regarded the upper bound of the actual social-economic losses. Second, since the socio-economic activities of the households that entail gasoline consumption is only a part of all socio- economic activities in Tohoku region, the socio-economic loss estimated by Eq. (4) can be regarded the lower bound of the actual social-economic losses.

[3]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).

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 shortage is approximately 290 (lower) to 360 (upper) billion yen [4]. 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 145–180 billion yen; and that of Strategy L is 206–256 billion yen.

Table 6: Economic loss and costs of gasoline distribution strategies

	Base Case	Strategy-S	Strategy-L
Volume of unrealized demand (10^3kL)	54	27	16
Macroscopic economic loss -upper bound- (billion JPY)	-360	-180	-104
Upper economic effect of strategy (billion JPY)	–	+180	+256
Sum. pent up demand (10^3kL × day)	508	254	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 period of 3/12 ∼ 4/3 (10^6kL × 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 average- sized (i.e., 18 kL-capacity) tanker truck in Japan for one day (8 hours). According to the results shown 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 cost-benefit ratio is far larger than 1. Thus, we can conclude that distribution strategies S and L yield tremendous economic effects relative to the additional required cost.

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

Table 7: Cost-benefit analyses of each strategies

	Strategy-S	Strategy-L
Economic Effect of strategy (billion JPY)	+145 $\sim$ +180	+206 $\sim$ +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 that occurred after the Great East Japan Earthquake and the subsequent economic losses could have been reduced by an appropriate gasoline distribution strategy. Specifically, we first estimated the time-space distribution of the gasoline shortage and demonstrated that the loss of gasoline demand after the 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 two 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 a quick resolution of 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., 1–2 weeks).

In many regional cities in the world, the percentage of workers who commute by car is as high as that in 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 and thereby enable a successful *socio-economic activity continuation plan* (SACP).

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, the government should devise concrete gasoline shipment plans clarifying bottlenecks or physical constraints that might thwart the plans, such as fleet limitations (tanker trucks, oil tankers, and their crews), the capacities of transportation network (oil tanker lines, maritime ports, oil terminals, road sections, etc.), and so on. It is obvious that these bottlenecks should be resolved within an appropriate prioritization. Third, 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. Finally, once an earthquake occurs, the government should assess the capacity for supplying gasoline within the affected areas, compare it with the gasoline demand, and determine whether a regional gasoline shortage exists. 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.

References

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