Exploring the Features of Macroscopic Fundamental Diagram and its Formation Mechanism Based on Long-term Detectors Data:

Empirical Studies on Urban Road Networks in Japan

MFD Seminar

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Flow of this presentation

- Section 1
  - Self-introduction
- Section 2
  - MFD features for *Sendai/Kyoto street networks*
  - MFD features for *Naha street networks*
  - MFD features for *Tokyo metropolitan expressway networks*
- Section 3
  - Future research directions

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Section 1

Self-introduction

Resume (1)

- Education
  - Oct. 2013-Sep. 2016: Ph.D., Doctor of Information Science, Tohoku University (Supervisor: Prof. Takashi Akamatsu)
  - Oct. 2008-Sep. 2010: Master of Information Science, Tohoku University
  - Sep. 2004-Jul. 2007: Bachelor of Engineering, North China University of Science and Technology
- Positions
  - Sep. 2016-Present: Lecturer, College of Urban Construction, Hebei Normal University of Science & Technology
  - Sep. 2010-Sep. 2013: Assistant Professor, College of Urban Construction, Hebei Normal University of Science & Technology

Resume (2)

- Association membership
  - Mar. 2015-Present: Editor, *Urban Transport of China* (a refereed academic Journal in China)
  - Mar. 2017-Present: Member, Committee of *World Transport Convention* (WTC)
  - Apr. 2017-Present: Member, Qinhuangdao Municipal Committee of the *Chinese People's Political Consultative Conference* (CPPCC)

Resume (3)

- Awards
  - Sep. 2015: *Professor Fujino Incentive Award*, Tohoku University
  - Jun. 2016: *Construction Engineering Research Award*, Society for the Promotion of Construction Engineering
  - Apr. 2017: *Chinese Government Award for Outstanding Self-financed Students Abroad*, China Scholarship Council

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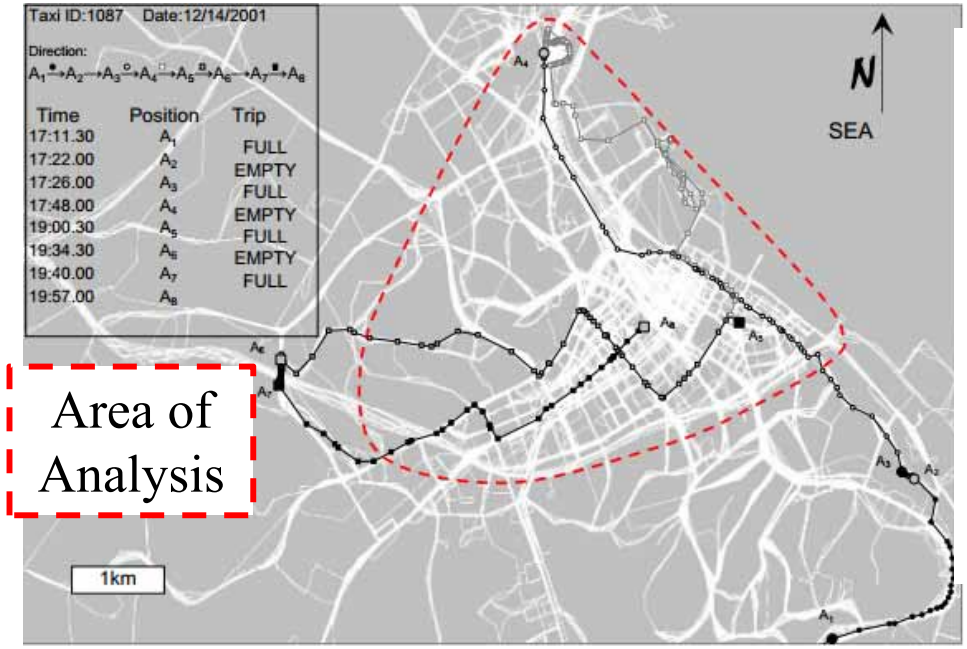
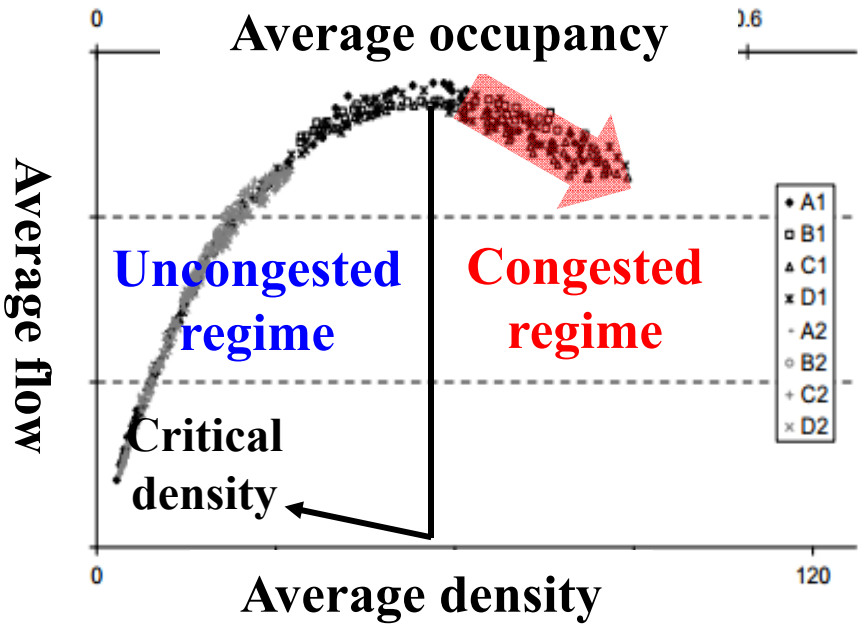
Section 2

MFD features and formation mechanism for some urban road networks in Japan

Literature review (1)

- Geroliminis and Daganzo (2008) [Empirical study]
  - Demonstrated that the well-defined MFD exists with a field experiment in downtown Yokohama, Japan
  - It is reproducible and invariant when the traffic demand changes both within-day and day-to-day



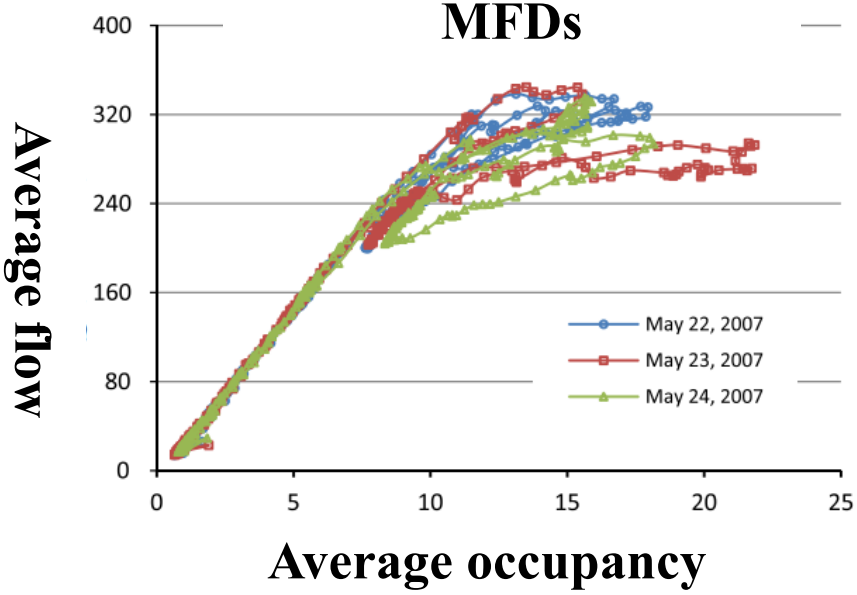


[Geroliminis and Daganzo (2008)]

Literature review (2)

- Analysis on MFD features
  - MFD features: hysteresis loop, congested regime
  - Analyzed the relationship between the MFD features and the spatial distribution of link density

MFDs



Spatial distribution of link density

[Geroliminis and Sun (2011b)]

It is difficult to understand the formation mechanism of the MFD features

Previous empirical studies on MFD (1)

- Urban street networks

Paper	City	Period
Geroliminis and Daganzo (2008)	Yokohama	2 days
Bussion and Ladier (2009)	Toulouse	3 days
Gao (2011)	Stockholm	1 day
Zhu et al. (2012)	Beijing	13 days
Lu et al. (2014)	Changsha	1 day
Tsubota et al. (2014)	Brisbane	7 days
Ji et al. (2012)	Shenzhen	1 day
Saeedmanesh and Geroliminis (2015)	Sydney	1 day

Detectors data from only several days

Previous empirical studies on MFD (2)

- Expressway networks

Paper	City	Period
Bussion and Ladier (2009)	Toulouse	3 days
Cassidy et al. (2011)	California	7 days
Geroliminis and Sun (2011b)	Minneapolis	3 days
Saberi and Mahmassani (2012)	Portland	5 days
Saberi and Mahmassani (2013)	Irvine and Chicago	4, 6 days
He et al. (2014)	Beijing	1 day
He et al. (2015)	Beijing	4 days
Yao et al. (2016)	Shanghai	18 days
Fu et al. (2017)	Shanghai	18 days

Limitations of previous empirical studies

- The number of empirical studies is few (especially, for urban street networks)
  - They used data for only several days at most, which may be insufficient to investigate the robust features of MFD
  - They do not verify the findings from simulation studies are whether established robustly in real road networks or not

- Do not capture formation mechanism of MFD features
  - They do not explore the relationship between the MFD features and spatial congestion pattern on networks
  - They do not establish a model to explain the formation mechanism of MFD features

Purposes of this thesis

- Clarify the robust features of MFD for some urban street and expressway networks (in Japan)
- Explain the formation mechanism of MFD features
  - Firstly, we need to examine the relationship between the MFD features and the spatial congestion pattern
  - Secondly, based on the relationship, we establish a model to explain the formation mechanism of MFD features

- To achieve the goals, we use ***long-term detectors data***
  - 5/1/2012 ~ 4/30/2013: Sendai, Kyoto, Naha street networks
  - 1/1/2014 ~ 12/31/2014: Tokyo expressway networks

Organization of Section 2

	Section 2.1	Section 2.2	Section 2.3
Country	Sendai Kyoto	Naha	Tokyo
Network Type	Street	Street	Expressway
MFD Features	Hysteresis Loop	Congested Regime	Hysteresis Loop Congested Regime

Section 2.1

	Section 2.1	Section 2.2	Section 2.3
Country	**Sendai Kyoto**	Naha	Tokyo
Network Type	**Street**	Street	Expressway
MFD Features	**Hysteresis Loop**	Congested Regime	Hysteresis Loop Congested Regime

Contents of **Section 2.1**

- Basic information of detectors data
  - Road networks and detectors data
  - MFD definition
- Characterization of MFDs
  - MFD classification
  - MFD features under different demand/supply conditions
    - Traffic demand: weekday vs. weekend
    - Network supple: sunny day vs. bad weather day
- MFD features vs. Congestion pattern
  - Number of queue-spillbacks
  - Spatial distribution of congested links
  - Discussion for the relationship

