



# INVESTIGATION OF THE GASOLINE SUPPLY PROBLEM IN THE GREAT EAST JAPAN EARTHQUAKE BY USING SYSTEM DYNAMICS APPROACH

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**ABSTRACT:** The Great East Japan Earthquake exerted serious damage over an unprecedentedly wide range. The earthquake prevented the supply of materials indispensable to restoration and revival in its aftermath, including fuels such as gasoline. In this study, we apply a system dynamics solution to investigate the causes and bottlenecks of this problem in order to ameliorate similar problems in wide-ranging disasters that are expected to occur, such as the Huge Nankai Trough Quake.

**Key Words:** Great East Japan Earthquake, gasoline, supply, system dynamics

## INTRODUCTION

The Great East Japan Earthquake, which occurred in March 2011, exerted tremendous damage in an unprecedentedly wide range. One serious problem that arose immediately after the earthquake that demands consideration was the delayed supply of materials indispensable to restoration and revival, such as gasoline. These delays were due not only to (a) damage to oil company supply tanks, but also to (b) the severing of roads and railways used for supply traffic; furthermore, in addition to damaged areas in the Tohoku region, the Tokyo metropolitan area also suffered from gasoline supply delays.

In this study, we used a system dynamics solution (Tsuchigane 2005, Nojima et al. 2006) to model (a) and (b). The purpose of this study is to ameliorate similar problems in wide-ranging disasters that are expected to occur, such as the Huge Nankai Trough Quake.

This study comprises nine steps, as shown in Fig. 1. In the pilot study, we determined (a) damage to suppliers and (b) damage to supply routes. We then analyzed the results of interviews conducted on July 5, 2012 with workers at the Sendai oil refinery of the JX Nippon Oil and Energy Corporation (subsequently referred to as JX) to collect parameters for modeling and derive objectives. These parameters and necessary tasks were integrated into a system dynamics model. Based on the case of the Great East Japan Earthquake, we formulated measures to be implemented in the Huge Nankai Trough Quake to obtain particular objectives. The targets of this study are shown in Steps (1)–(4), and part of Step (5) in Fig. 1.

## OUTLINE OF DAMAGE TO GASOLINE SUPPLIERS AND SUPPLY ROUTES

### Transport of gasoline and facilities' damage and recovery

The transport of gasoline starts at oil refineries, which produce petrochemical products from crude oil. Generally, gasoline from oil refineries is transported to gas stations (SSs) by tank lorries via oil terminals that store gasoline temporarily. As an example of the damage that oil suppliers can incur, 6 of the 27 oil refineries in our country halted operations immediately after the Great East Japan Earthquake (Agency of Natural Resources and Energy 2011a). Fig. 2 illustrates the damage to oil refineries caused by the Great East Japan Earthquake. Eight oil terminals in the vicinity of the Pacific Ocean stopped shipments or were shut down as of March 12, 2011. The Kamaishi, Kesenuma, Onahama, and Hitachi oil terminals remained unable to resume shipments as of March 21, 2011 (The Petroleum Association of Japan 2012). Many argued for the urgent restoration of the Shiogama oil terminal, essential to gasoline supply in the Tohoku region (Agency of Natural Resources and Energy 2011b). Accordingly, two oil terminals restarted operations on March 17 and 20, 2011. As of March 21, 2011, two additional oil terminals remained mired in preparations for resuming operations and could not accept large vessels (The Petroleum Association of Japan 2012).

### Supplying gasoline to damaged areas

On March 17, 2011, the Agency of Natural Resources and Energy provided figures on gasoline that would be supplied from oil refineries in western Japan to the damaged areas (Agency of Natural Resources and Energy 2011b).

First, the Agency stated that it would increase the operation rate of oil refineries in western Japan to 95% or higher (the operation rate of Japanese oil refineries in 2010 was 77.8% (Kakimi 2012)) and constrain exports and demand; this additional production (approximately 20,000 kL/day) would be transferred to the Tohoku region. The Agency also stated that it would collect additional gasoline from two oil refineries in Hokkaido (Tomakomai and Muroran) in order to secure approximately 38,000 kL/day of gasoline in total, an amount that was equal to the demand per day in the Tohoku region prior to the earthquake.

As shown in Fig. 2, three oil refineries in the Kanto region that stopped operations during the earthquake had resumed operations by March 21, 2011 and supply shortages were nearly eliminated. Because of concerns several days prior to March 21 regarding the insufficient gasoline supply, oil companies were instructed to transfer and bring to market in the Kanto region, within approximately three days, 50,000 kL of oil inventory stored at refineries in western Japan. The oil companies made available oil stocks produced by their in-service oil refineries in the Kanto region (approximately 30,000 kL) and established an effective supply system through collaboration—for example, companies provided tank lorries to other companies.

Fig. 3 illustrates these efforts and Fig. 4 shows the locations of the 27 oil refineries in Japan and their crude oil processing capacity (The Petroleum Association of Japan 2011).

The Agency also sought to prepare additional tank lorries. Immediately after the earthquake, the number of tank lorries that supplied gasoline in the Tohoku region was around 1,100, of which 400 transported gasoline from the oil terminals to SSs. In the aftermath of the earthquake and tsunami, the largest regional supply bottleneck was a lack of tank lorries to transport gasoline from oil terminals to SSs. Additional tank lorries from the Kansai region and other areas (300 units) were requested to establish a supply system comprising 700 tank lorries.

