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

International Workshop on
Transportation Networks under Hazardous Conditions

2, March, 2013

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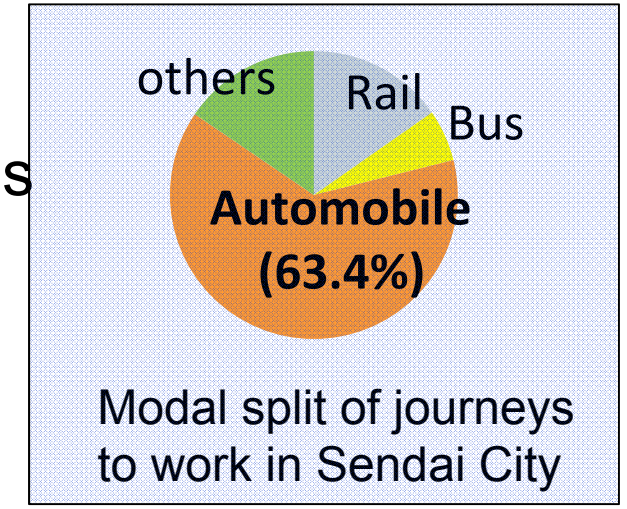
Background (1)

- After 3.11, 2011, ***Oil Shortage*** spread over a wide area of the ***Tohoku region***, and it ***lasted for about a month***.

- The lack of automotive fuel
  - ➢ became a major constraints hindering relief efforts and delivery of emergency supplies in ***affected areas along the coast***
  - ➢ greatly suppressed economic activities such as commuter traffic and recovery efforts **in *inland areas***

⇒ caused ***Huge Economic Losses***



Modal split of journeys to work in Sendai City

Background (2)

- The root cause of the oil shortage was the event that oil refinery in Sendai and port facilities in the Tohoku region were struck by the earthquake.
- The Ministry of Economy, Trade & Industry (METI) and the oil industry ***have not yet released*** sufficient information that allow ***systematic understanding*** of the problem:
  - *How the situation developed ?*
  - *What measures were implemented ?*
  - *Why the oil shortage lasted for a month ? etc.*

➡ ***Many people attributed the main cause of the protracted oil shortage to "hoarding by consumers".***

Purpose of the Study

- Provide a Quantitative & Systematic View of the Oil Shortage Problem following the Earthquake.

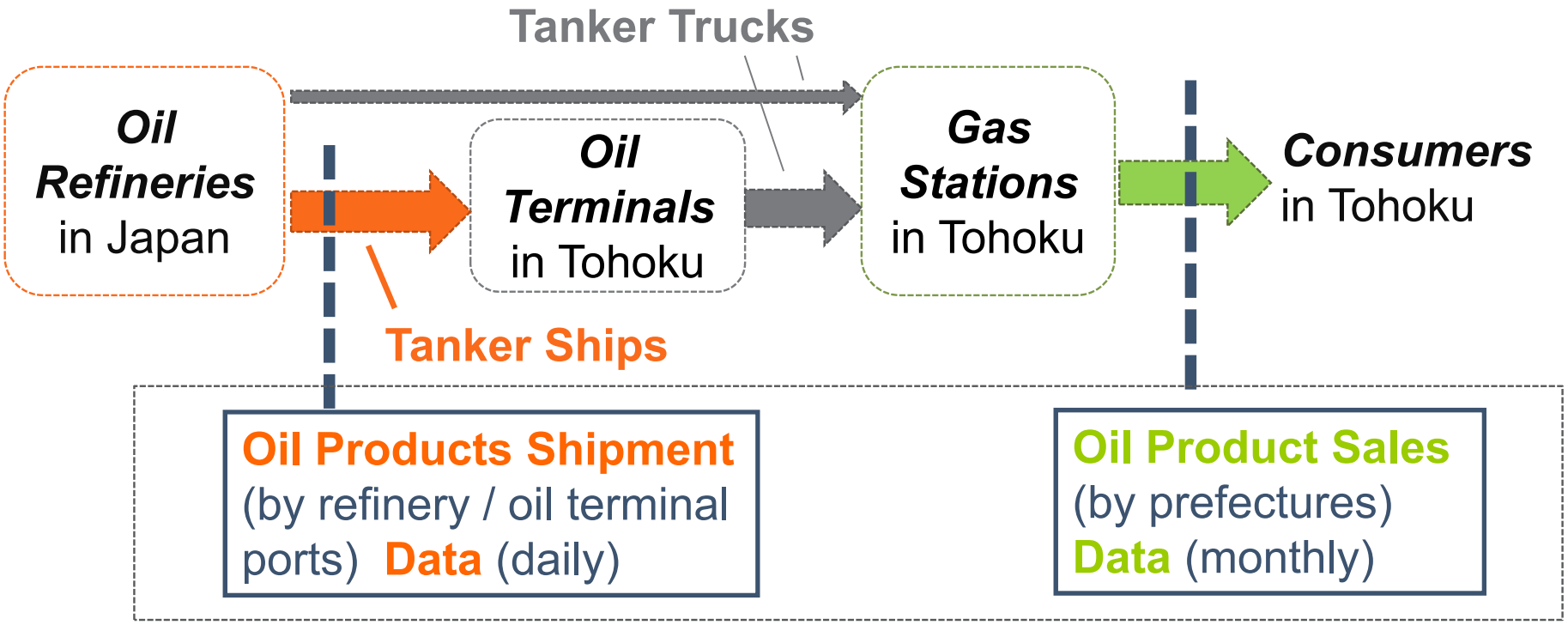
Basic Analysis for the entire Tohoku region

- ***What measures (oil transportation) were implemented ?***
- ***What were the outcomes of those measures ?***
- ***Why the oil shortage lasted nearly a month ?***

Spatio-temporal Analysis based on Quantitative Models

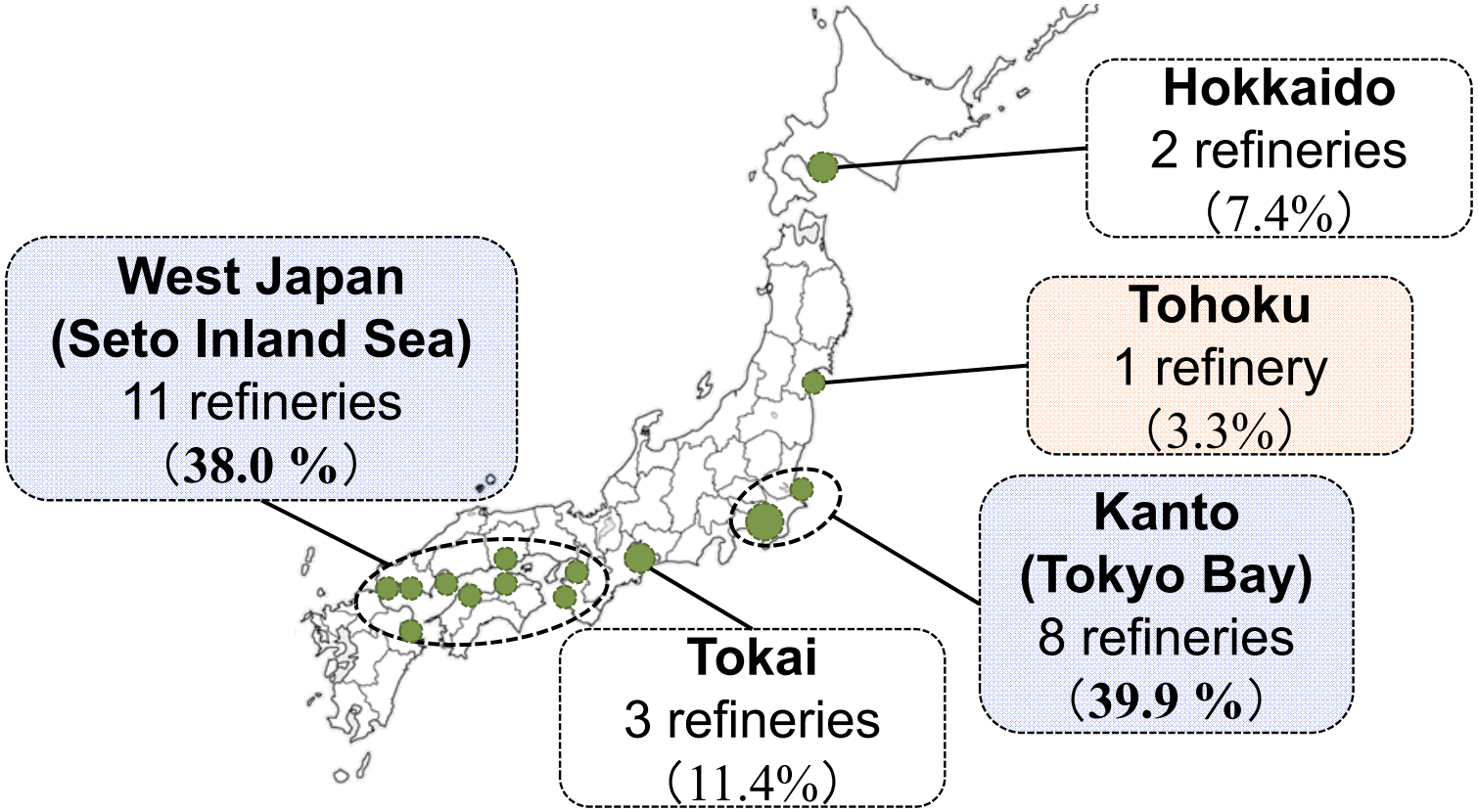
- ***Estimate the development of "demand-supply gaps" by municipality in the Tohoku region.***