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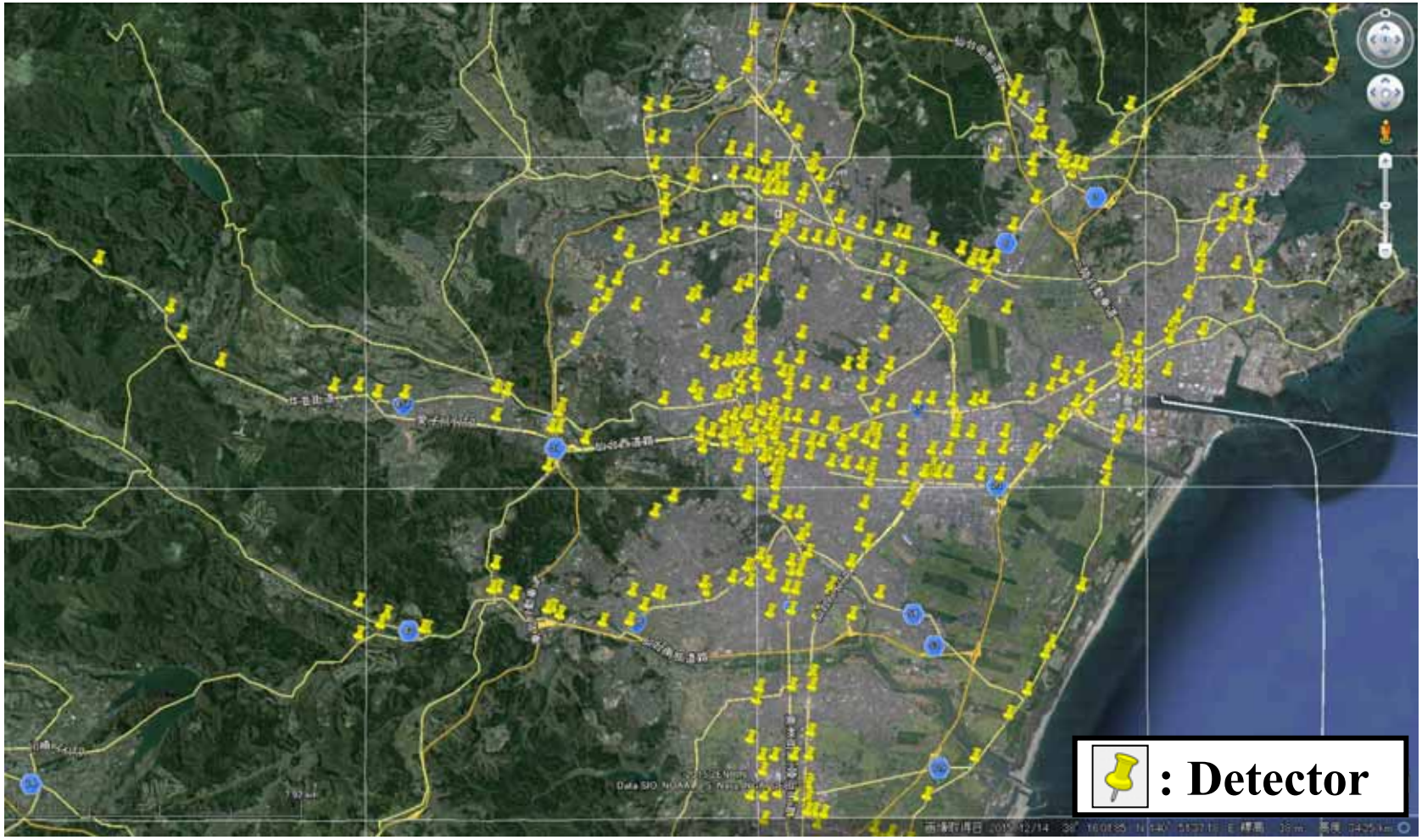
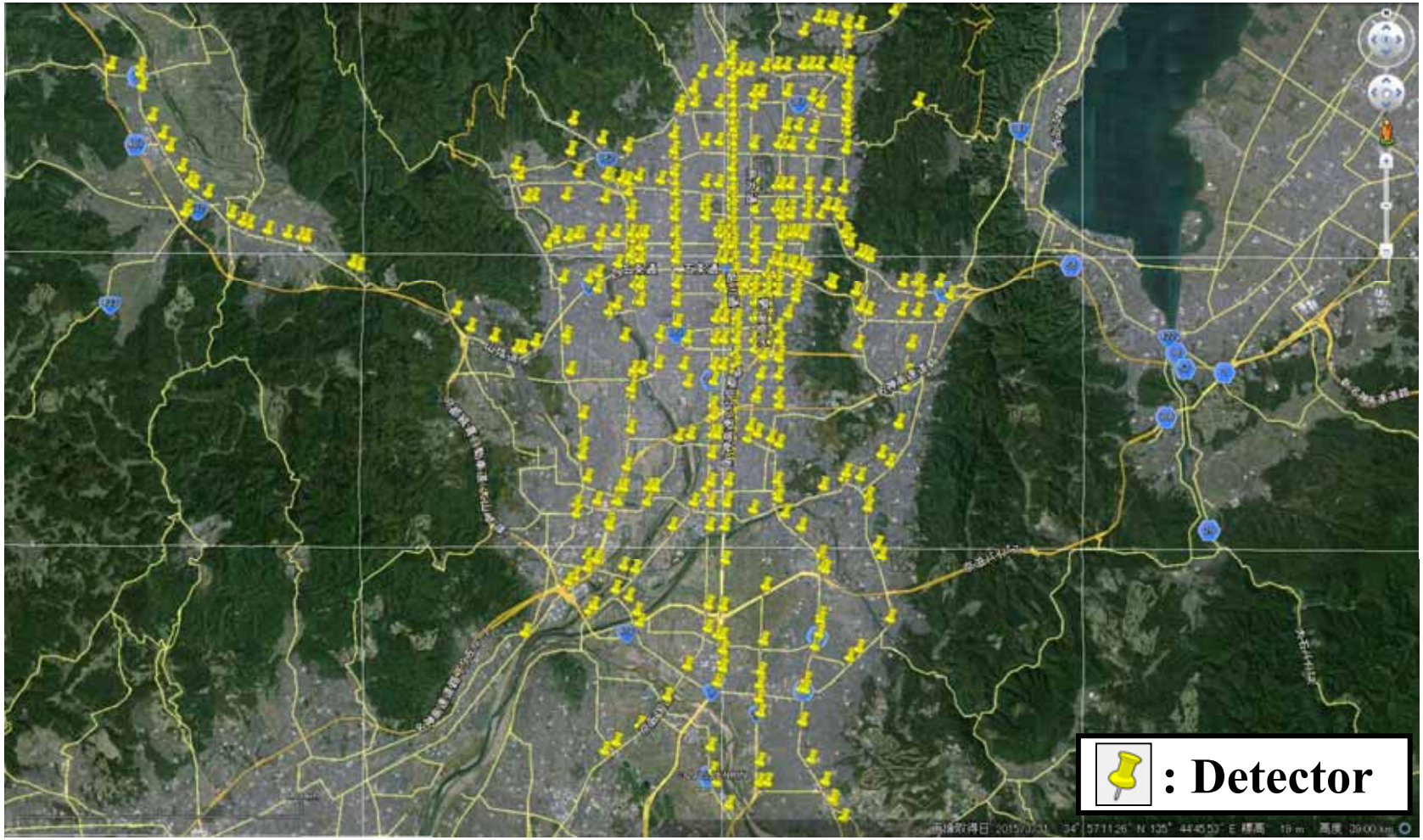
Basic information of detectors data (1)

- Sendai street networks
  - Number of detectors: 878



Basic information of detectors data (2)

- Kyoto street networks
  - Number of detectors: 831



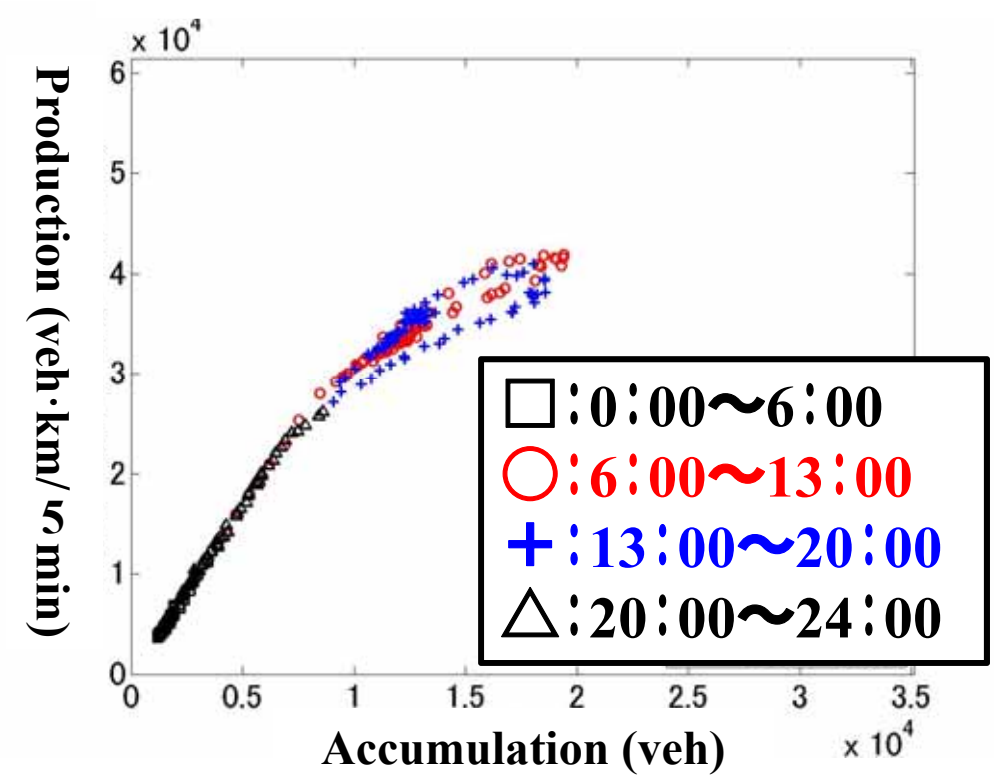
Basic information of detectors data (3)

- Analysis period
  - 5/1/2012 ~ 4/30/2013 (One year)
    - Sendai: 336 days (about 92.5% of one year)
    - Kyoto: 346 days (about 94.8% of one year)
  - 5-min period during each 24-h day (T=288)

- Data records of detector *i* during *t* (5-min period)
  - Traffic flow: q_t^i
  - Vehicle speed: v_t^i
  - Traffic density: $k_t^i = q_t^i / v_t^i$

MFD definition

- The calculation of coordinates for each plot
  - Accumulation: $N_t = \sum_{i=1}^{|I|} k_t^i l^i = \sum_{i=1}^{|I|} \left(q_t^i / v_t^i \right) l^i$
  - Traffic production: $P_t = \sum_{i=1}^{|I|} q_t^i l^i$ l^i:length of link i