Furthermore, the supply of gasoline to major SSs in the damaged areas was prioritized. SSs were specified as essential based on whether they were:

- critical for ensuring the functioning of fire and police emergency vehicles
- critical for maintaining the distribution of relief goods
- critical for supporting the lives of evacuees and inhabitants

On March 21, 2011, to ensure the supply of oil throughout the country, facilitate the provision of petroleum products, and encourage mutual accommodation between business operators and regions,

civilian oil stocks were substantially reduced. Taking prior reductions into account, civilian oil stocks were reduced by 25 days' worth. Consequently, the number of days that civilian oil stocks were rationed was reduced from 70 to 45 (Agency of Natural Resources and Energy 2011c).

**Damage and recovery of supply routes**

Nearly all of the highways and open roads used for gasoline transport, as mentioned in (b) in Section 1, were traversable by March 21, 2011 (Emergency Mapping Team (EMT) 2011) with the exception of Route 45 along the Sanriku coast, which was shut down by the tsunami, and Route 6, which runs close to the Fukushima No. 1 Nuclear Power Plant. Furthermore, it was decided that a comb-like route from Route 4 to Route 45/Route 6 had to be prioritized as a relief route and cleared of road obstacles. This route became traversable between March 12 and March 15, 2011 (Nikkei Construction 2011).