Available Data for Estimating Oil Transportation



- Petroleum products: gasoline, diesel fuel, & heating oil
- Regions: 5 Prefectures in Tohoku, excluding of Fukushima (Aomori, Akita, Yamagata, Iwate & Miyagi)

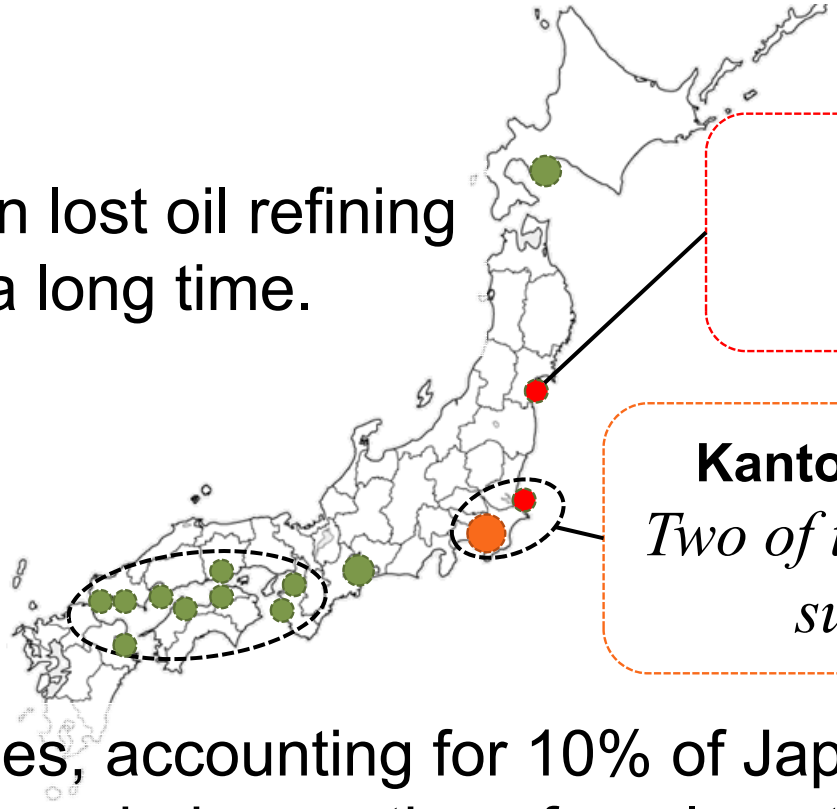
Japan's Refineries and Supply Capacities



- Many of the refineries are concentrated around **Kanto (Tokyo Bay)** and **West Japan (Seto Inland Sea)**.
- **Only one** - Sendai refinery- is located in the **Tohoku** region

Damages to Japan's Refineries by Tsunami

- Tohoku region lost oil refining capacity for a long time.



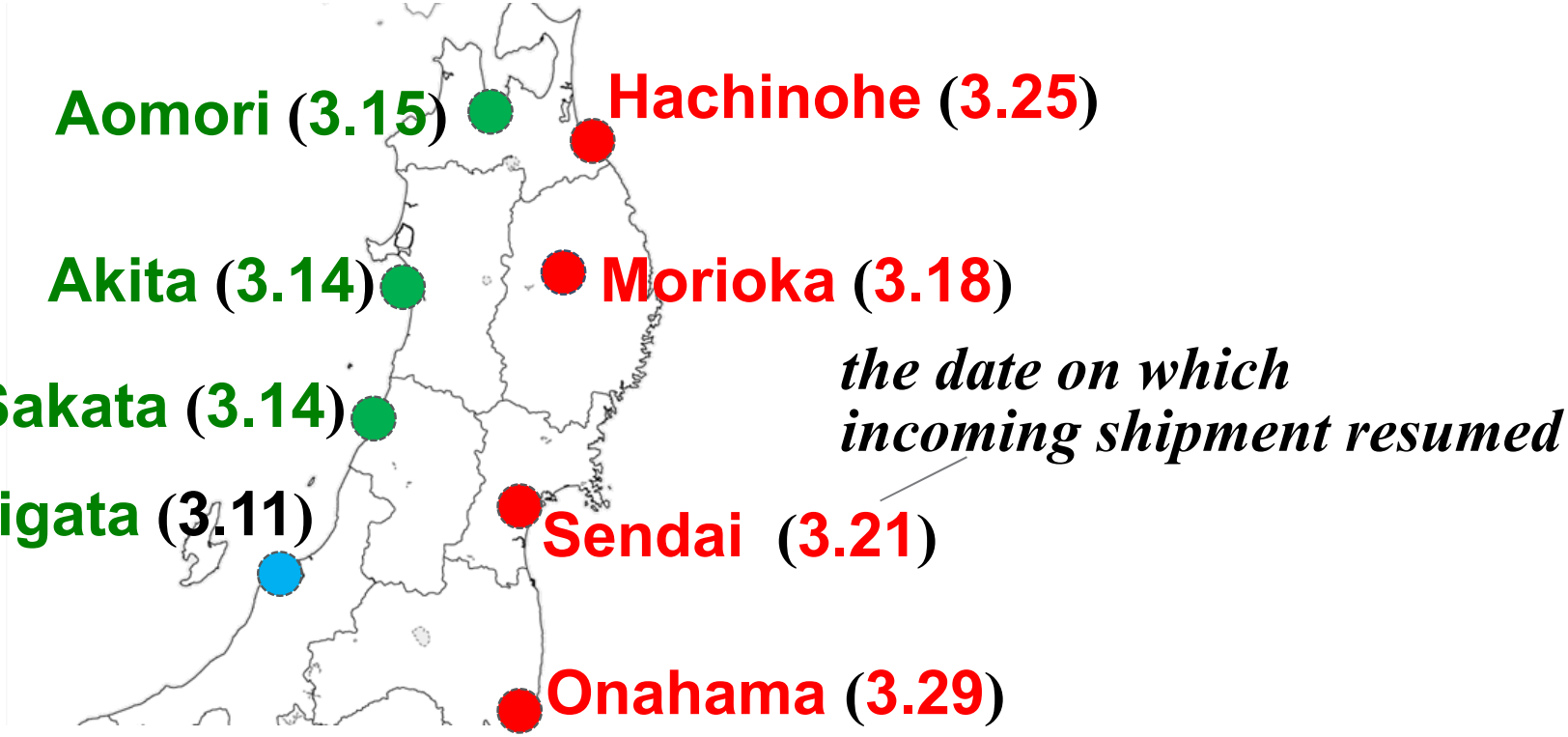
Tohoku
One refinery suspended

Kanto (Tokyo Bay)
Two of the 8 refineries suspended

- Three refineries, accounting for 10% of Japan's total crude capacity, suspended operations for a long time.

➡ ***The damage to refineries was not the fundamental cause of the oil shortage in the Tohoku region.***

Damages to Major Oil Terminals in Tohoku



3.11 – 3.13: all oil terminals (except Niigata) are **inoperable**

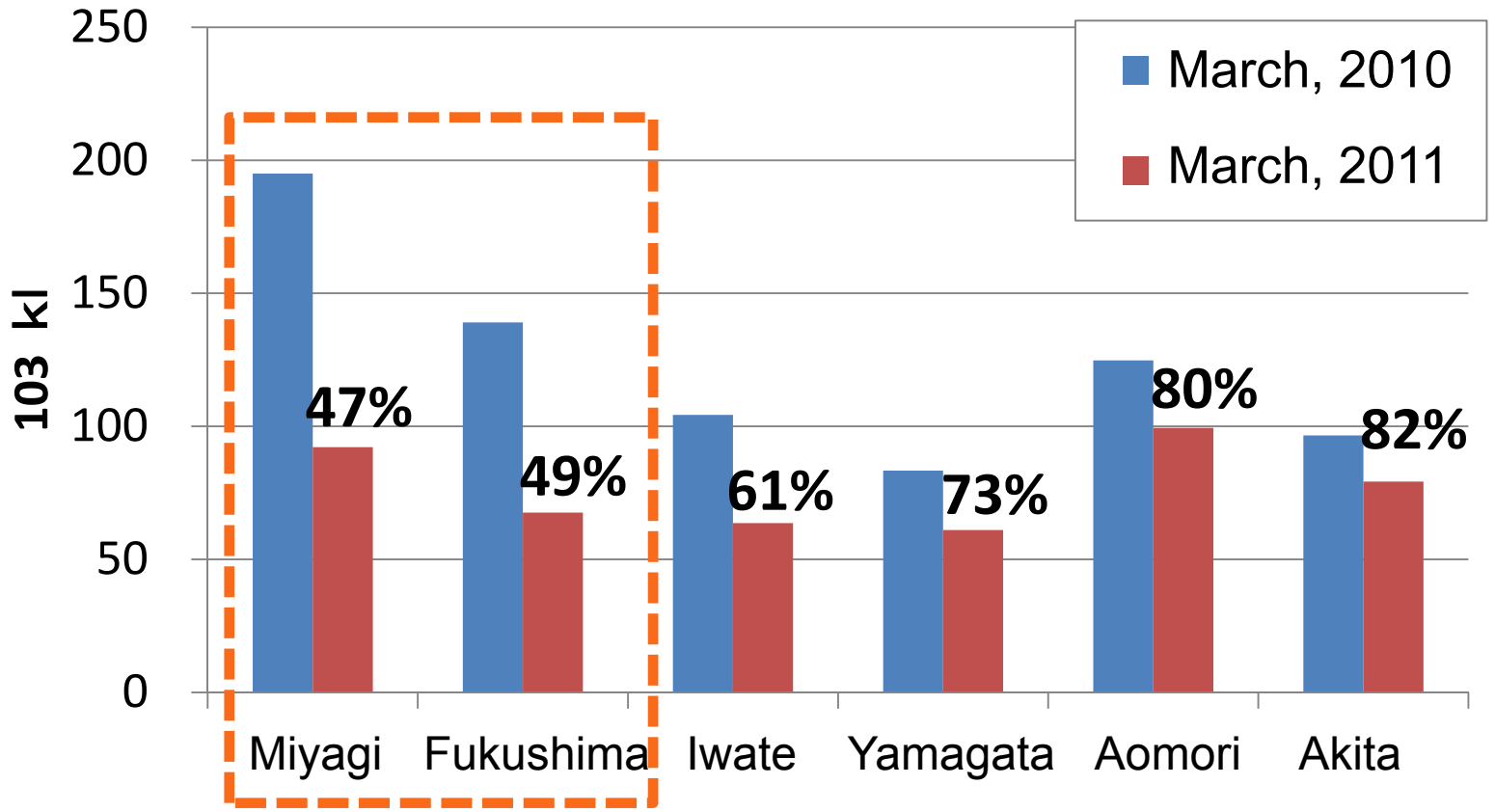
3.14 – 3.21: terminals on the Pacific Ocean are **inoperable**;
only the terminals on the Japan Sea are **operable**.