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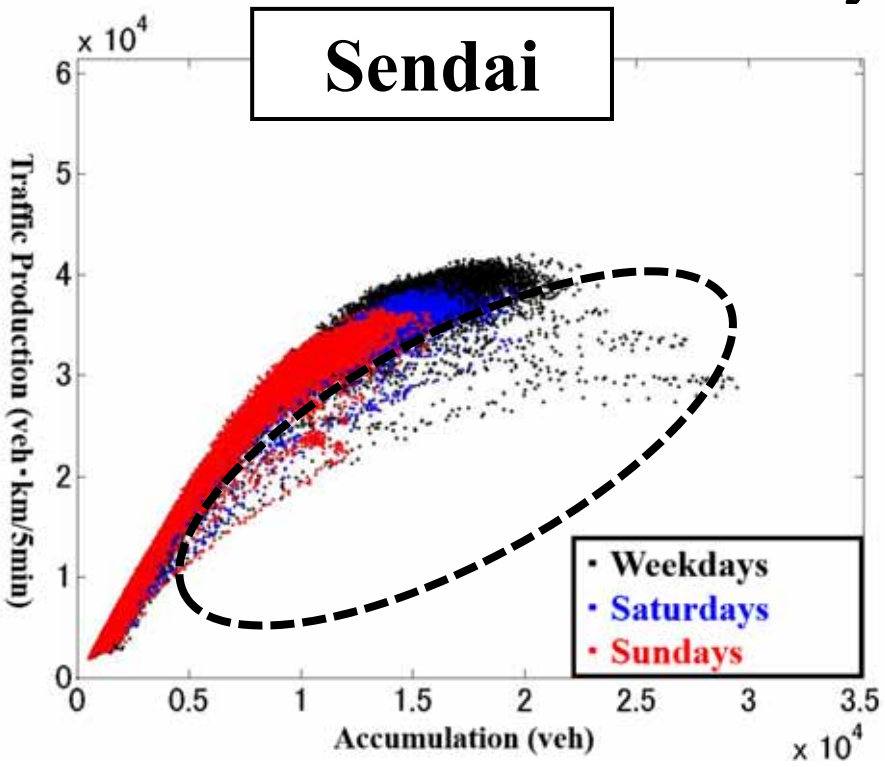
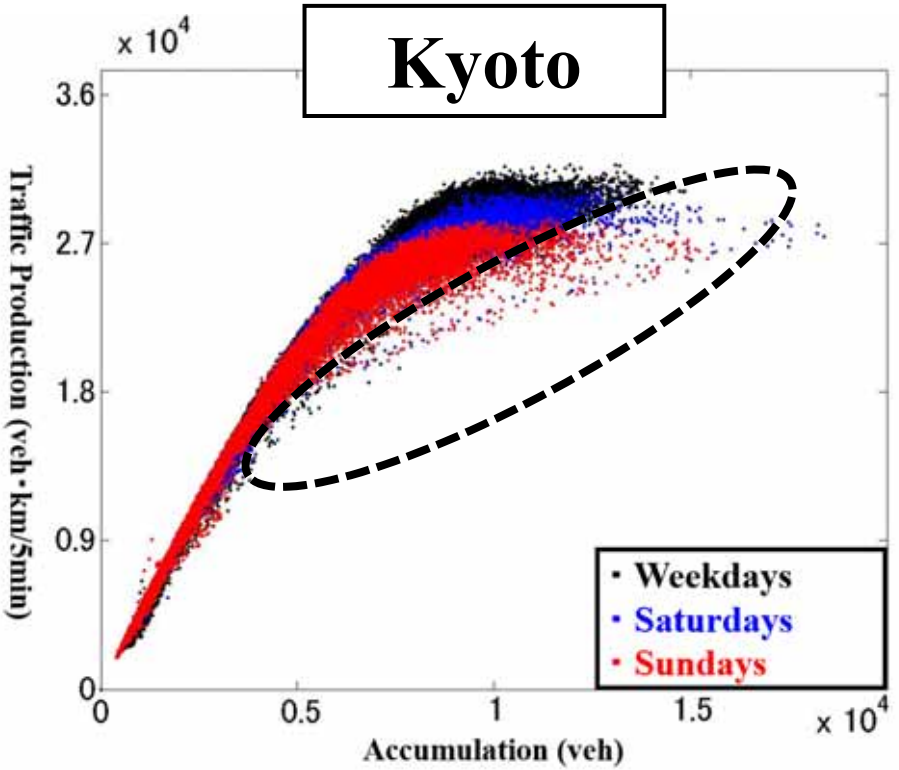
MFD classification

- MFDs for the entire year

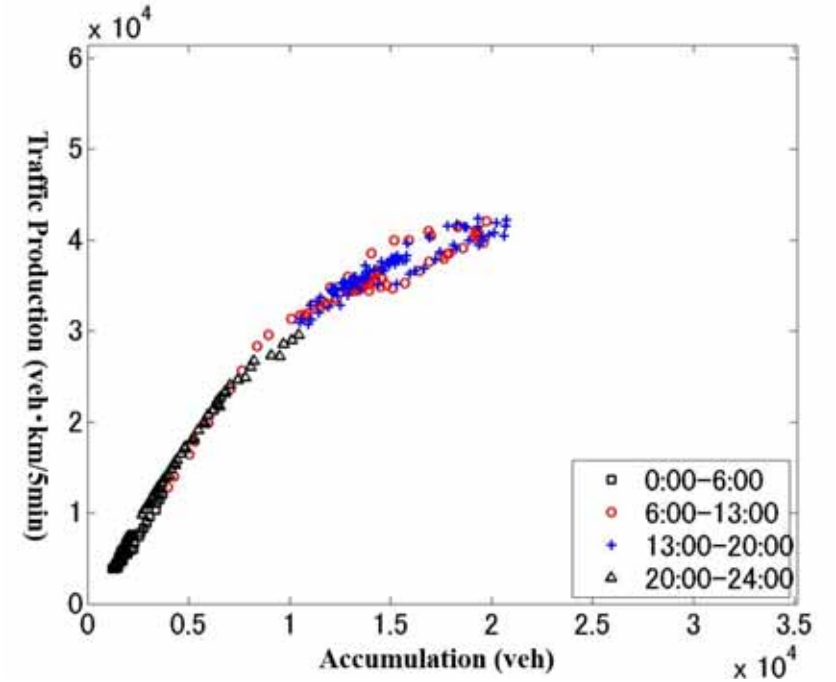


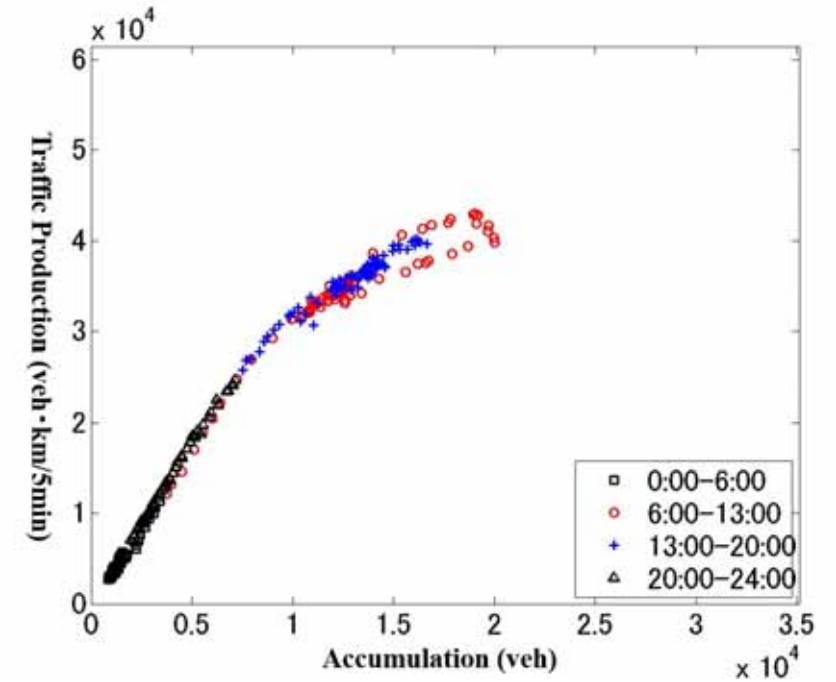


- Congested regime does not occur in these two networks
- The traffic production is low obviously on only several bad weather weekdays or weekends (within dashed lines)

MFDs on different demand condition (1)

- MFDs on sunny weekdays, Sendai

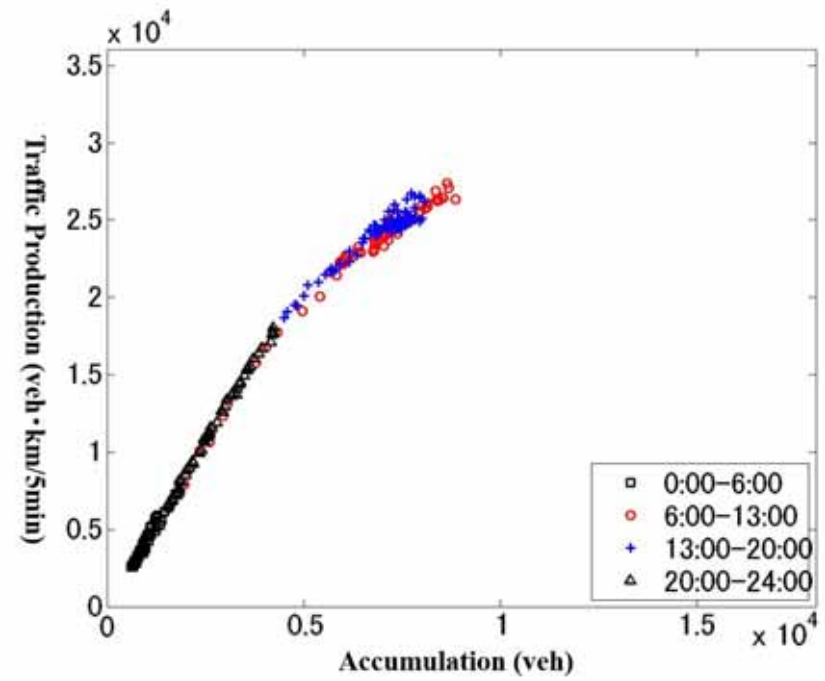


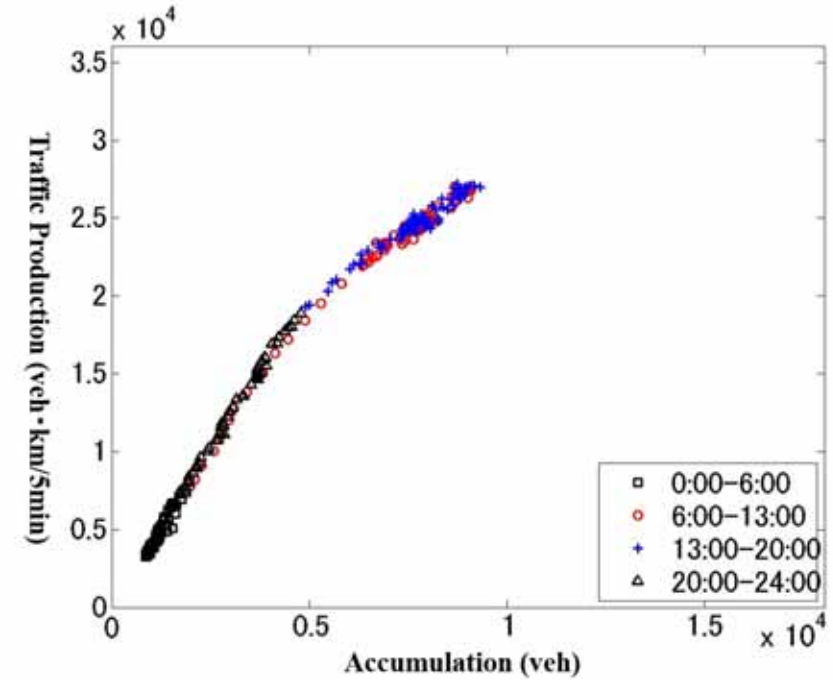


- Morning peak hours: (a single) hysteresis loop must form
- Evening peak hours: (a single) hysteresis loop may form (64.2%) or it may not