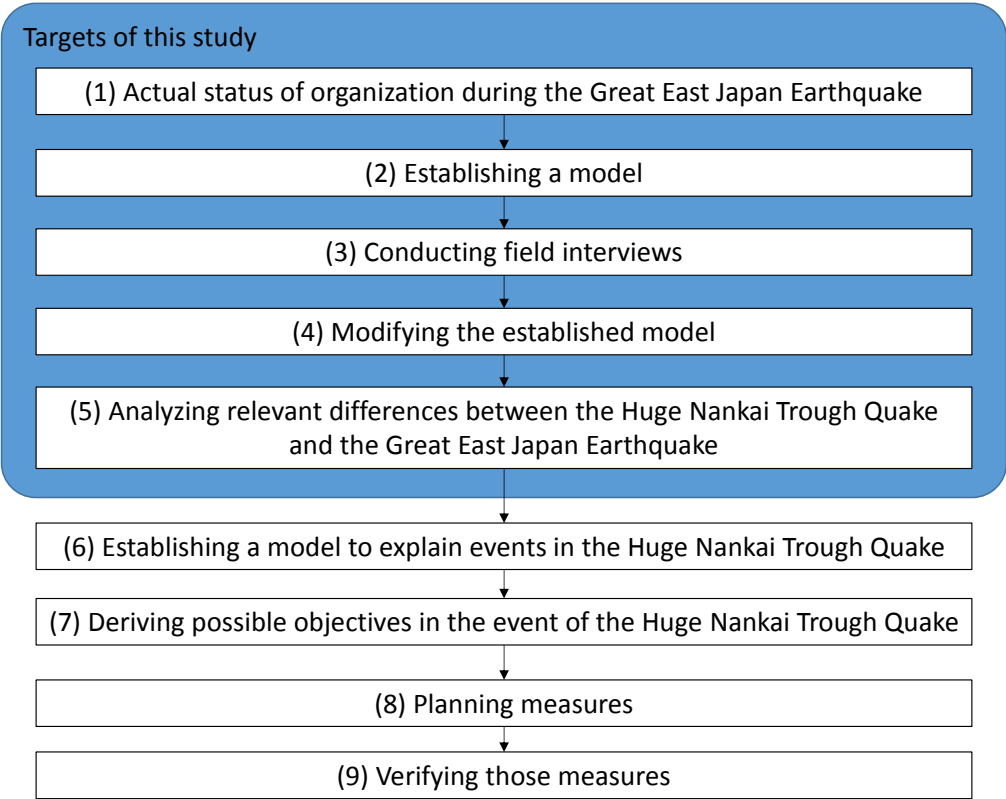


Fig. 1 Overall steps and targets of this study

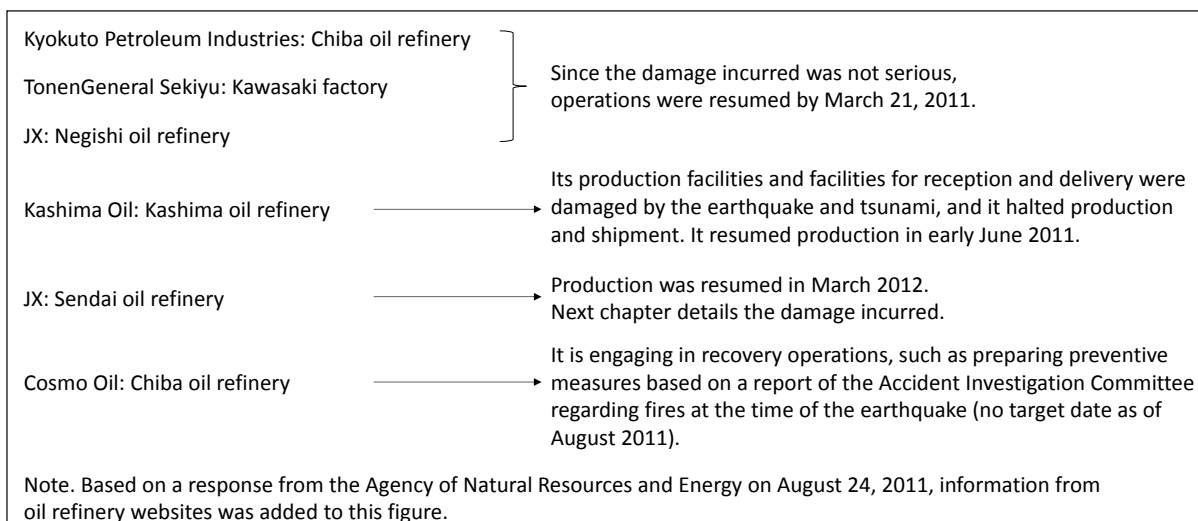


Fig. 2 Damage to oil refineries caused by the Great East Japan Earthquake

## INTERVIEWS WITH WORKERS AT THE JX SENDAI OIL REFINERY

### Outline of the JX Sendai oil refinery

The JX Sendai oil refinery started operations in 1971. It is the only oil refinery in the Tohoku region. Located on a 1.5-million m<sup>2</sup> site along the seashore that stretches across Sendai City, Tagajo City, and Shichigahama-machi, the refinery is capable of producing 145,000 BD (23,000 kL/day). This oil refinery is one of six that stopped operations during the Great East Japan Earthquake. The inside of the factory flooded with water from the tsunami that reached a height of 2.5 to 3.5 m, and two days later, the pipes caught fire. The transferal of oil drums began on March 18, 2011, shipments started from a temporary scaffold lorry rack on March 21, 2011. New temporary lorry racks were built in the eastern section of the refinery site, from which shipment started on May 3. These new lorry racks were transferred from the Asaka oil terminal and the Matsumoto oil terminal, and were capable of loading 9 lorries at the same time. Until the third pier started operations on May 8, the Sendai oil refinery temporarily served as an oil terminal: gasoline and other petroleum products transported by oil tankers from the Tokyo metropolitan area were stored at the oil refinery and subsequently transferred to tank lorries for distribution to SSs. The first pier began operations on September 23 and the second, fourth, sixth, and seventh piers began operations on November 2. Trial operations of a petroleum-refining device were initiated on January 14, 2012.

JX is the only oil company with a refinery in the Sendai area. Other oil companies, including Idemitsu Kosan, Showa Shell Sekiyu, and Cosmo Oil, do not have oil refineries in the Sendai area but operate oil terminals in the Shiogama area; these oil terminals store petroleum products transported by oil tankers from the Tokyo Metropolitan area.

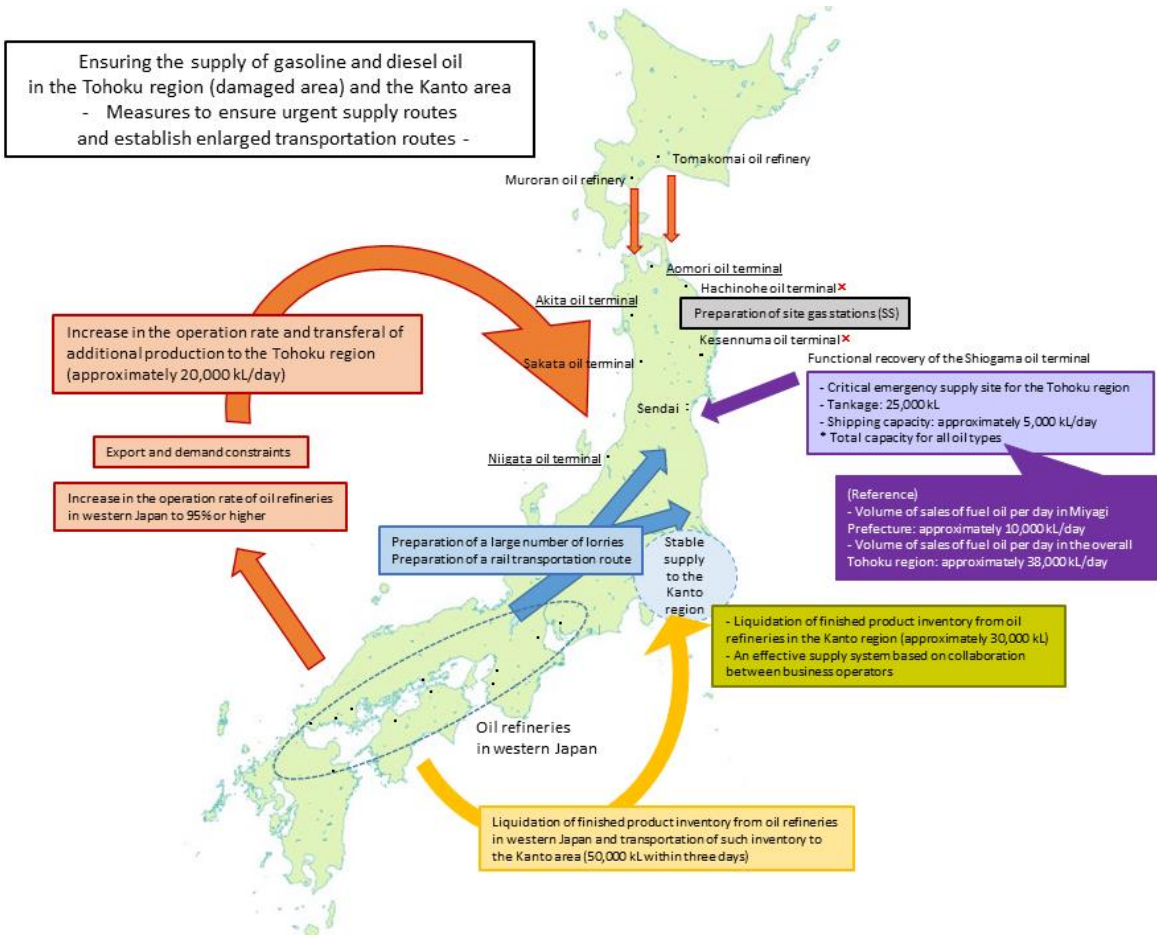


Fig. 3 Gasoline supply routes (Agency of Natural Resources and Energy 2011b)