3.21 - : the Pacific terminals **gradually resume**

What was the Fundamental Cause of the Oil Shortage in Tohoku after 3.11 ?

What Measures were Implemented?

Petroleum Product Sales in Tohoku (3/11~3/31)



Attributing the main cause of the oil shortage to "hoarding by consumers" is evidently wrong !!

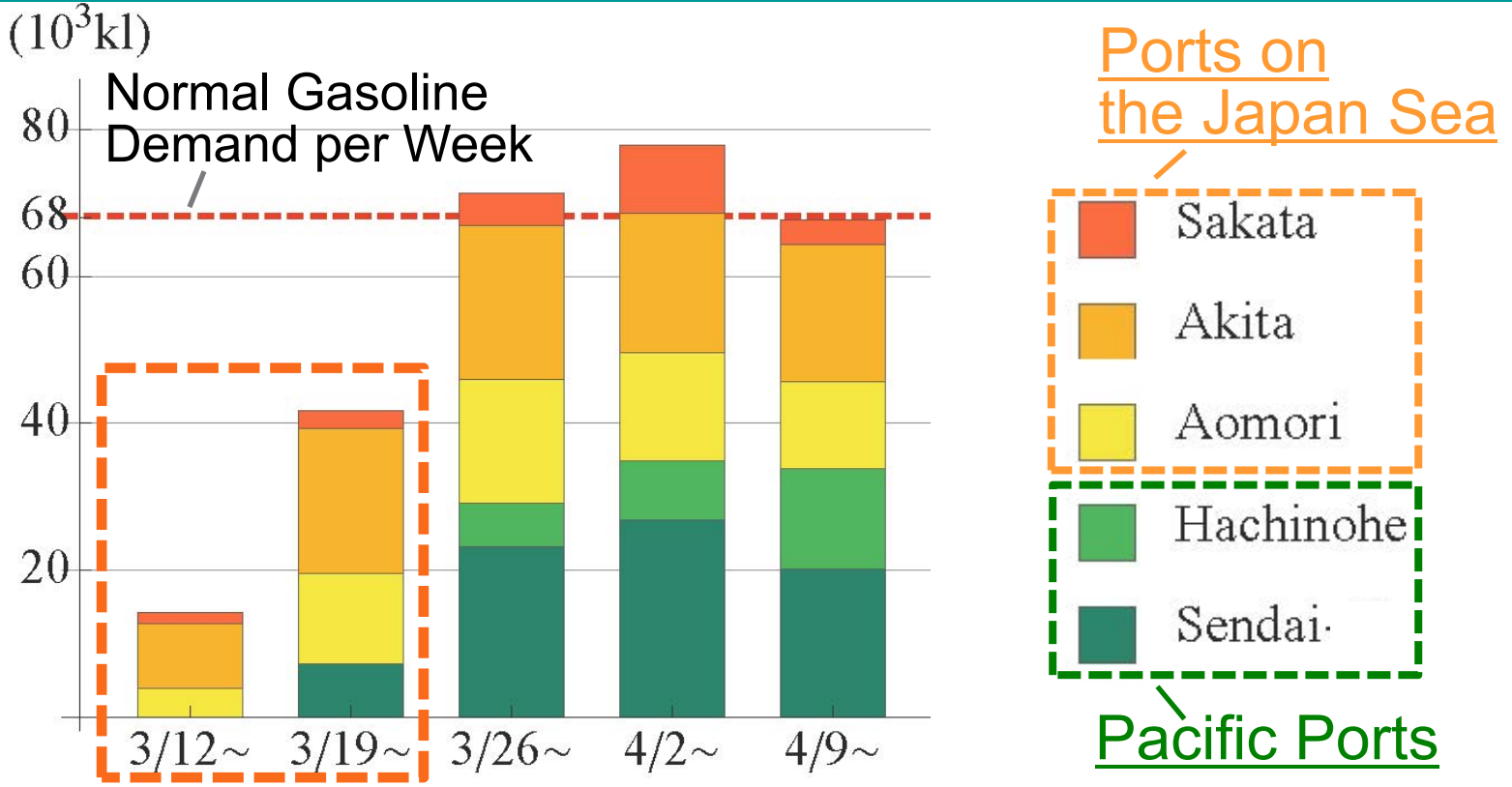
Shipments from Refineries to Tohoku

Comparison of the volumes of oil product shipments from other regions in **one month** before & after the earthquake

	Hokaido	Kanto	Tokai	West Japan	Others	Total
Before (10^3kl)	235	367	21	42	33	698
After (10^3kl)	303	137	31	56	4	530
Increase (10^3kl)	68	-230	10	14	-29	-168

METI declared *(2011.3.17)* ***"20*** *(10^3 kl)* ***per day of oil will be supplied from West Japan"***, *but* ***the actual transported volume was less than 1/10 of the declaration***.

Inbound Shipments to the Ports in Tohoku



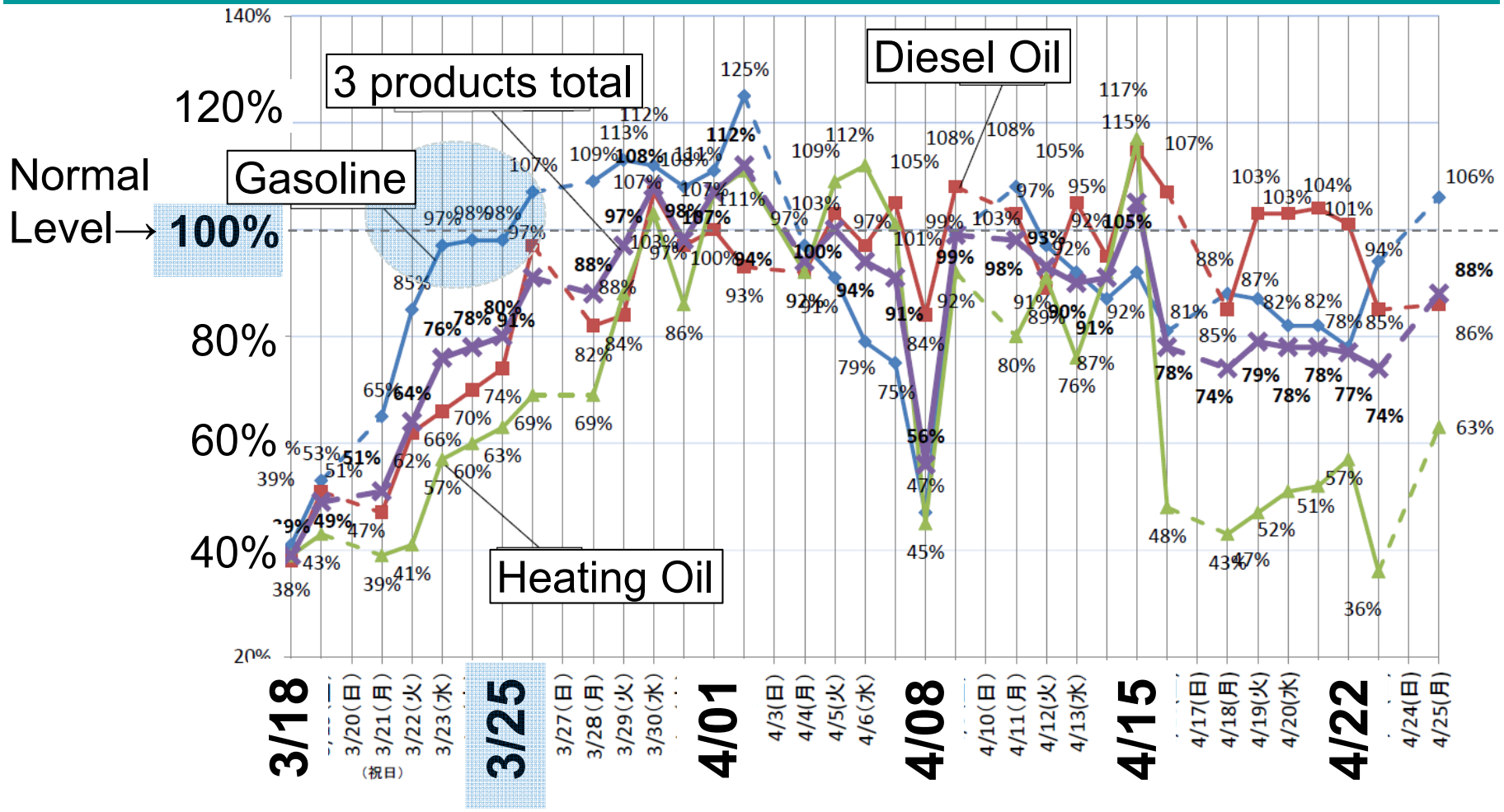
The supply to the entire Tohoku region remained

insufficient until the recovery of the Pacific ports

Why the Oil Shortage Lasted nearly a Month ?