MFDs on different demand condition (2)

- MFDs on sunny weekdays, Kyoto

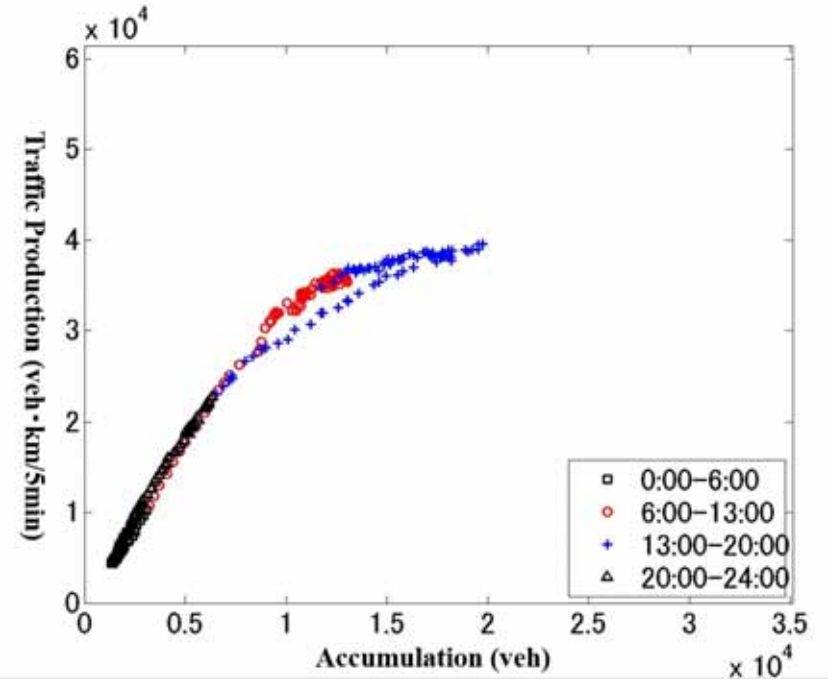


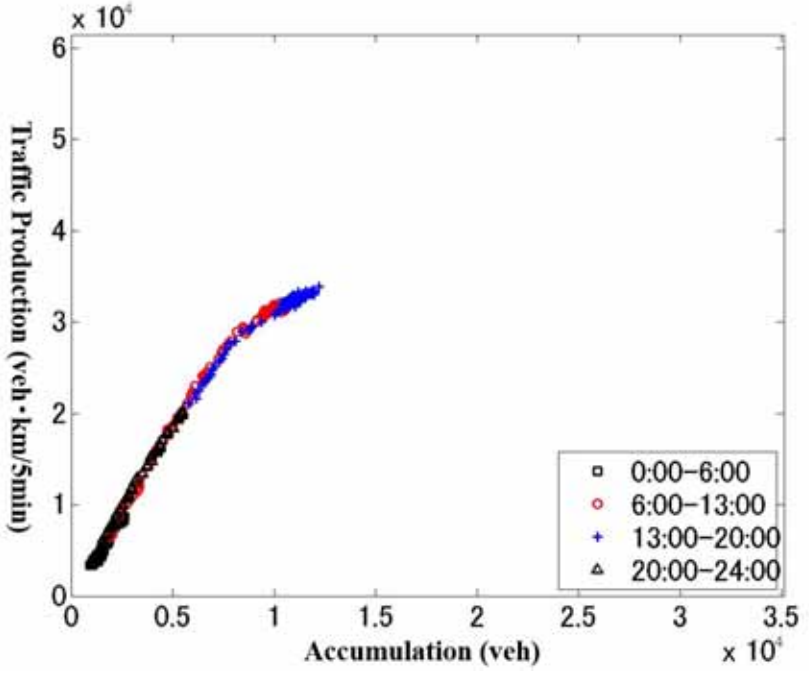


- Hysteresis loop does not form in MFDs

MFDs on different demand condition (3)

- MFDs on sunny weekends, Sendai

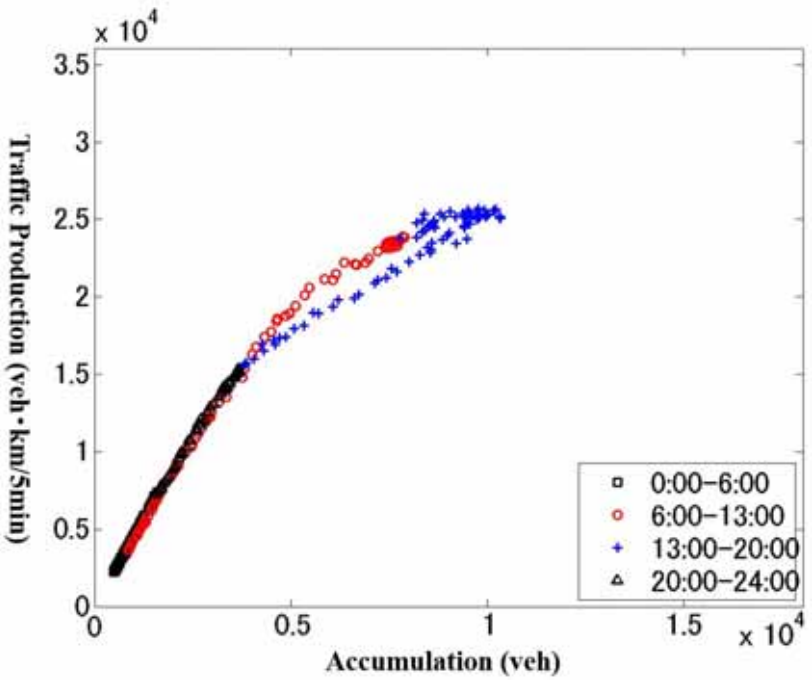


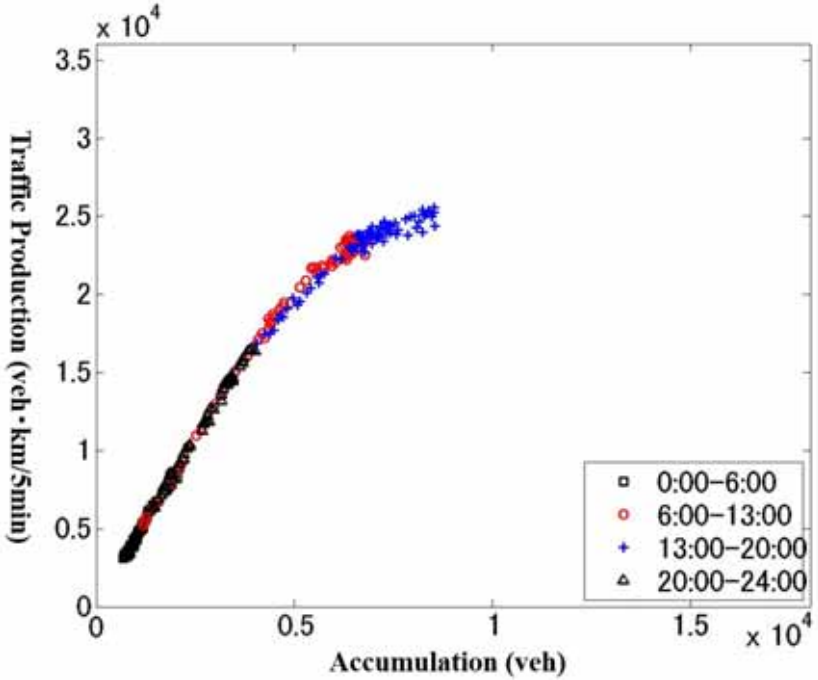


- Saturdays: (a single) hysteresis loop may form (66.7%) or it may not
- Sundays (holidays): (a single) hysteresis loop may form (17.2%) or it may not

MFDs on different demand condition (4)

- MFDs on sunny weekends, Kyoto

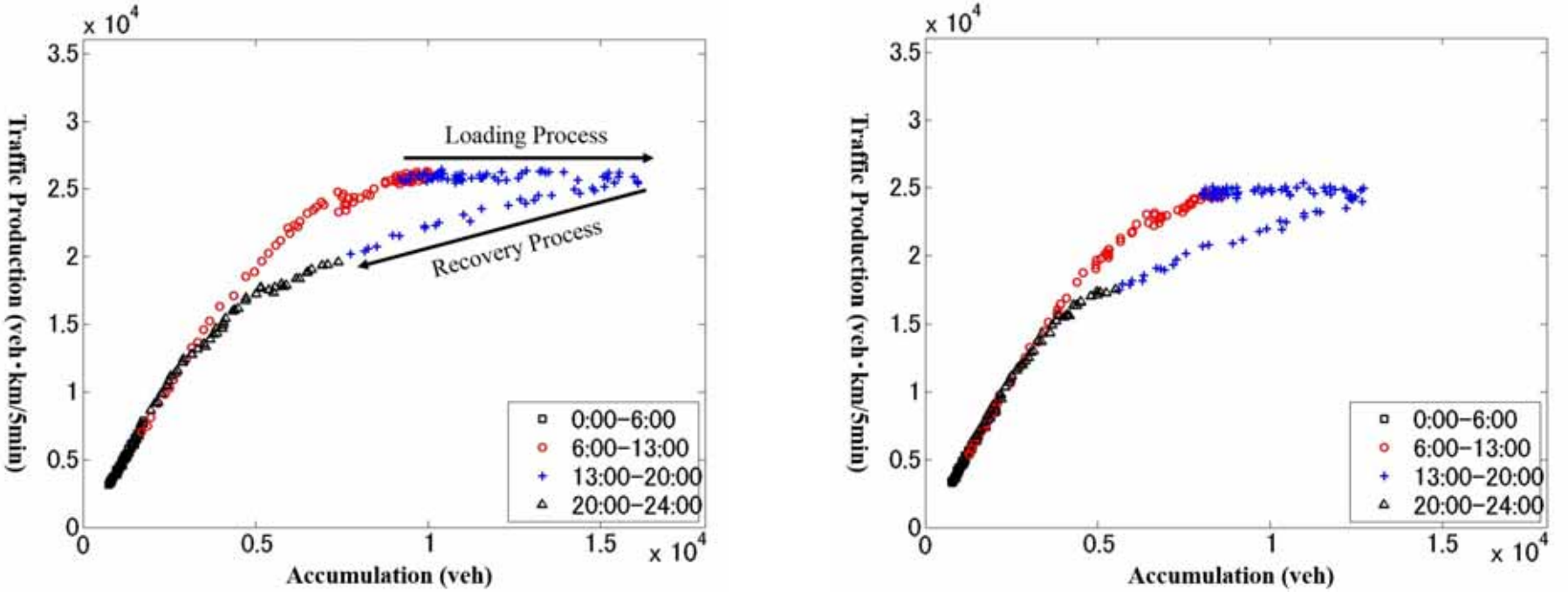




- Saturdays: (a single) hysteresis loop may form (66.7%) or it may not
- Sundays (holidays): (a single) hysteresis loop may form (46.3%) or it may not