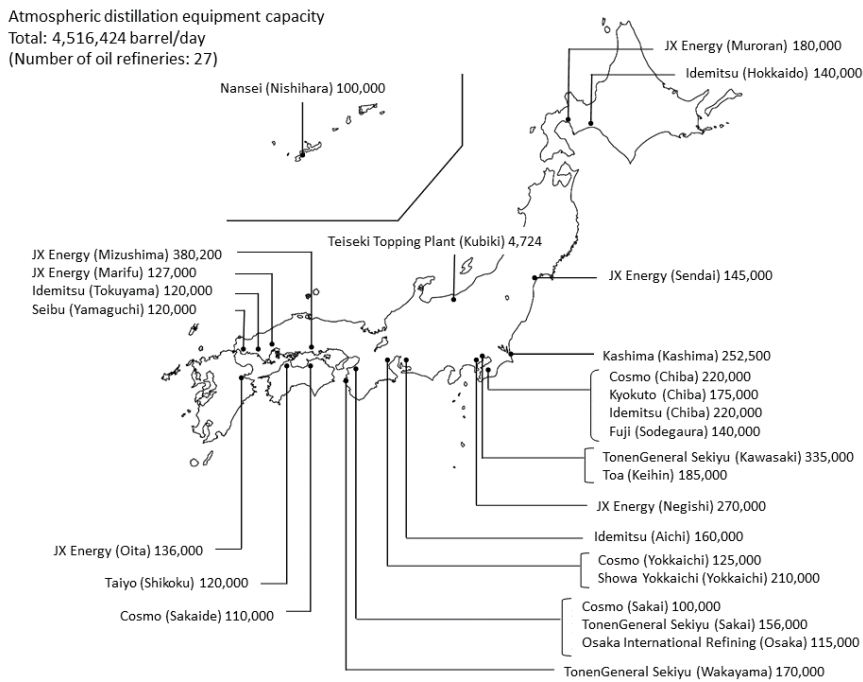


Fig. 4 Location of the oil refinery and its crude oil processing capacity (as of January 2011)  
 (The Petroleum Association of Japan 2011)

## Items and responses for interviews with workers at the JX Sendai oil refinery

Table 1 shows the main items that were addressed in interviews with workers at the JX Sendai oil refinery.

Table 1: Major interview items

(1) Restoration of functions at the JX Sendai oil refinery
(2) The quantity of stocks stored in the oil refinery and the oil terminal when the earthquake occurred
(3) Oil transportation by rail after the earthquake
(4) Area in which the tank lorries transported gasoline under normal conditions and after the earthquake
(5) The rate at which gasoline was directly transported to SSs, bypassing oil terminals

(1) Section 3.1 outlines the restoration of functions at the JX Sendai oil refinery. Because of the temporary lorry racks built in May, the Sendai oil refinery was equipped to carry out oil terminal functions, improving the transportation of gasoline to SSs immensely.

(2) As of 0:00 on March 11, 2011, the JX oil refinery had 1.06 million kL in oil stocks (equivalent to the amount of crude oil the refinery could refine in 46 days), broken down as follows: 300,000 kL of crude oil, 200,000 kL of LPG, 230,000 kL of fuel oil products, 300,000 kL of half-finished fuel oil products, and 40,000 kL of other products. The 230,000 kL figure for fuel oil products is inclusive of all gasoline, kerosene, diesel oil, and heavy fuel oil; the amount of gasoline alone was equivalent to the amount required for several days in the Tohoku region per day (38,000 kL).

(3) Until the Tohoku Line was completely reopened in mid-April, 2011, railway transportation from the Yokohama and the Negishi oil refineries via Niigata to Morioka in Iwate Prefecture and Koriyama in Fukushima Prefecture played an important role in oil transportation.

(4) Following the earthquake, tank lorries typically traveled within a 100- to 150-km radius of the oil refinery and the oil terminal and could make three roundtrips per day. The number of roundtrips could increase with an increase in the number of lorry racks at the oil refinery and the oil terminal rather than an increase in the number of lorries. At the JX Sendai oil refinery, the number of roundtrips substantially increased once regular lorry racks were operational in November 2011.

(5) Approximately 60% of gasoline from the JX oil refinery was transported by lorries directly to SSs.

## INTEGRATION OF THE CASE OF THE GREAT EAST JAPAN EARTHQUAKE WITH THE SYSTEM DYNAMICS MODEL

Taking the interview results into consideration, we decided to employ a system dynamics model. Fig. 5 shows the model flow, and Table 2 shows the major points of consideration and tentative conditions. In setting tentative conditions, detailed points regarding the gasoline supply were neglected; the conclusion provided in this chapter is only partial and based on estimated objectives.