- Analysis of Demand-Supply Gap in Tohoku -

Daily Oil Products Shipment *flow* to Tohoku

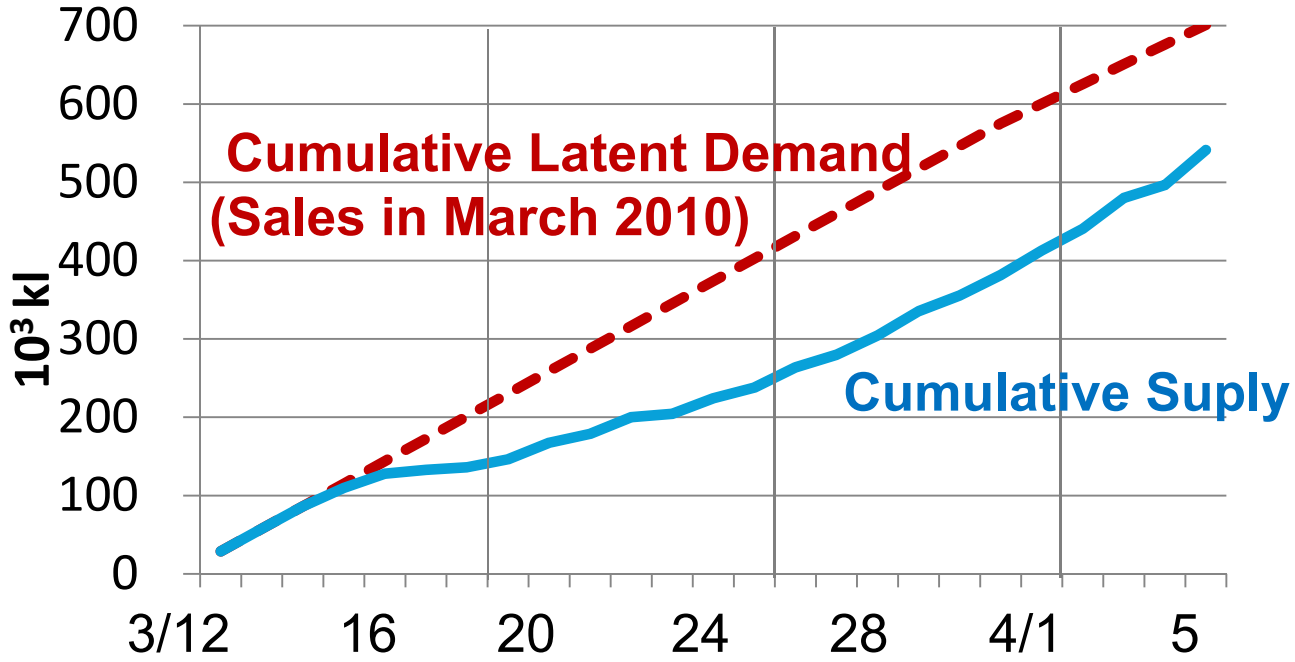


On March 24, gasoline supply recovered to the level of 98%

⇒ ***Gasoline shortage resolved within two weeks ???***

Cumulative Latent Demand & Supply in Tohoku

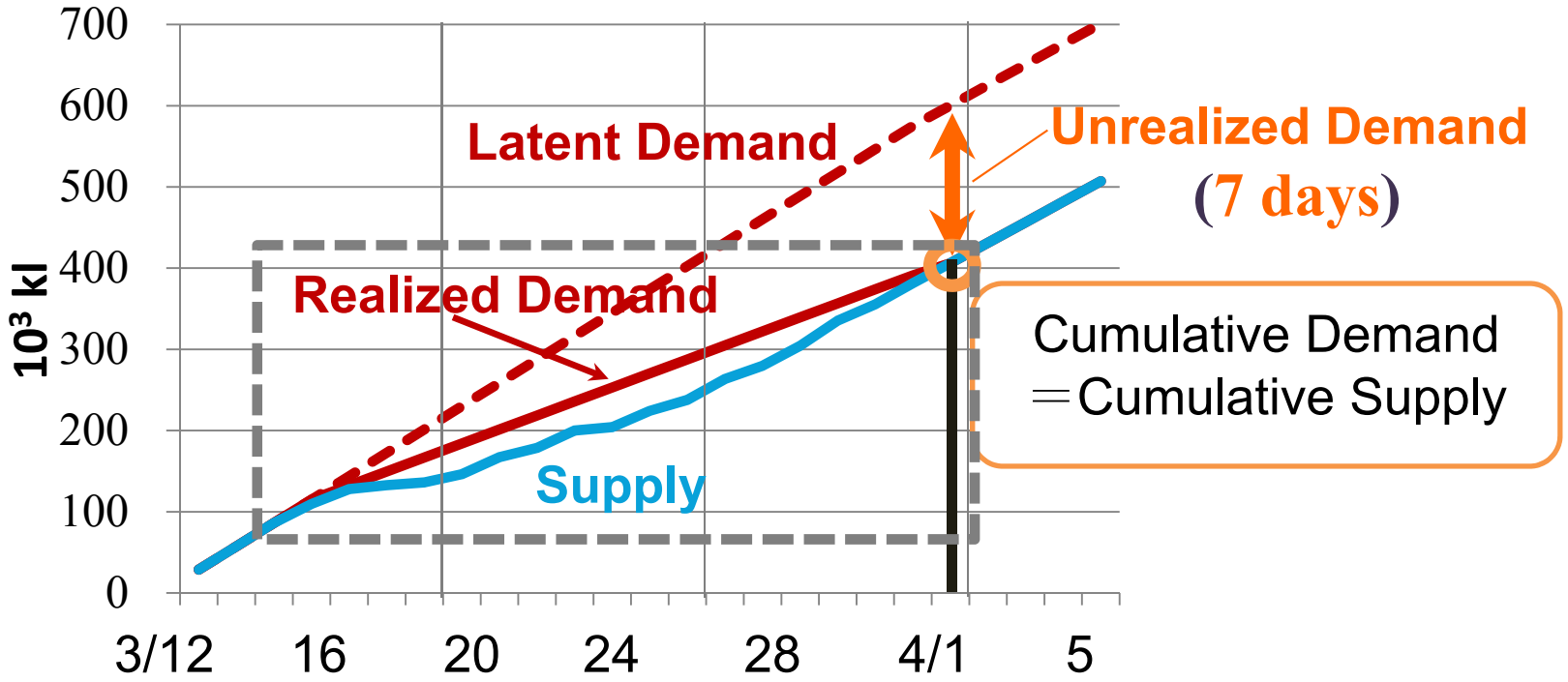
- ***Cumulative Curves*** for Latent Demand & Supply



- Cmltv latent demand continued to exceed cmltv supply

➡ ***Consumers gave up getting a portion of the latent demand*** (*i.e,* "***Unrealized Demand***" *arose*).

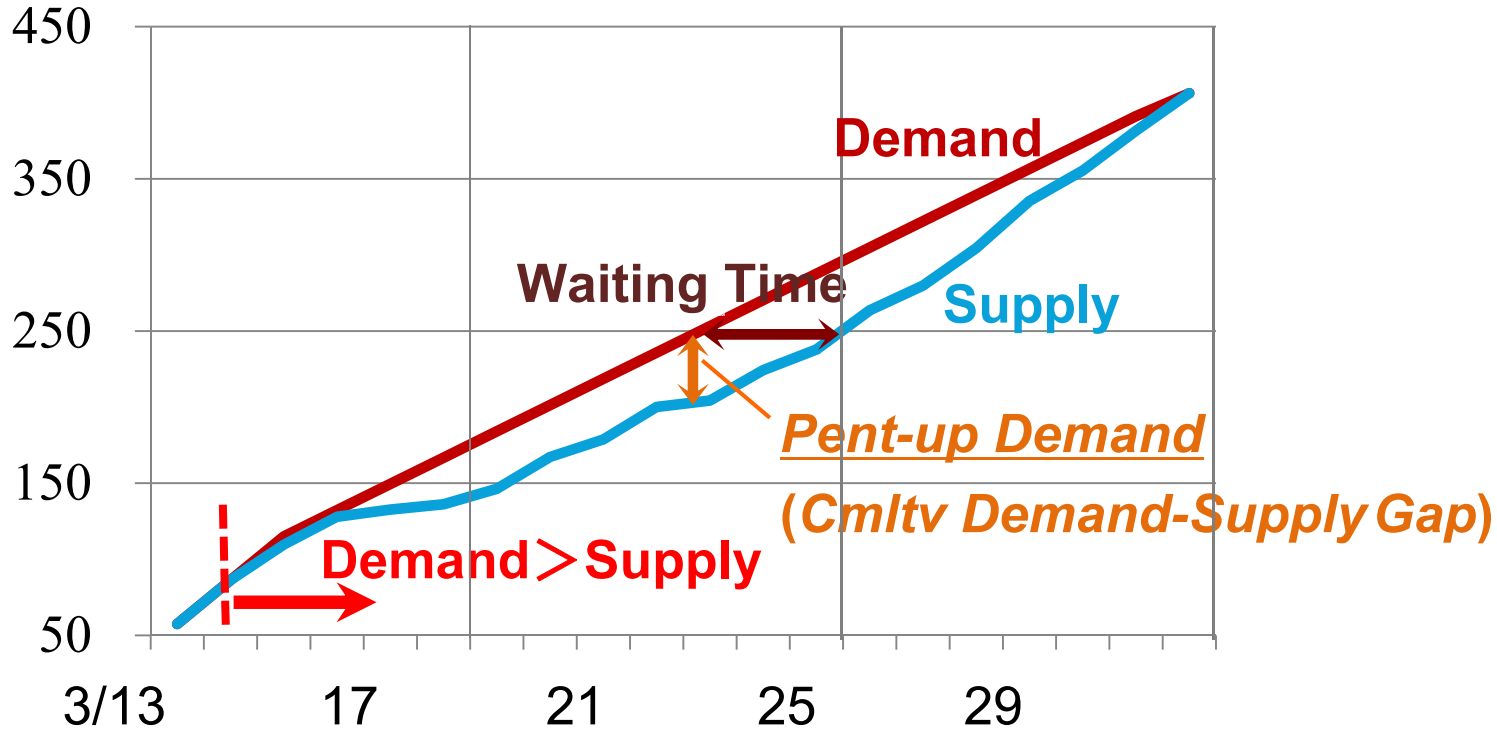
“Unrealized Demand” in Tohoku



- The volume of unrealized demand was approximately 1/3 (**1 week’s worth**) of the latent demand.