MFDs on different demand condition (5)

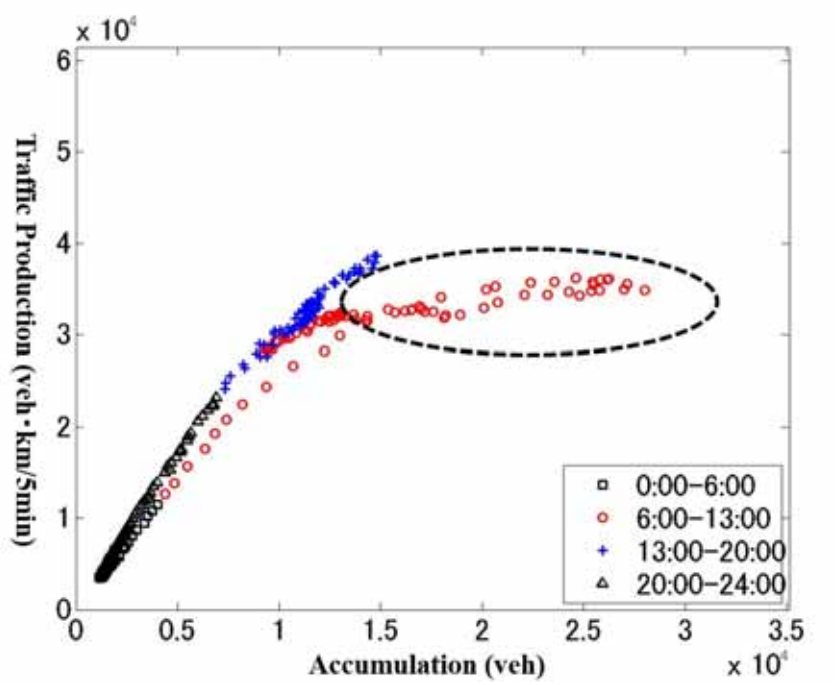
- MFDs on sunny weekends during ***autumn maple viewing***, Kyoto (***a rare phenomenon***)

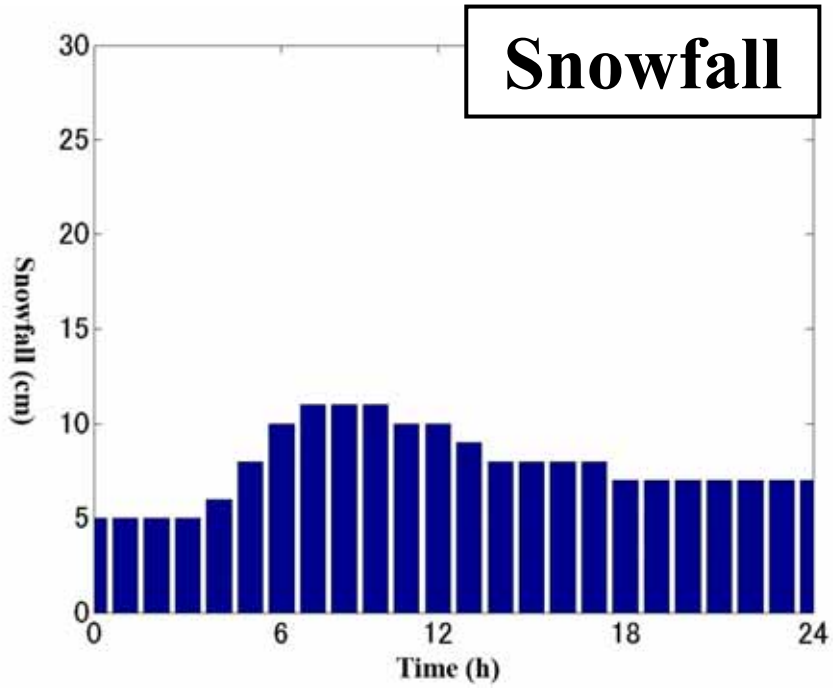


- During the traffic loading process: the traffic production maintains a certain level with the increase of accumulation
- During the traffic unloading process: a large loop forms

MFDs on different supply condition (1)

- MFDs on bad weather weekdays, Sendai

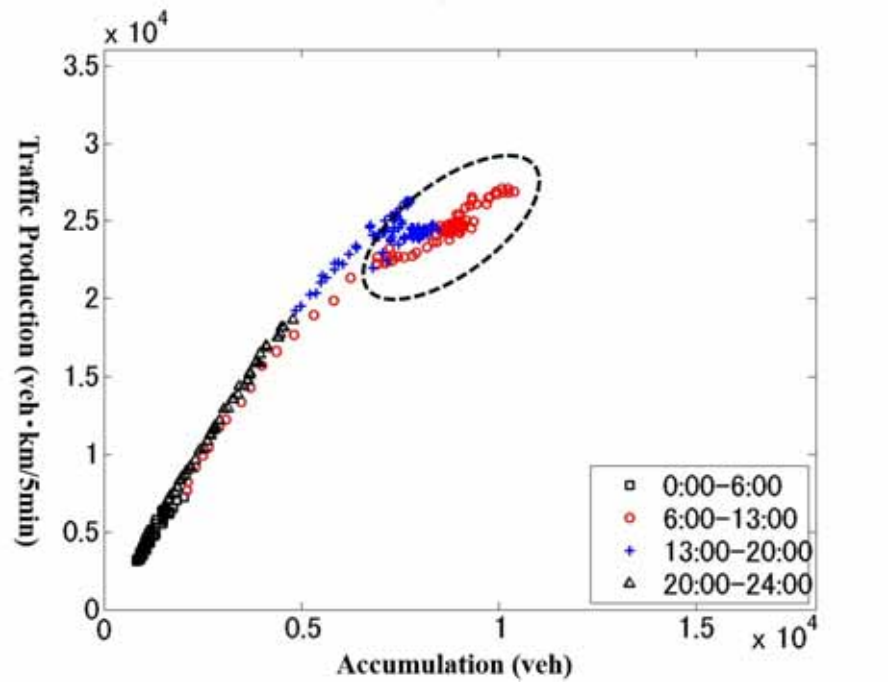


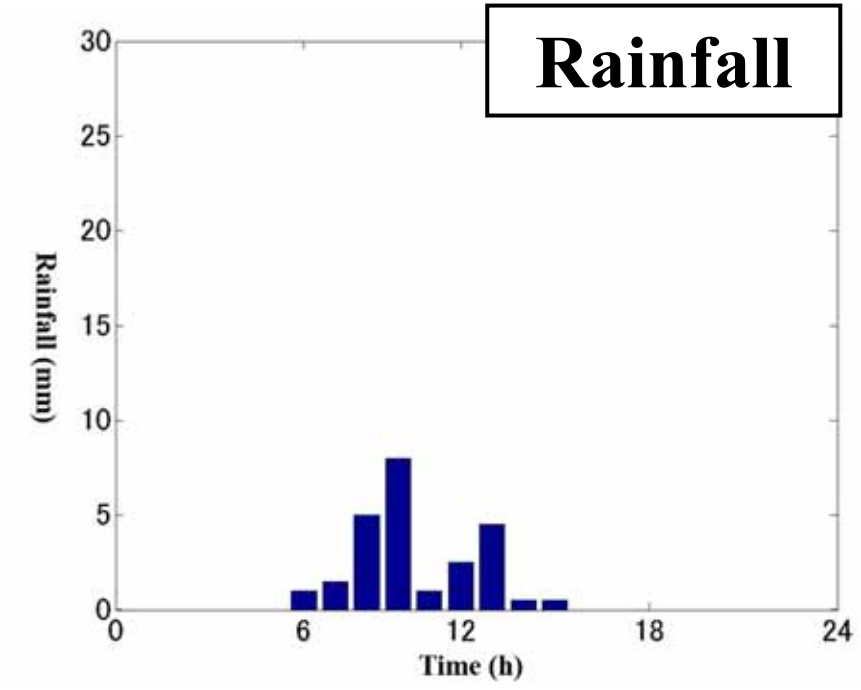


- The MFD sometimes have different shape
  - The traffic production decreases
  - The variation (the range of traffic production for each accumulation level) of MFDs increases

MFDs on different supply condition (2)

- MFDs on bad weather weekdays, Kyoto





- The difference always occurs while the rainfall or snowfall increases

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What shall we do in this part?