To determine the number of tank lorries, based on the information released by the Agency of Natural Resources and Energy (Agency of Natural Resources and Energy 2011b) as shown in Fig. 6, we added 300 units to the number of tank lorries available at the time the earthquake occurred (400 units) and conducted estimation based on a system with 700 units in total.

The responses of the JX Sendai oil refinery and the Petroleum Association of Japan to our inquiries indicated that the Sendai oil refinery, Shiogama oil terminal, Morioka oil terminal, and Koriyama oil terminal adjusted warehousing to prevent the build-up of gasoline stocks. In consideration of this information, we checked and adjusted transportation data pertaining to tankers and railways separately. The Tohoku region requires 38,000 kL of gasoline per day; we estimated that the amount of gasoline transported from the Tokyo metropolitan area and western Japan directly after the earthquake would be 50% of that value and would be able to increase up to 100% over 10 days.

Based on the conditions above, we calculated the total cumulative amount of gasoline transported from the Tokyo metropolitan area and western Japan; the amount of gasoline stored in the Sendai oil

refinery, the Shiogama oil terminal, the Morioka oil terminal, and the Koriyama oil terminal; and the total cumulative amount of gasoline transported from the Sendai oil refinery, Shiogama oil terminal, Morioka oil terminal, and Koriyama oil terminal to the SSs.

Fig. 7 illustrates gasoline transportation given two tank lorry roundtrips per day, and Fig. 8 illustrates gasoline transportation given three tank lorry roundtrips per day.

Given two tank lorry roundtrips per day, as shown in Fig. 7, the transportation capacity of the tank lorries to the SSs is insufficient and the Sendai oil refinery, Shiogama oil terminal, Morioka oil terminal, and Koriyama oil terminal must engage in adjust warehousing to prevent the amount of gasoline received from exceeding tank capacity, thus limiting the amount of gasoline that can be transported from the Tokyo metropolitan area and western Japan to less than the required amount. By contrast, at three roundtrips per day, as shown in Fig. 8, the transportation capacity of the tank lorries to the SSs is sufficient. Therefore, the Sendai oil refinery, Shiogama oil terminal, Morioka oil terminal, and Koriyama oil terminal require no warehousing adjustments, and it is expected that the amount of gasoline transported from the Tokyo metropolitan area and western Japan can almost equal the required amount.

As interviews at the JX Sendai oil refinery indicated, under normal conditions, three roundtrips per day are standard. This number was consistent with the simulation results (Fig. 8), which indicated that three roundtrips per day enabled the successful transportation of gasoline to the SSs without necessitating warehousing adjustment. However, damage to lorry racks at the oil refineries or oil terminals could decrease the number of possible tank lorry roundtrips per day. The JX Sendai oil refinery completely restored lorry rack capacity in May 2011; before this, the actual number of possible roundtrips per day was less than three, and transportation capacity to the SSs was reduced.