➡ ***One week’s worth of economic activities vanished*.**

Aggregate “Demand-Supply Gap” in Tohoku



- Supply shortage for the first two weeks caused building up a huge backlog of demand (***Pent-up Demand***).
- ***It took four weeks for the backlog to be cleared; this is why the oil shortage problem was protracted.***

Conclusion of the Basic Analysis

- Fundamental cause of the gasoline shortage in Tohoku was ***insufficient supply due to the failure to adjust shipping volumes & patterns*** in response to disaster damages.
  - *Attributing to "hoarding by consumers" is wrong*.
  - The amount of gasoline *transported during the two week* after the earthquake was *only 1/3* of the normal demand.
  - The amount brought into the Pacific region from oil terminals along the Sea of Japan was also insufficient.
  - This two-week supply shortage caused the level of cumulative latent demand to substantially exceed cumulative supply, *building up a backlog of demand*.
  - The emergence of the a demand backlog that *lasted a month* resulted in *diminishing 1 week's worth of demand.*

Spatio-Temporal Analysis of Gasoline Shortage in Tohoku Region after the Great East Japan Earthquake

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Outline

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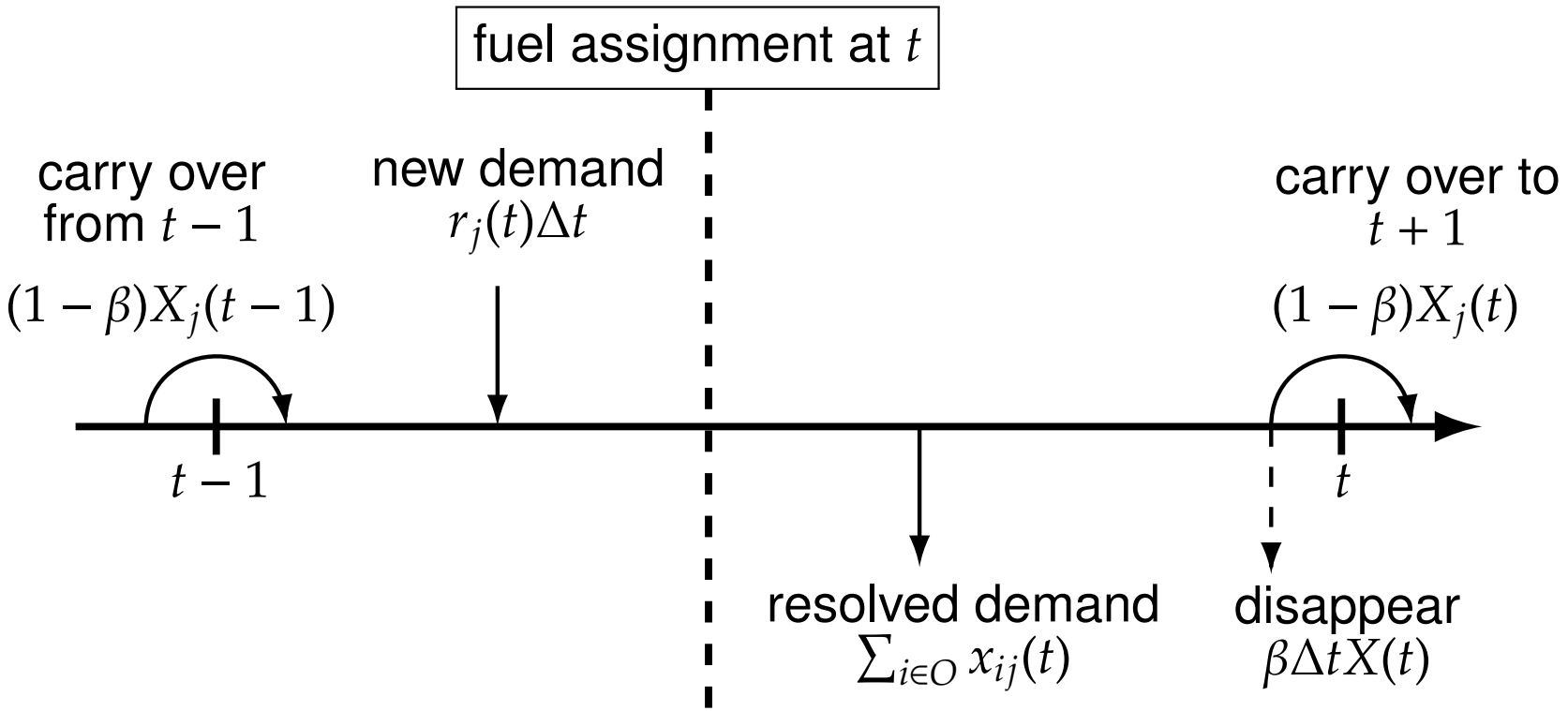
Framework

- $T = \{1, 2, \cdots, \mathrm{T}\}$: set of time periods with interval Δt;
- $O = \{1, 2, \cdots, \mathrm{O}\}$: set of oil terminals (fuel suppliers);
- $D = \{1, 2, \cdots, \mathrm{D}\}$: set of municipalities (fuel consumers).
- Time sequence



Fuel Demand Dynamics (inter-temporal model)

The fuel demand queue at the end of period t follows the dynamics:

$$X_j(t) = \underbrace{\underbrace{(1-\beta\Delta t)X_j(t-1)}_{\text{carry over from } t-1} + \underbrace{r_j(t)\Delta t}_{\text{demand "inflow" at } t}}_{\text{revealed demand at } t} - \underbrace{\sum_{i\in O} x_{i,j}(t)\Delta t}_{\text{demand "outflow" at } t}$$

- $X_j(t)$: Unresolved demand stock (ie. “queue”) at the end of period t of municipality $j \in D$
- $r_j(t)$: Latent fuel demand flow at period t;
- $x_{ij}(t)$: Fuel flow from oil terminal i to municipality j.
- β : Disappearance rate of fuel demand.

Fuel Assignment Model (intra-temporal model)

$$\min_{\boldsymbol{x}(t),\boldsymbol{X}(t)} \sum_{i\in O}\sum_{j\in D} c_{i,j}x_{i,j}(t) \qquad \text{(min. total transptn. cost)}$$

$$\text{s.t.} \sum_{j\in D} x_{i,j}(t)\Delta t = p_i(t), \quad \forall i \in O, \qquad \text{(flow reservation)} \qquad (1)$$

$$\sum_{i\in O} x_{i,j}(t)\Delta t + X_j(t) = q_i(t), \quad \forall j \in D, \qquad \text{(flow reservation)} \qquad (2)$$

$$x_{i,j}(t) \geq 0, \quad \forall (i,j) \in O \times D, \qquad \text{(flow non-negativity)} \qquad (3)$$

$$X_j(t) \geq 0, \quad j \in D \qquad \text{(stock non-negativity)} \qquad (4)$$

- c_{ij} : transportation cost from i to j
- $p_i(t)$: fuel production
- $q_j(t) := (1-\beta\Delta t)X_j(t) + r_j(t)\Delta t$: revealed demand

Model Expansion to Take Fairness into Account

- Measurement of inequality: a weighted entropy of "unresolved rate" of revealed demand

$$\mathcal{H}(\boldsymbol{X}) := -\sum_{j \in D} q_j(t) \left(\frac{X_j(t)}{q_j(t)} \right) \ln \left(\frac{X_j(t)}{q_j(t)} \right) = -\sum_{j \in D} X_j(t) \ln \left(\frac{X_j(t)}{q_j(t)} \right)$$

  - $X_j(t)$: unresolved demand at t (carried over to $t+1$)
  - $q_j(t)$: revealed demand at t

- Fuel assignment model with fairness consideration

$$\min_{\boldsymbol{x}(t), \boldsymbol{X}(t)} \sum_{i,j} c_{i,j} x_{i,j}(t) - \theta \mathcal{H}(\boldsymbol{X}) \quad \text{s.t. (1)} \sim \text{(4)}$$

  - θ : a weight parameter of the inequality against the total transportation cost

Outline

Parameter Estimation I

- Relevant parameters
  Fuel distribution model is characterized by two parameters:
  - β : disappearance rate of fuel demand
  - θ : weight of the inequality against the transpotation cost
- Total sales in each prefecture
  Denote the total sales in prefecture k under (β, θ) for a certain duration $\check{T}$ by

$$\hat{S}_k(\beta, \theta) = \sum_{t \in \check{T}} \sum_{j \in D_k} \sum_{i \in O} x_{i,j}(t) \Delta t = \sum_{j \in D_k} s_j(t) \Delta t n$$

  - $s_j(t) := \sum_{i \in O} x_{i,j}(t)$: fuel sales flow in j at period t;
  - D_k : set of municipalities in prefecture k.