- Purposes (using the spatial congestion pattern)
  - Sendai: why the hysteresis loop forms/does not form during evening peak hours on sunny weekdays
  - Kyoto: why the hysteresis loop forms on sunny weekends
- Aggregated index: number of queue-spillbacks
  - The formation of hysteresis loop
    - Upper curve vs. Lower curve
- Spatial distribution of congested links
  - Compare the spatial distribution of congested links
    - Upper curve vs. Lower curve

Aggregated analysis on congested pattern

- Definition of queue-spillbacks S_t

$$S_t = \sum_{k \in K} S_t^k = \sum_{k \in K} \sum_{u \in IN(k)} \sum_{d \in OUT(k)} s_t^{k,(u,d)}$$

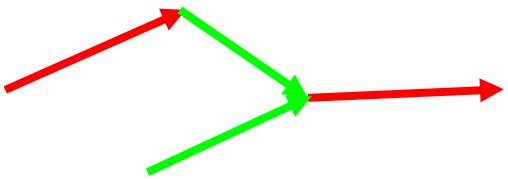
Sets of the upstream (u) and downstream (d) link at intersection k

$$\begin{cases} s_t^{k,(u,d)} = 1 & \text{if } v_t^{k,u} \le 20 \text{ and } v_t^{k,d} \le 20 \\ s_t^{k,(u,d)} = 0 & \text{otherwise} \end{cases}$$

Vehicle speed of the upstream (u) and downstream (d) link at intersection k

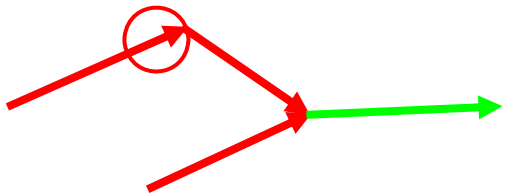
- Cases (congested pattern at time period t)

Case-1



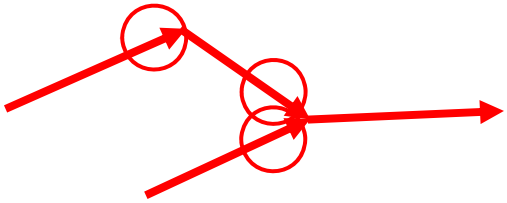
$S_t = 0$

Case-2



$S_t = 1$

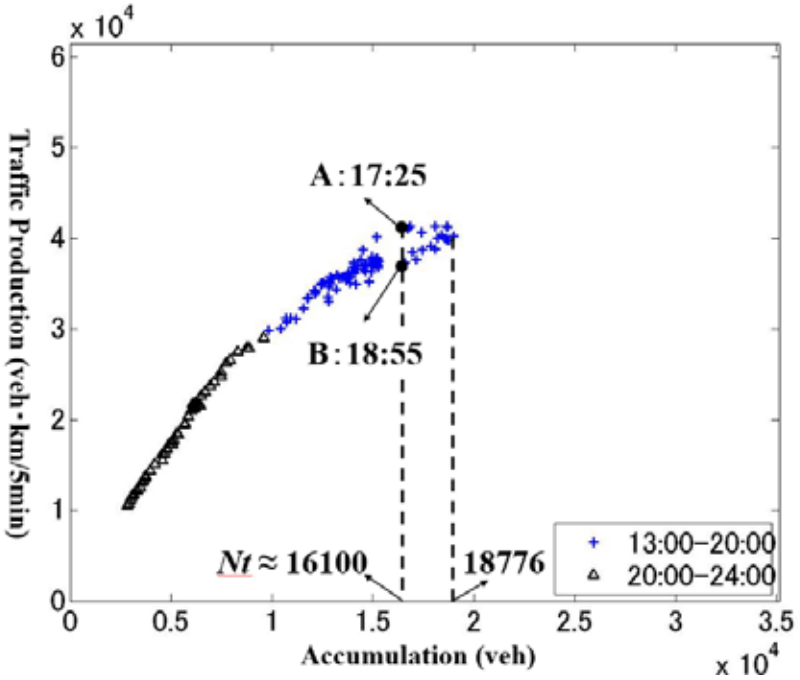
Case-3

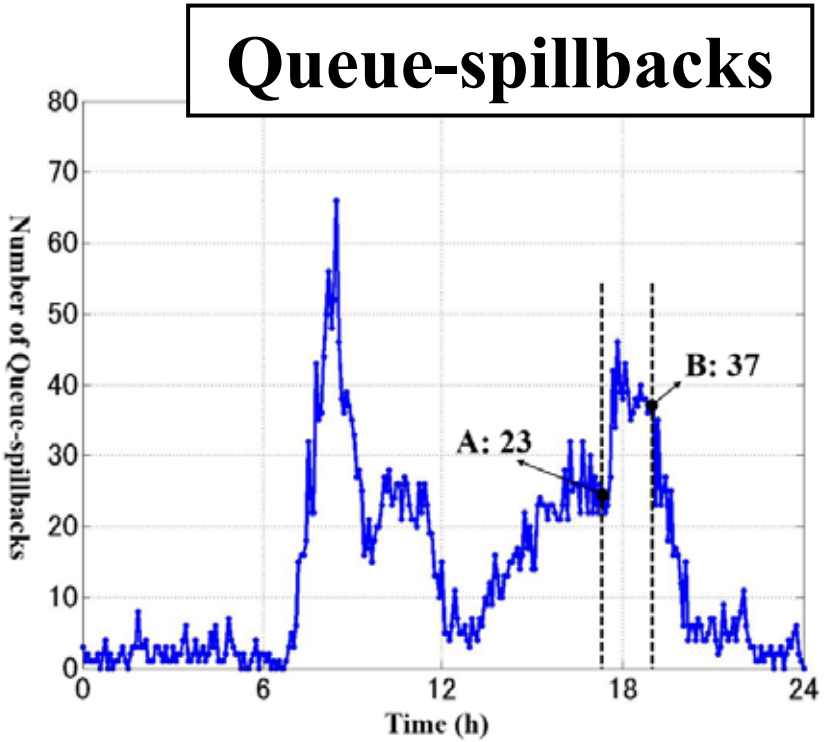


$S_t = 3$

Number of queue-spillbacks (1): **Sendai**

- Loop weekdays: Upper curve vs. Lower curve

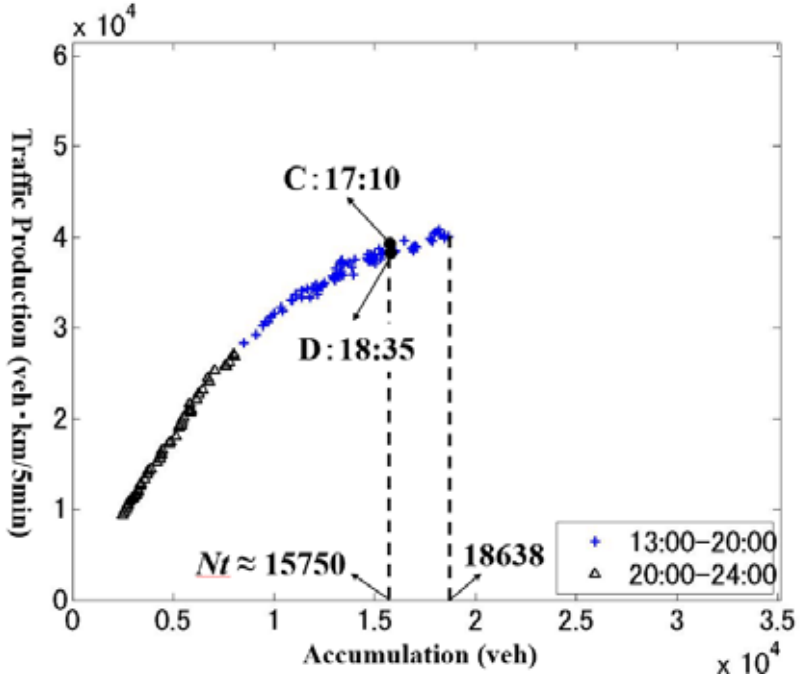


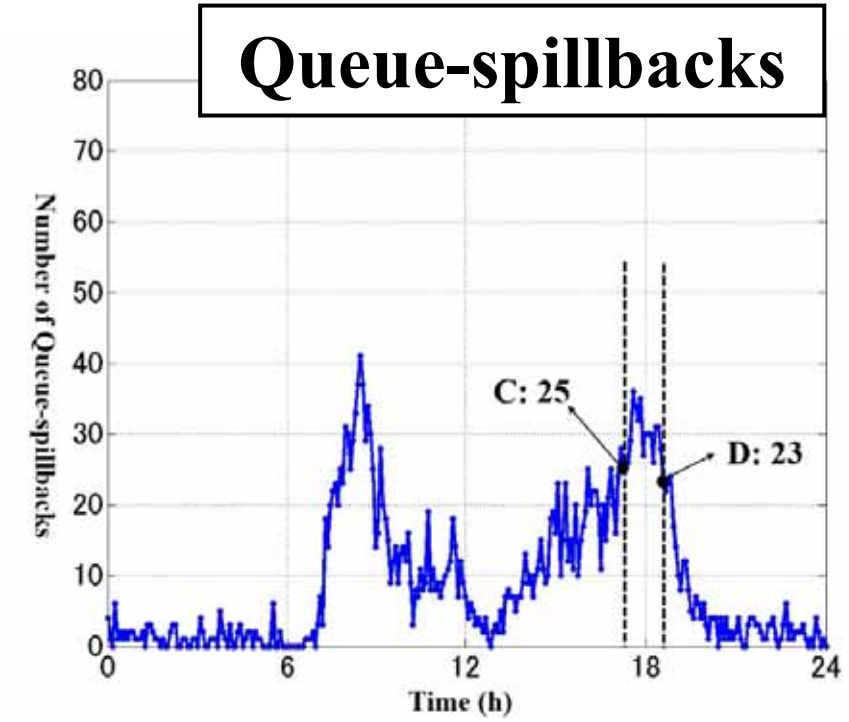


- Plot A and plot B have the same accumulation level
- Number of queue-spillbacks of plot A (upper curve) is smaller than that of plot B (lower curve)