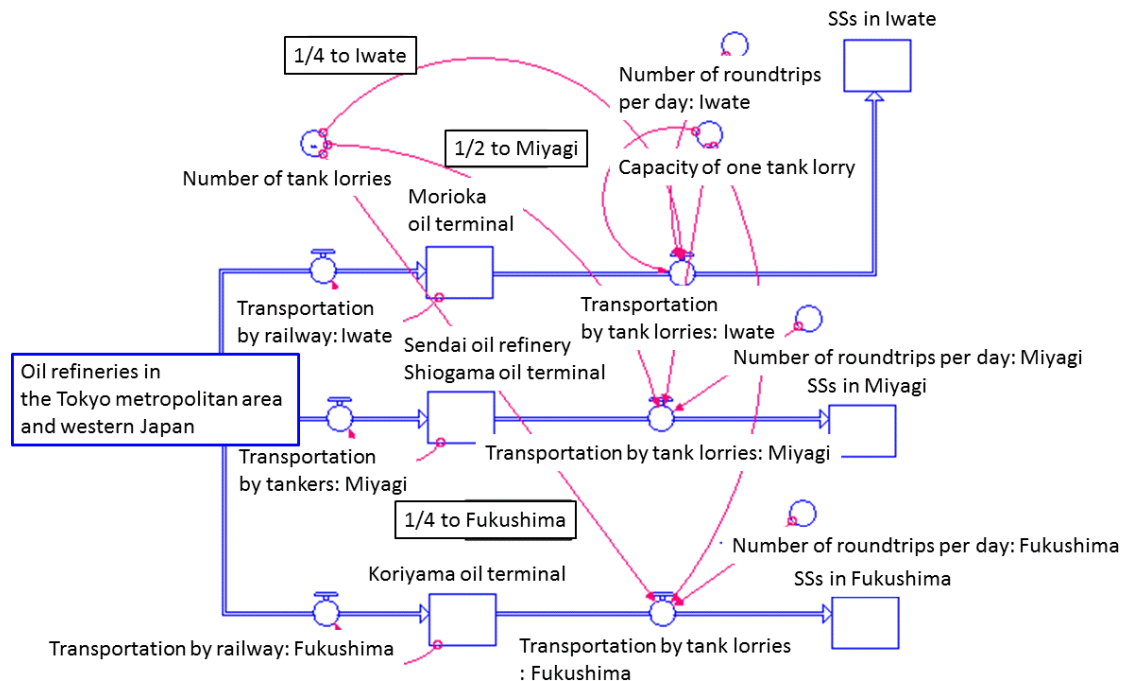


Fig. 5 Flow of the system dynamics model



Table 2: Major points of consideration and tentative conditions

- Since the required amount of gasoline per day in the Tohoku region is 38,000 kL, we estimated that the amount of gasoline transported from the Tokyo metropolitan area and western Japan directly after the earthquake would be 50% of that value, and would be able to increase up to 100% over 10 days.
- In Miyagi Prefecture, gasoline is transported by tankers from the Tokyo metropolitan area to the Sendai oil refinery and the Shiogama oil terminal, and is transferred from there by tank lorries.
- In Iwate Prefecture, gasoline is transported by rail from the Tokyo metropolitan area to the Morioka oil terminal, and is transferred from there by tank lorries.
- In Fukushima Prefecture, gasoline is transported by rail from the Tokyo metropolitan area to the Koriyama oil terminal, and is transferred from there by tank lorries.
- In response to our inquiries, the Sendai oil refinery indicated that they had maintained oil stocks equivalent to the amount required for several days in the Tohoku region (per day, the Tohoku region requires 38,000 kL). Subsequently, we estimated that the Sendai oil refinery had maintained oil stocks equivalent to the amount required for five days when the disaster occurred. Data from the Morioka oil terminal and the Koriyama oil terminal were unavailable; we estimated that these oil terminals had each maintained oil stocks equivalent to the amount required for one day when the disaster occurred.
- We estimated that the amount of gasoline supplied from western Japan and Hokkaido satisfied the required amount per day in the Tohoku region (38,000 kL/day) by no later than March 21. On March 11, 50% of that amount was supplied; following a linear trend, the amount increased to 100% on March 21 (38,000 kL/day). Half of that amount was distributed to Sendai and Shiogama, and one-quarter was distributed to Morioka and Koriyama each.

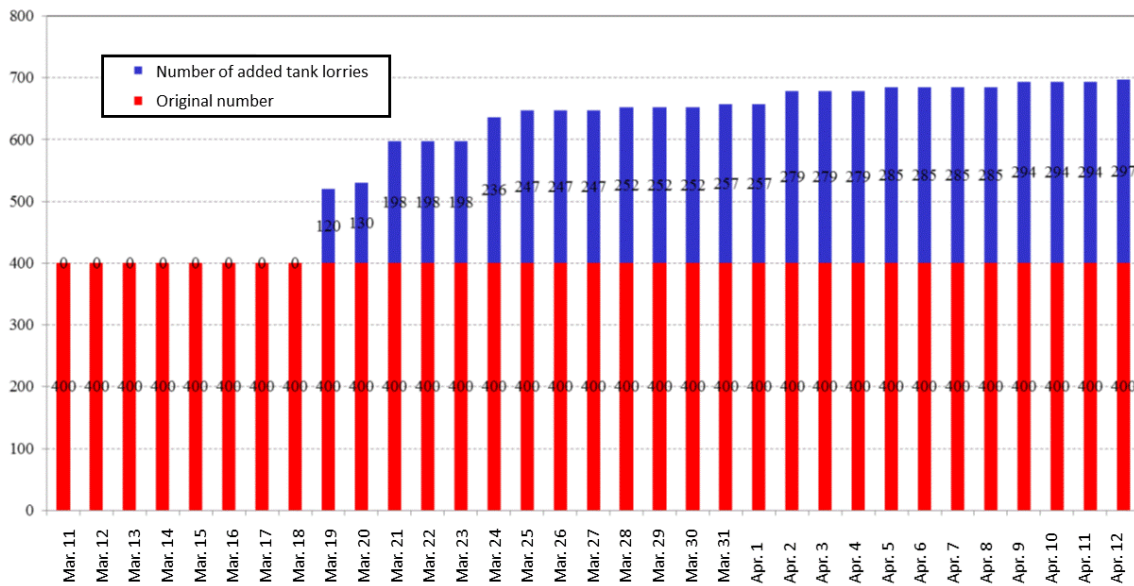


Fig. 6 Changes in the number of tank lorries



## OBJECTIVES FOR THE FUTURE HUGE NANKAI TROUGH QUAKE

According to data and information provided by the Agency of Natural Resources and Energy (Agency of Natural Resources and Energy 2011b) and interviews with workers at the JX Sendai oil refinery, we determined the following bottlenecks in gasoline supply in the damaged areas: (1) the number of tank lorries transporting gasoline from the oil refinery and oil terminal to the SSs was insufficient. (2) The standard number of tank lorry roundtrips per day was three, but damage to lorry racks at the oil refineries or oil terminals could decrease the number of tank lorry roundtrips.

Based on these points, we considered how the system dynamics model we formulated based on the case of the Great East Japan Earthquake could be applied to the future, expected Huge Nankai Trough Quake. We determined the influence of the Great East Japan Earthquake and the expected Huge Nankai Trough Quake according to damage to (a) supply sources and (b) supply routes, as shown in Table 3.