Parameter Estimation II

- Best estimator
  Find the best parameter pair (β^*, θ^*) that explains the actual sales

$$(\beta^*, \theta^*) := \arg\min_{\beta,\theta} \sum_{k \in K} \left| S_k - \hat{S}_k(\beta, \theta) \right|$$

  - K : set of prefecture;
  - S_k : actual fuel sales in prefecture k for the duration $\check{T}$.

Data

- Model settings

set of period, T	03/12 ($t = 1$) to 04/14 ($\mathrm{T} = 35$),2011
oil terminal set, O	Aomori, Hachinohe, Sakata, Sendai-Shiogama and Morioka
municipality set, D	165 municipalities in Tohoku area
target duration, $\check{T}$	03/01 to 03/31, 2011

- Available data set

	data name	duration	precision
(a)	the total gasoline sales	March to April, 2010	monthly, by prefecture
(b)	the total gasoline sales	March to April, 2011	monthly, by prefecture
(c)	the amount of gasoline transported into oil terminals	03/12 to 04/14, 2011	daily, by oil terminal
(d)	the population of municipality	2010	by municipality

- Model inputs

model input	data source
oil production $\{p_i\}$	(c)
latent demand rate $\{r_j\}$	(a),(d)
actual sales S_k	(b)

Estimated Parameters

The best parameter is $(\beta^*, \theta^*) = (0.130, 44.0)$, under which the fuel sales of each prefecture is estimated as follows:

prefecture	actual sales (S_k)	estimated sales ($\hat{S}_k$)	relative error (ϵ_k)
Aomori	80,666	80,676	0.01%
Iwate	47,994	49,145	2.40%
Miyagi	62,877	63,215	0.54%
Akita	64,758	69,701	7.63%
Yamagata	39,074	32,636	-16.48%
		total error(ϵ)	4.36%

relative error: $\epsilon_k := \frac{\hat{S}_k - S_k}{S_k}$, total error: $\epsilon := \frac{\sum_k |\hat{S}_k - S_k|}{\sum_k S_k}$

Outline

Spatial Distribution of Demand-Supply Gap

- Demand-supply (D-S) gap of gasoline in municipality j at τ:

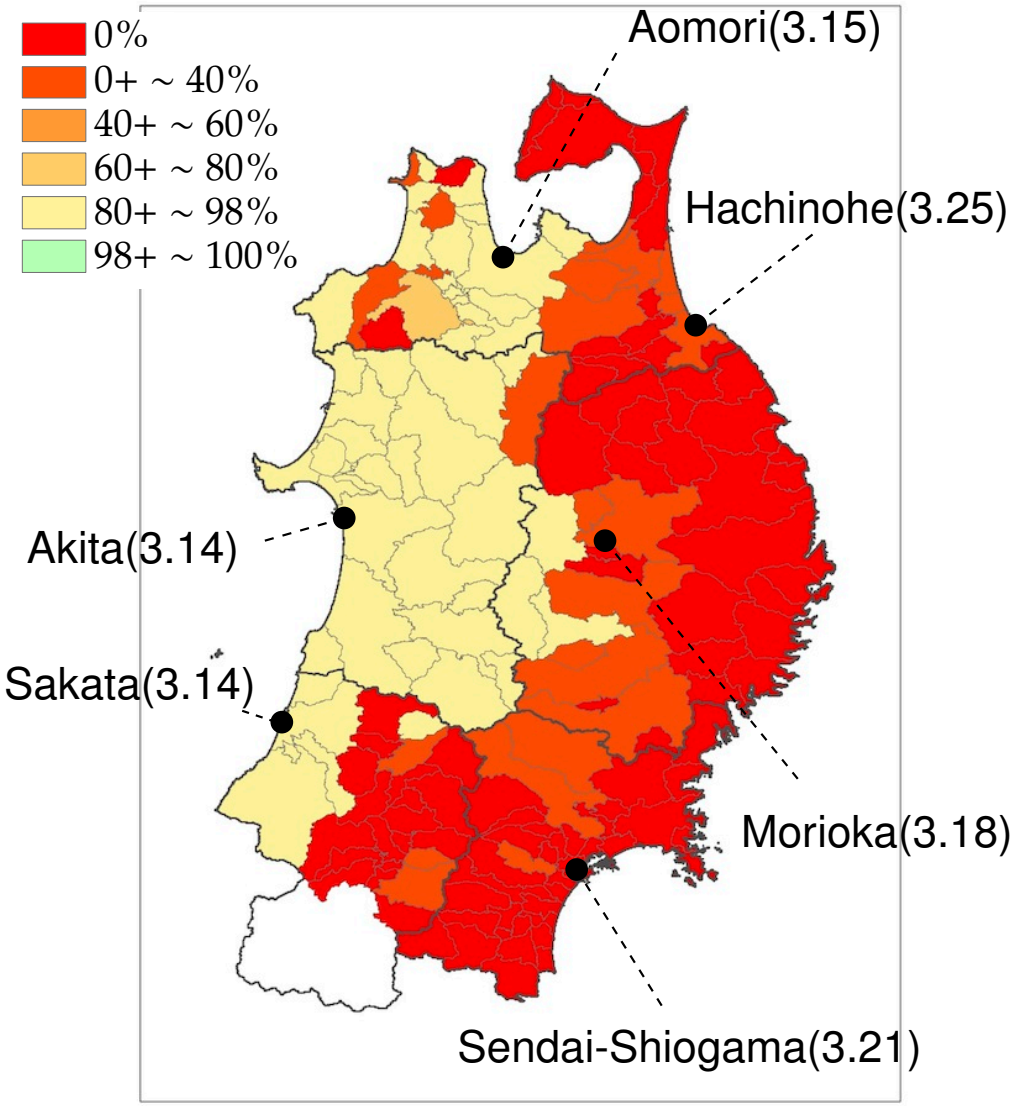
$$G_j(\tau) := \frac{\sum_{t=1}^{\tau} s_j(t)\Delta t}{\sum_{t=1}^{\tau} \left\{ r_j(t) - \beta X_j(t-1) \right\} \Delta t} = \frac{\text{Cmltv supply by } t}{\text{Cmltv realized demand by } t}$$

  - $s_j(t) = \sum_{i \in O} x_{i,j}(t)$: fuel sales flow in j at t;
  - $r_j(t)$: latent fuel demand flow in j at t;
  - $\beta X_j(t-1)$: disappeared fuel demand during the end of $t-1$ to the beginning of t.

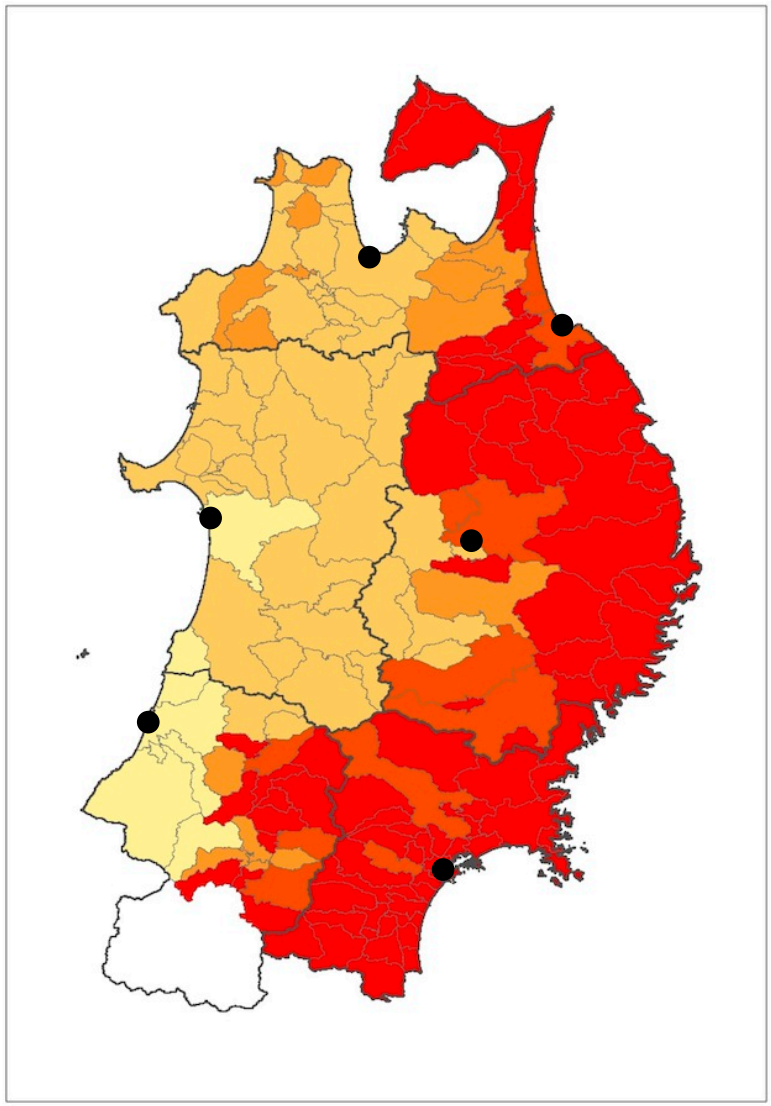
Spatio-Temporal Distribution of Demand-Supply Gap (summary)

- The subsequent 3 show:
  1. It was hard to resolve the D-S gap in the areas along the Pacific Sea. Especially, even 3 weeks after the earthquake, the D-S gaps remained in Miyagi and Iwate, whereas those in other prefectures were almost resolved;
  2. At each day, the D-S gap was greater in the eastern-southern regions compared to the western-northern regions.