Number of queue-spillbacks (2): **Sendai**

- No loop weekdays: Upper curve vs. Lower curve

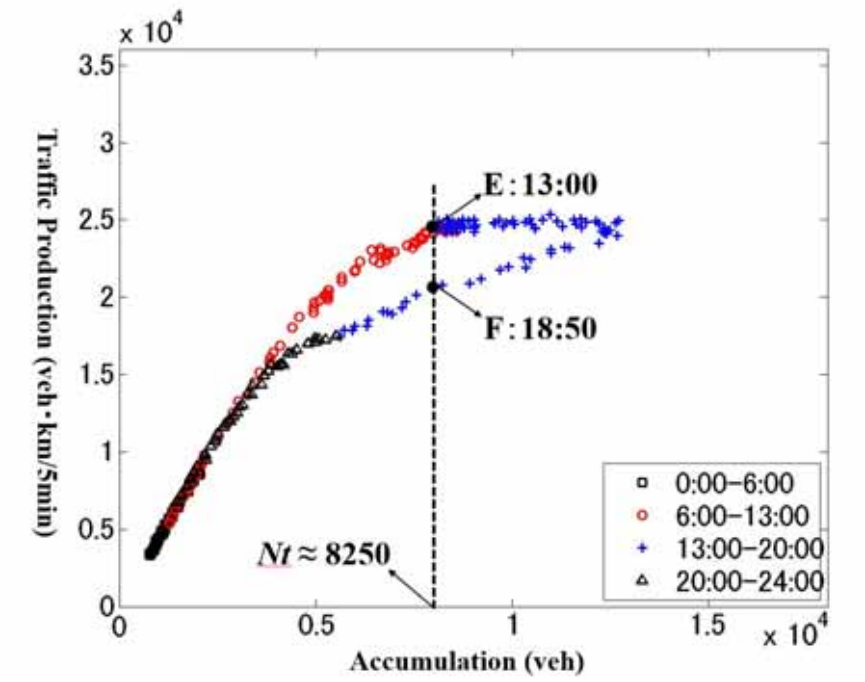


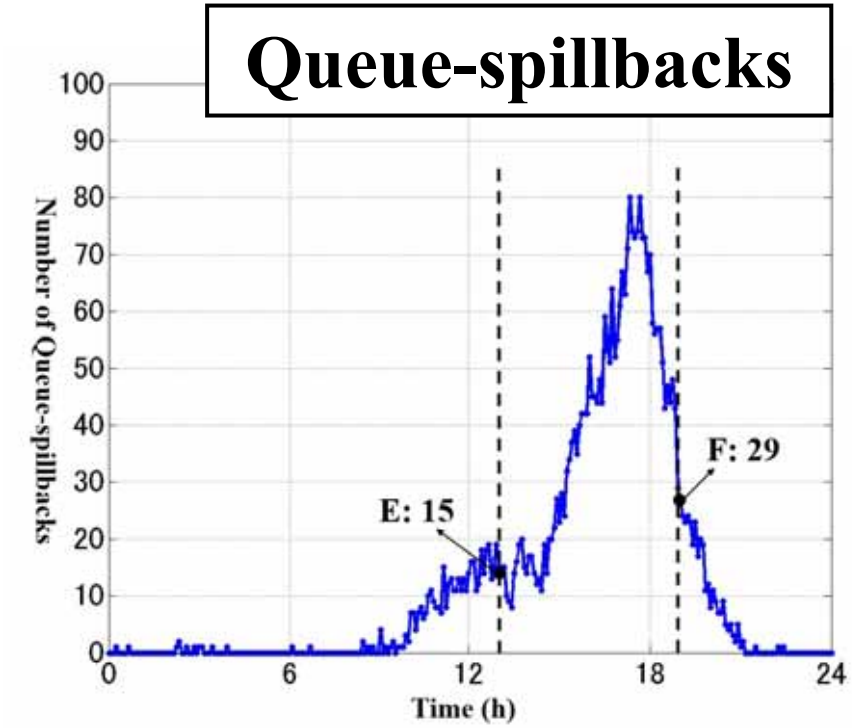


- Plot C and plot D have the same accumulation level
- Number of queue-spillbacks of plot C (upper curve) is equal to that of plot D (lower curve)

Number of queue-spillbacks (3): **Kyoto**

- Loop weekends: Upper curve vs. Lower curve

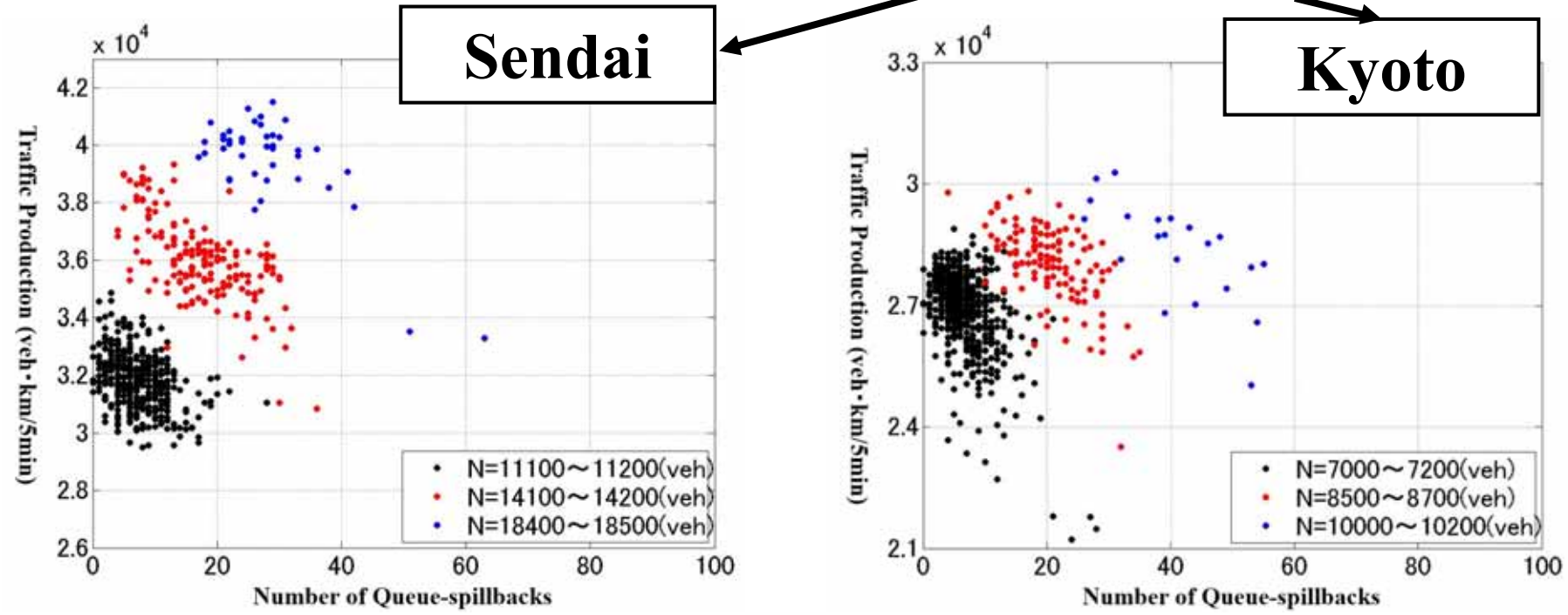




- Plot E and plot F have the same accumulation level
- Number of queue-spillbacks of plot E (upper curve) is smaller than that of plot F (lower curve)

Number of queue-spillbacks (4)

- Traffic production vs. Number of queue-spillbacks using all hysteresis loop weekdays or weekends

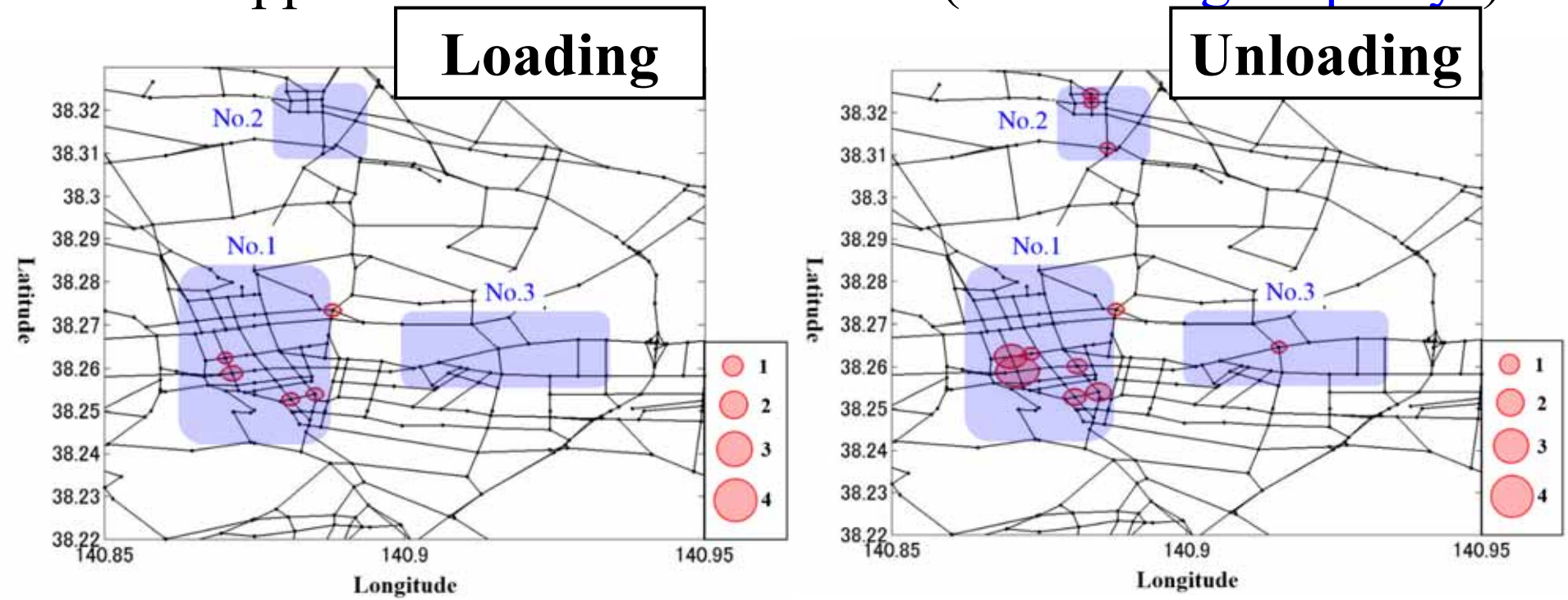


The relationship between the traffic production and the number of queue-spillbacks under the same accumulation level is ***almost negative linear***

It also ***verified the robustness*** of a conclusion from simulation studies!

Spatial congestion pattern (1): Sendai

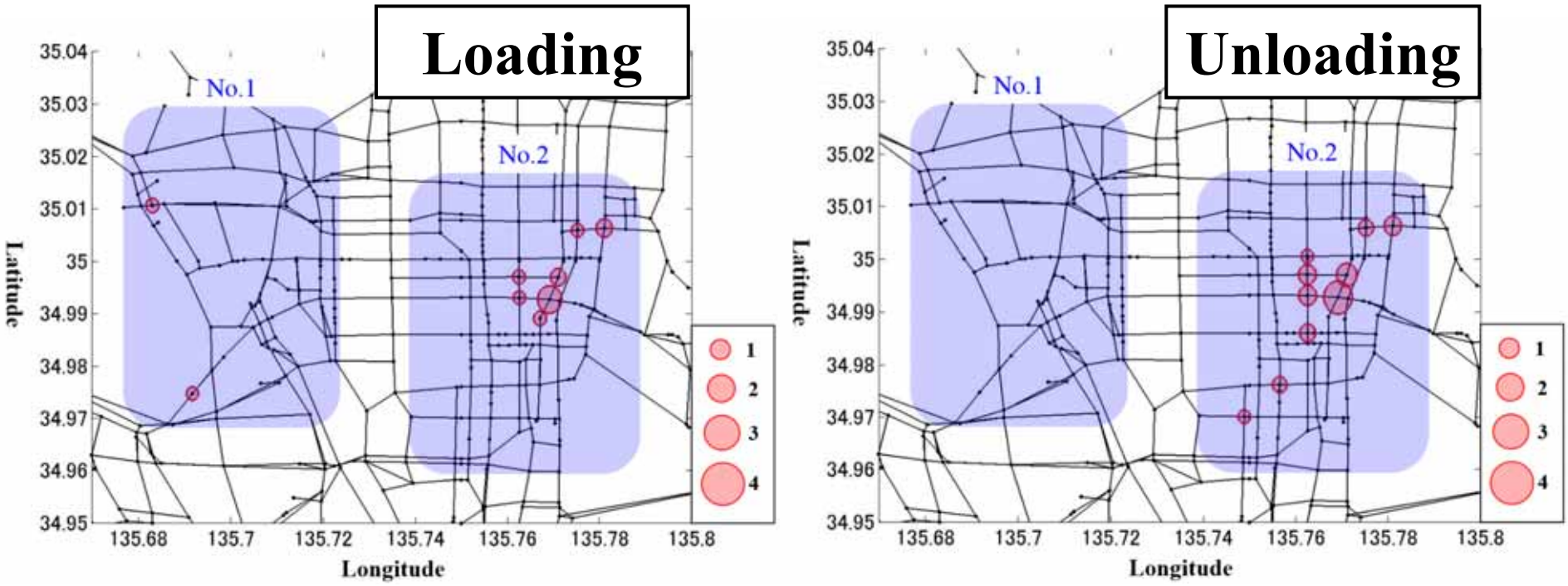
- Upper curve vs. Lower curve (all evening loop days)