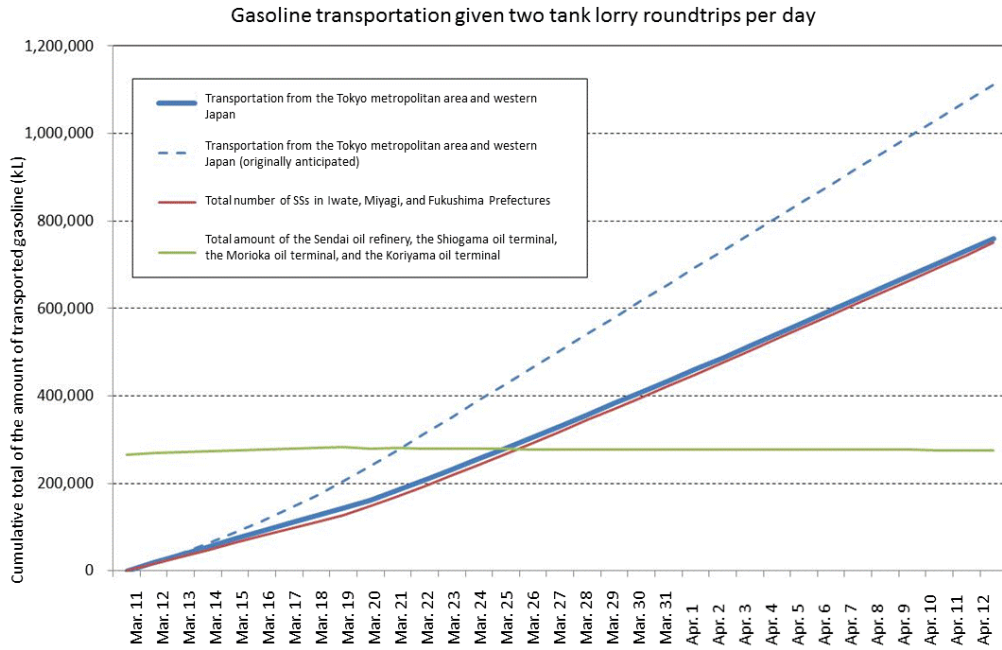
Table 3 shows that in the case of the Huge Nankai Trough Quake, western Japan has more oil refineries and other advantages than did the Tohoku region during the Great East Japan Earthquake in view of (a) supply sources. However, in view of (b) supply routes, roads in western Japan have no redundancy and damaged roads may be a bottleneck in disasters; this is a matter of concern.

To improve the system dynamics model, integrating the road restoration ratio with parameters such as the tank lorry roundtrips per day is necessary.

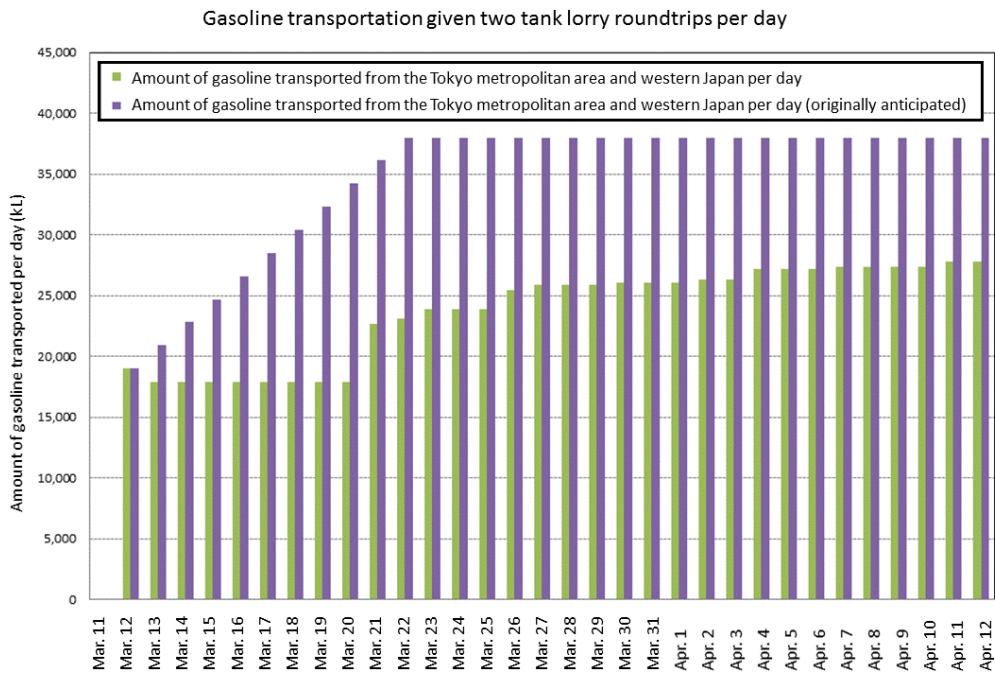
Furthermore, to increase the accuracy of the model, incorporating the influence of the increased demand of gasoline after disasters is necessary. However, because such figures are currently difficult to determine, we considered this a future objective.

Table 3: Influence of the Great East Japan Earthquake and the expected Huge Nankai Trough Quake on the gasoline supply

	Tohoku region in the Great East Japan Earthquake	Western Japan in the Huge Nankai Trough Quake
Supply source considerations based on bottlenecks and the formulated model	Due to the earthquake and tsunami, the number of the tank lorries was insufficient. The Tohoku region has only one oil refinery, JX Sendai, at which lorry racks were damaged. Thus, only long-distance transportation from other regions could be used to supply gasoline.	Western Japan has a number of oil refineries, mainly located around the Seto Inland Sea (see Figures 3 and 4). Regarding the expected damage of the Huge Nankai Trough Quake, the Cabinet Office (Cabinet Office 2013) estimated that tsunami height in the Seto Inland Sea would be lower relative to that on the Pacific coast. Therefore, if one area is damaged, other areas will be able to provide support. Preparing a sufficient number of tank lorries and ensuring that lorry racks at oil refineries and oil terminals incur no damage is desirable.
Supply route considerations	Even though Route 45 and Route 6 along the coast were damaged, the Tohoku Expressway and Route 4, an inland route, were usable. A comb-teeth-like route along these roads was employed for transporting the gasoline supply.	In contrast to the Tohoku region, roads have no redundancy. There are no expressways in the upper portion of the Kii Peninsula or in southeast and southwest Shikoku; thus, transportation is a serious potential problem.