Spatial Distribution of Demand-Supply Gap (1st week)

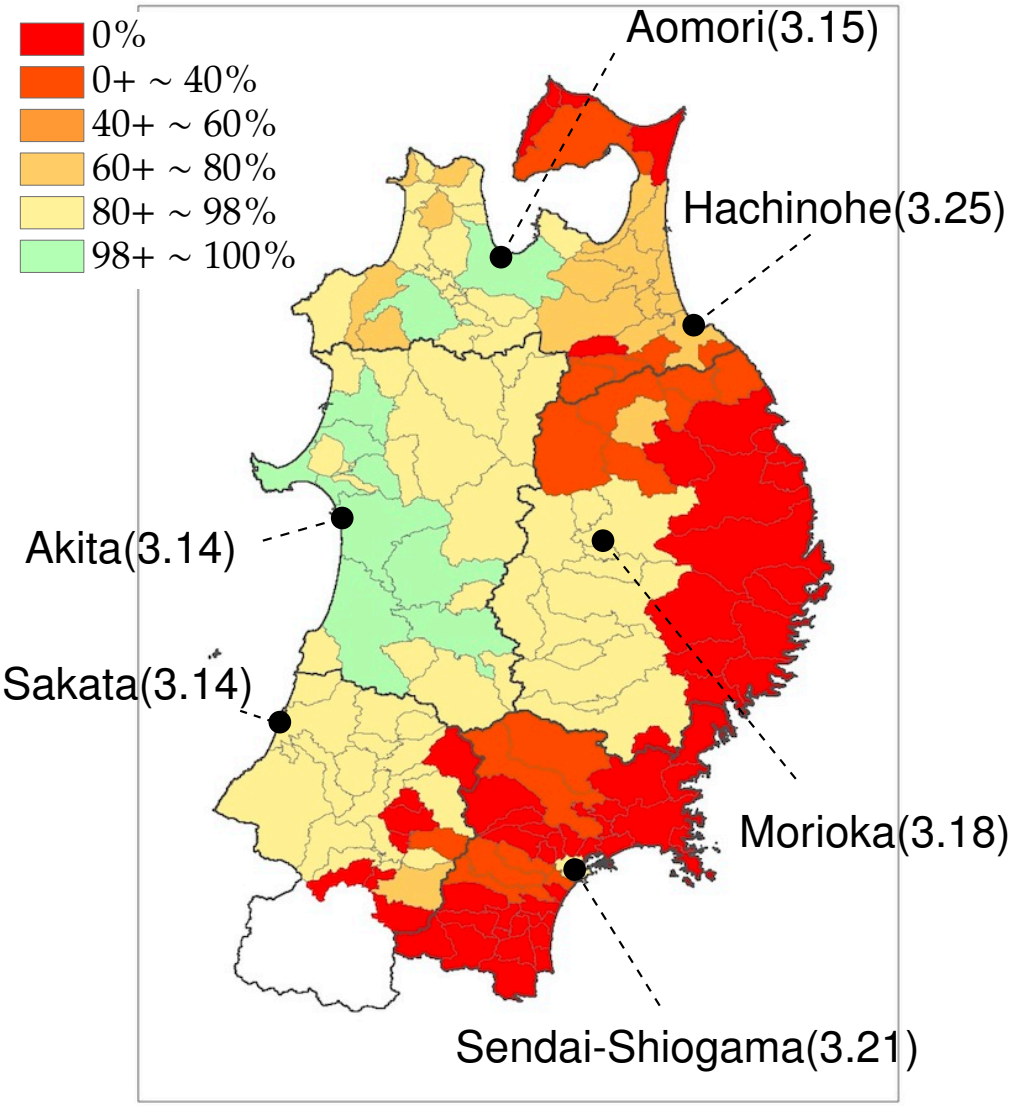


March 15 ($t = 4$)

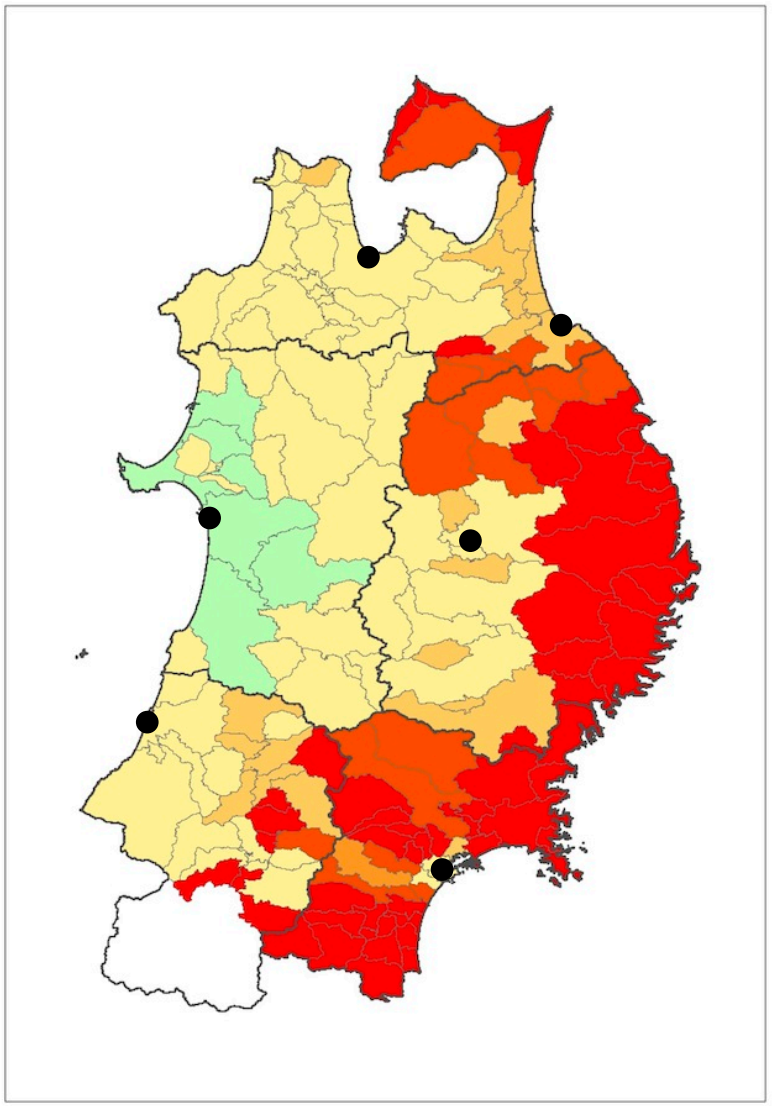


March 18 ($t = 7$)

Spatial Distribution of Demand-Supply Gap (2nd wk)

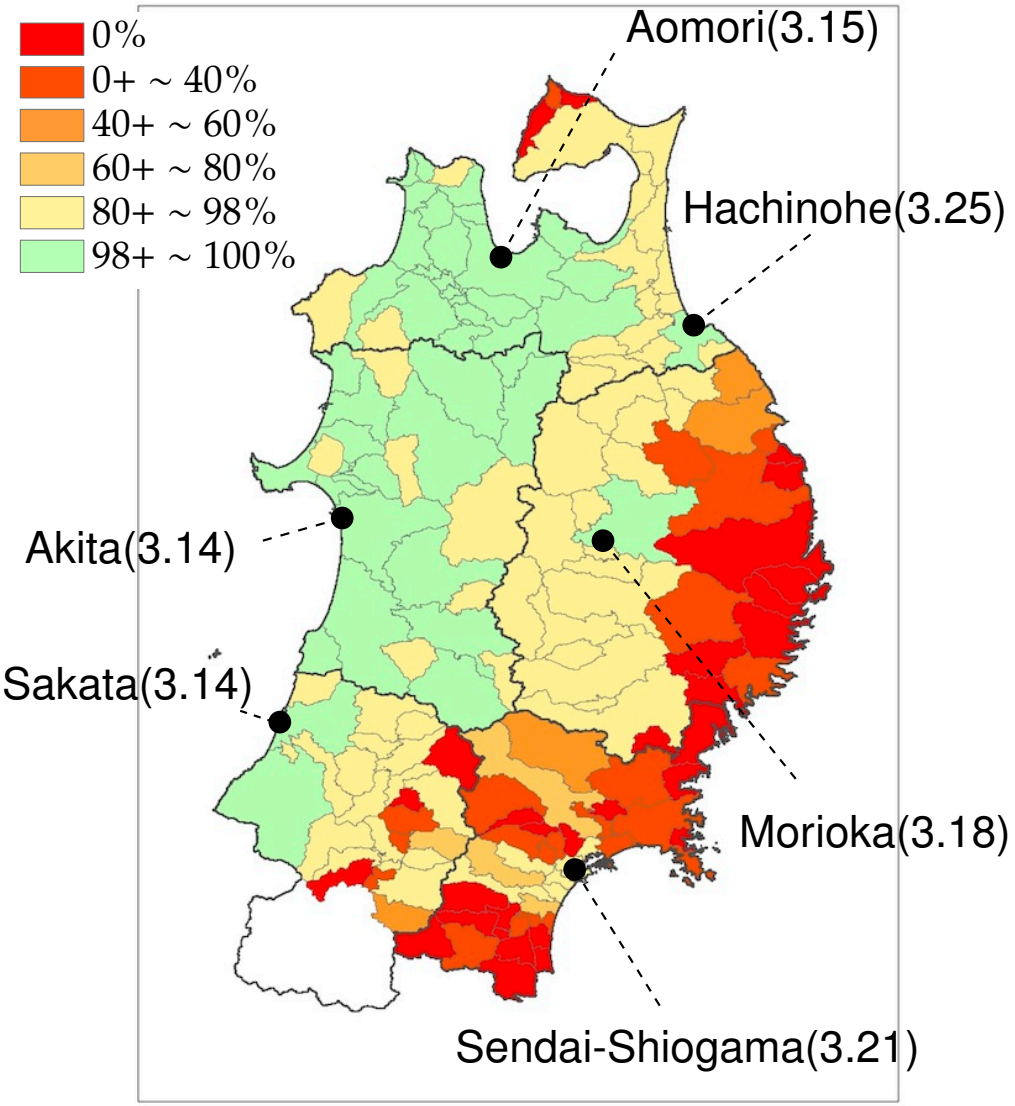


March 22 ($t = 11$)

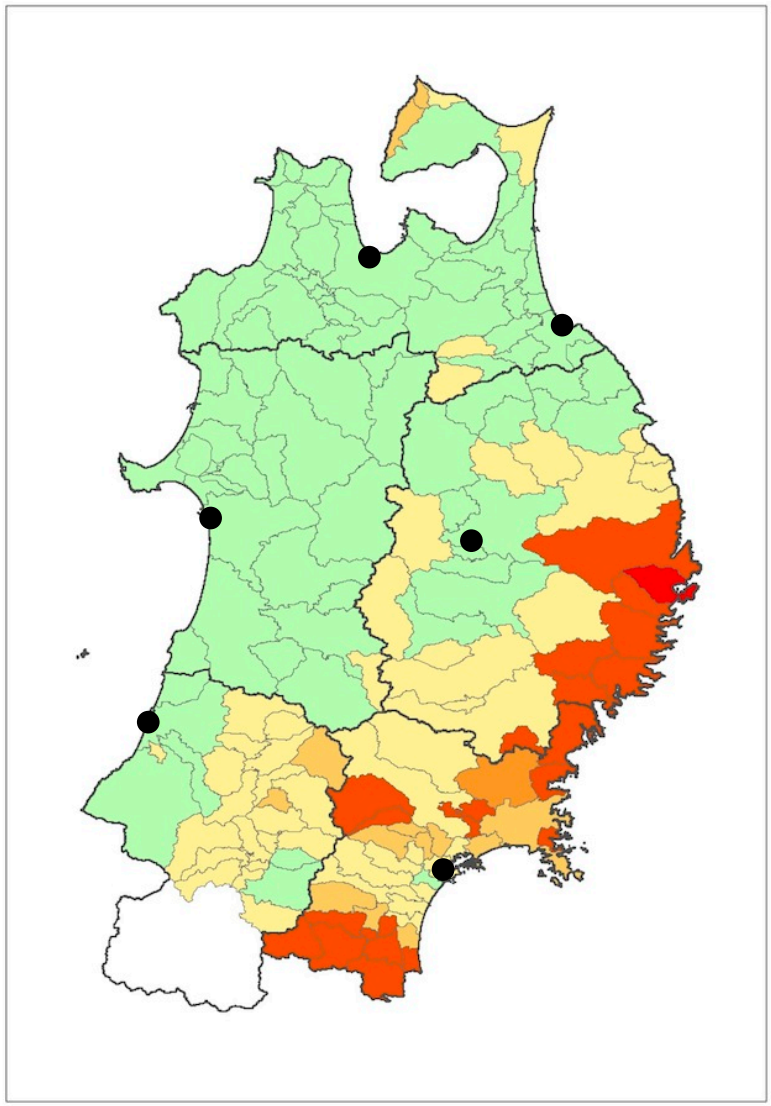


March 25 ($t = 14$)

Spatial Distribution of Demand-Supply Gap (3rd week)



March 29 ($t = 18$)



April 1 ($t = 21$)

Outline

Conclusion

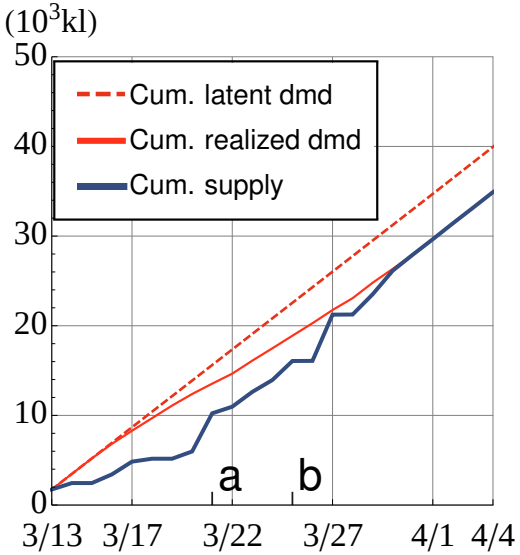
- We developed a model for estimating the spatio-temporal distribution of demand-supply (D-S) gap after Great East Japan Earthquake, taking into account the following aspects:
  1. Demand disappearance due to a huge backlog
  2. Fairness of the gasoline assignments between municipalities.
- Model parameters were estimated from available data
- Obtained spatio-temporal distributions of D-S gap, which show
  1. Even 3 weeks after the earthquake, the D-S gaps remained in Miyagi and Iwate, whereas those in other prefectures were almost resolved;
  2. At each day, the D-S gap was greater in the eastern-southern regions compared to the western-northern regions.

Outline

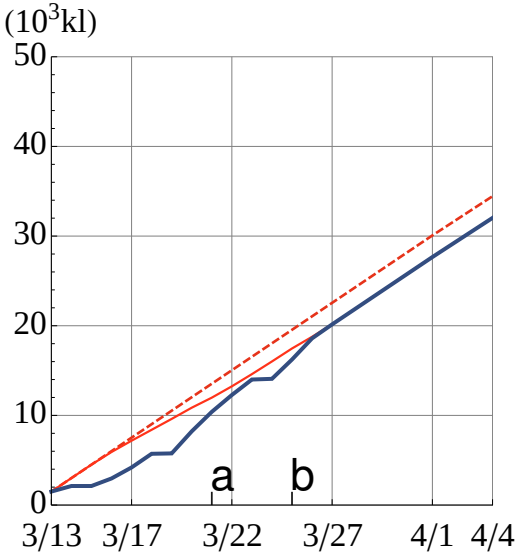
Cumulative Demand and Supply (Definitions)

- $R_j(\tau) = \sum_{t=1}^{\tau} r_j(t)\Delta t$: Cumulative latent demand by τ
- $E_j(\tau) = \sum_{t=1}^{\tau} \beta X_j(t-1)\Delta t$: Cumulative disappeared (pent-up) demand by τ
- $Q_j(\tau) = R_j(\tau) - E_j(\tau)$: Cumulative realized demand

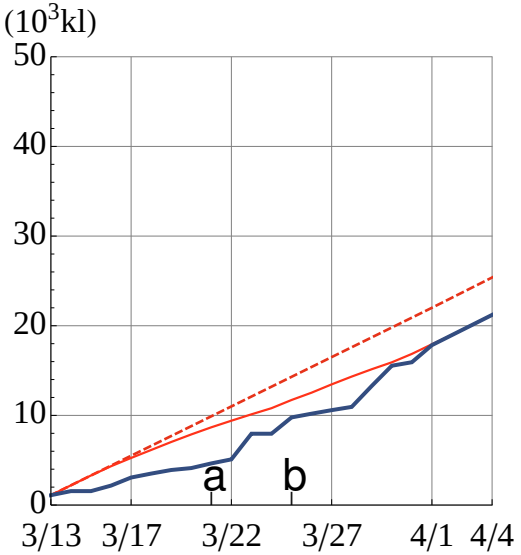
Cumulative Demand and Supply



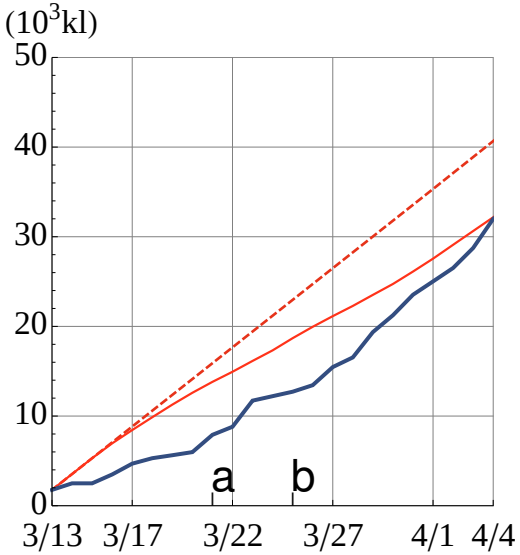
Aomori



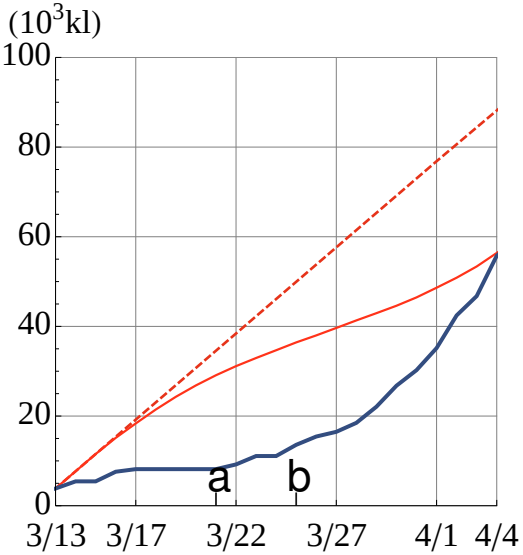
Akita



Yamagata



Iwate



Miyagi

a: Sendai-Shiogama port is opened
b: Hachinohe port is opened