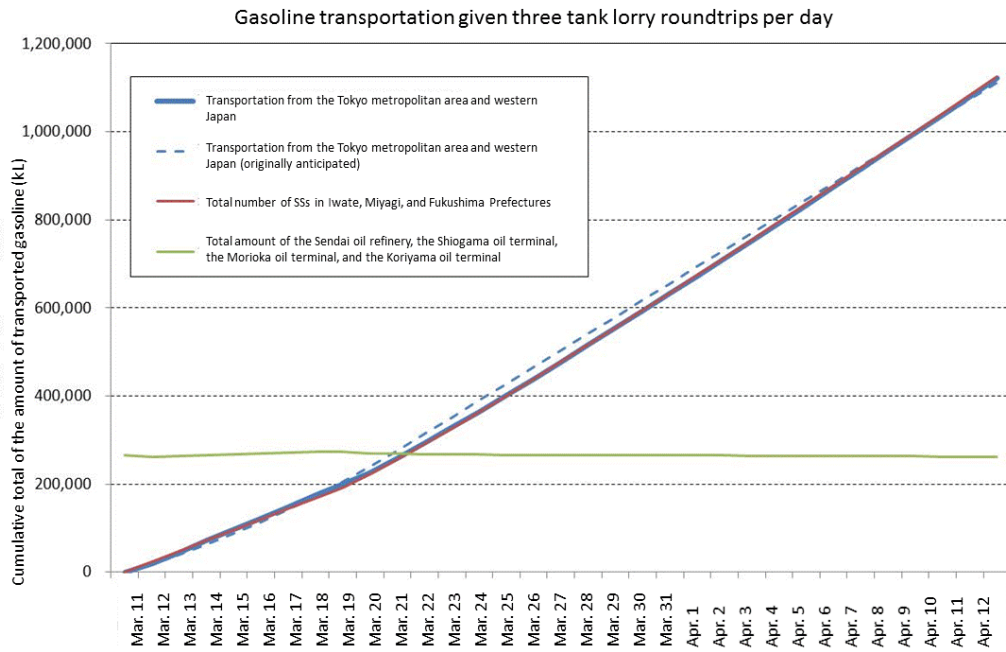


(a) Total cumulative amount of transported gasoline after the initial day of the disaster

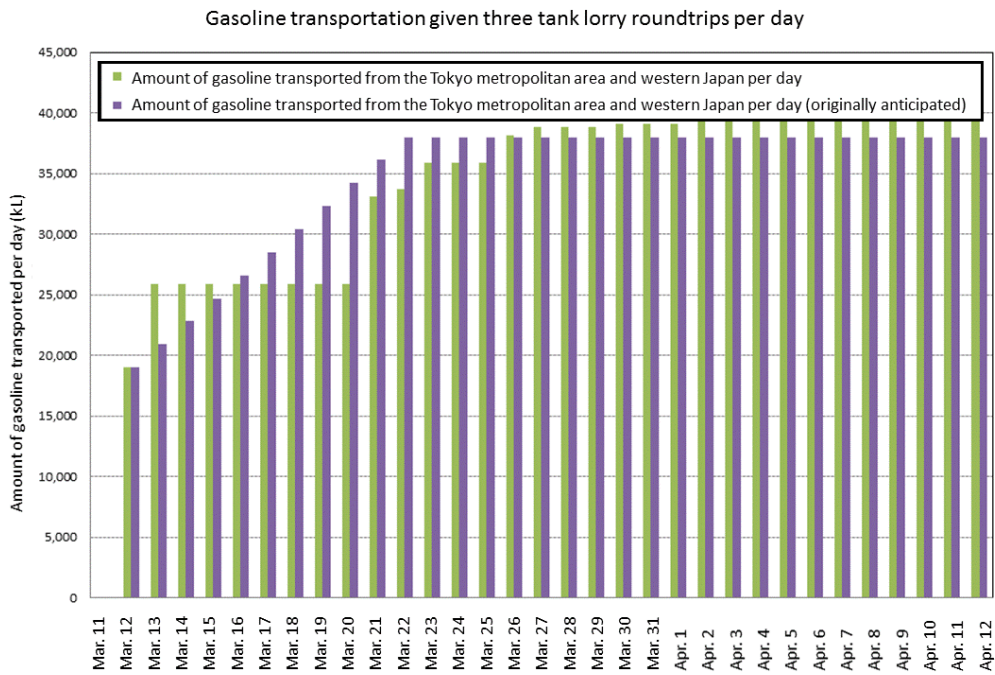


(b) Amount of transported gasoline per day

Fig. 7 Amount of transported gasoline (given two tank lorry roundtrips per day)



(a) Total cumulative amount of transported gasoline after the initial day of the disaster



(b) Amount of transported gasoline per day

Fig. 8 Amount of transported gasoline (given three tank lorry roundtrips per day)

## ACKNOWLEDGMENT

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