- Traffic loading process: the congestion always occurs in
  - CBD of Sendai
- Traffic unloading process: the congestion always occurs in
  - CBD of Sendai, center of Izumi District, around Route 45

Spatial congestion pattern (2): Kyoto

- Upper curve vs. Lower curve (all loop weekends)



- Traffic loading process: many queue-spillbacks distribute in cluster No.2, the others exist in cluster No.1
- Traffic unloading process: all queue-spillbacks centralize in cluster No.2

Discussion for the relationship (1)

- Why such spatial congestion pattern forms?
  - Sendai: the evening loop on weekdays is corresponding to the phenomenon that users come back home from works

The spatial distribution of destinations ***does not change*** significantly during the evening peak hours

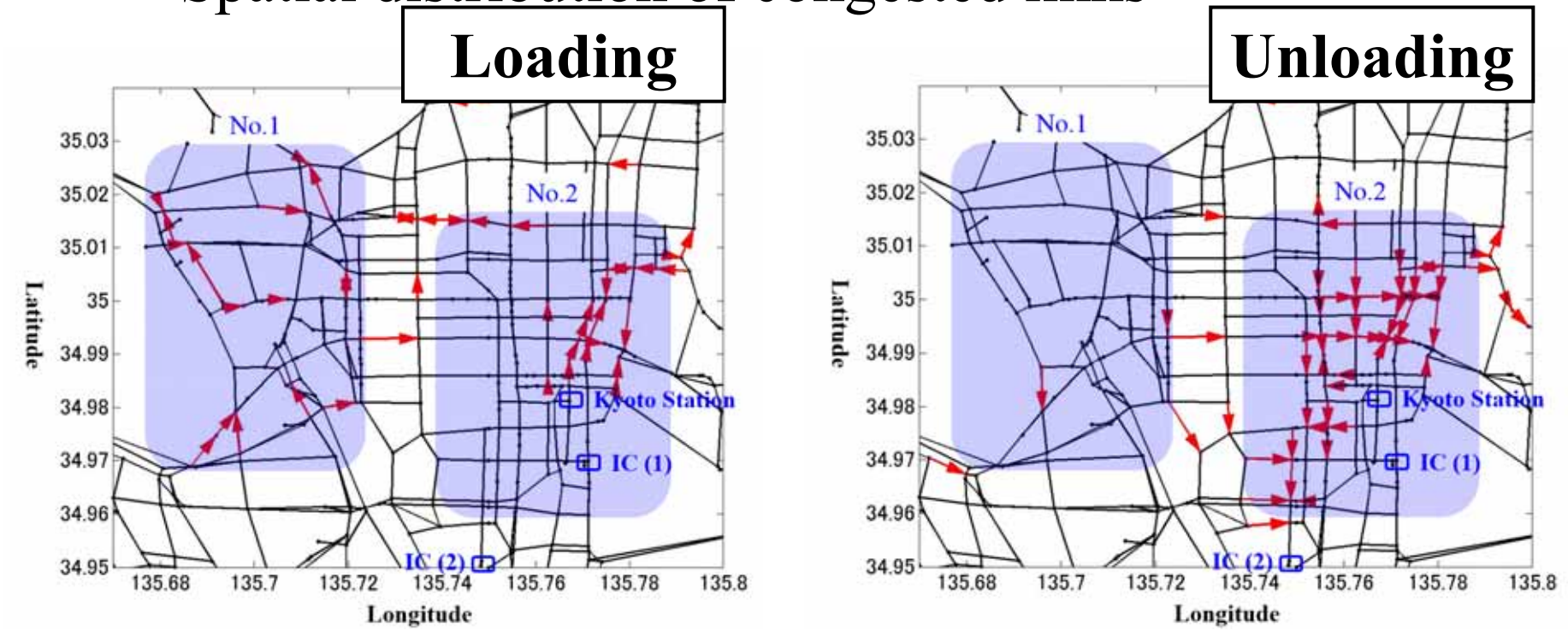
  - Kyoto: the loop on weekends during autumn maple viewing is corresponding to a sightseeing tour

The spatial distribution of destinations ***may change*** at the beginning and in the end of a sightseeing tour

Spatial distribution of destinations may affect the characteristics of spatial congestion pattern

Discussion for the relationship (2): Kyoto

- Spatial distribution of congested links



- Traffic loading process: congested links evenly distribute in clusters No.1 and No.2 (direction: west and north)
- Traffic unloading process: more than 90% of congested links mainly distribute in cluster No.1 (direction: south and east)

Summary of **Section 2.1** (1)

- Robust features of MFD
  - Sendai: Formation of hysteresis loop
    - Morning peak hours: 100% of sunny weekdays
    - Evening peak hours: 64.2% of sunny weekdays
  - Kyoto: Formation of hysteresis loop
    - Common phenomenon: 66.7% of sunny Saturdays, 46.3% of sunny Sundays (holidays)
    - Rare phenomenon: during the autumn maple viewing, in the traffic loading process, the traffic production maintains a certain level with the increase of accumulation

Summary of **Section 2.1** (2)

- MFD features vs. Congestion pattern
  - Under the same accumulation level, the relationship between the traffic production and the number of queue-spillbacks is almost negative linear
  - High number of queue-spillbacks is corresponding to the phenomenon that many congested links (destinations) centralized in some certain parts of analysis area

Section 2.2

	Section 2.1	Section 2.2	Section 2.3
Country	Sendai Kyoto	**Naha**	Tokyo
Network Type	Street	**Street**	Expressway
MFD Features	Hysteresis Loop	**Congested Regime**	Hysteresis Loop Congested Regime

Contents of **Section 2.2**

- Basic information of detectors data
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  - Detectors data
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  - MFD classification
  - MFD features under different demand/supply conditions
- MFD features vs. Congestion pattern
  - Number of queue-spillbacks
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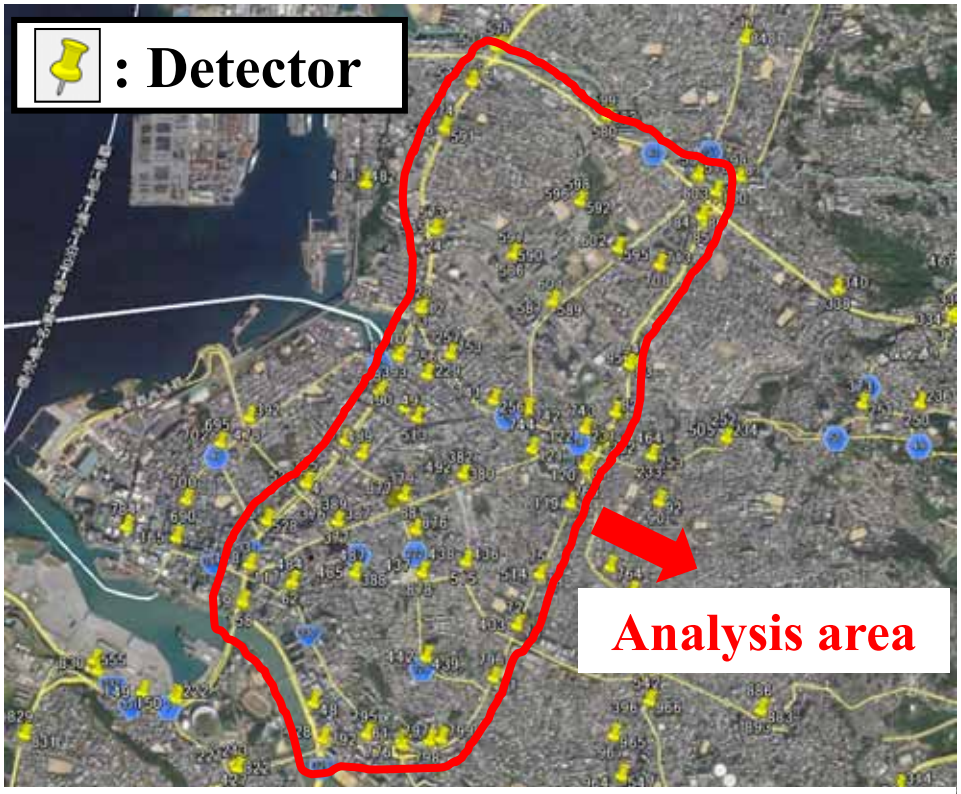
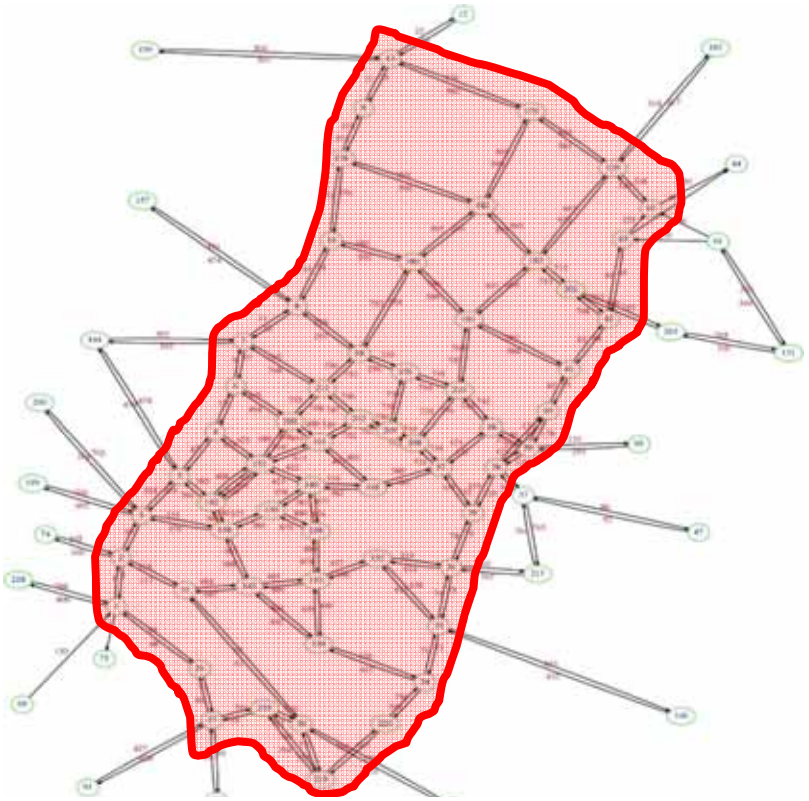
Basic information of detectors data (1)

- Analysis area
  - CBD street networks in Naha (approximate 6.2 km^2)
  - Number of detectors: 122



Spatial distribution of detectors in analysis area
[Origin：Google Earth]



Road network structure
in analysis area

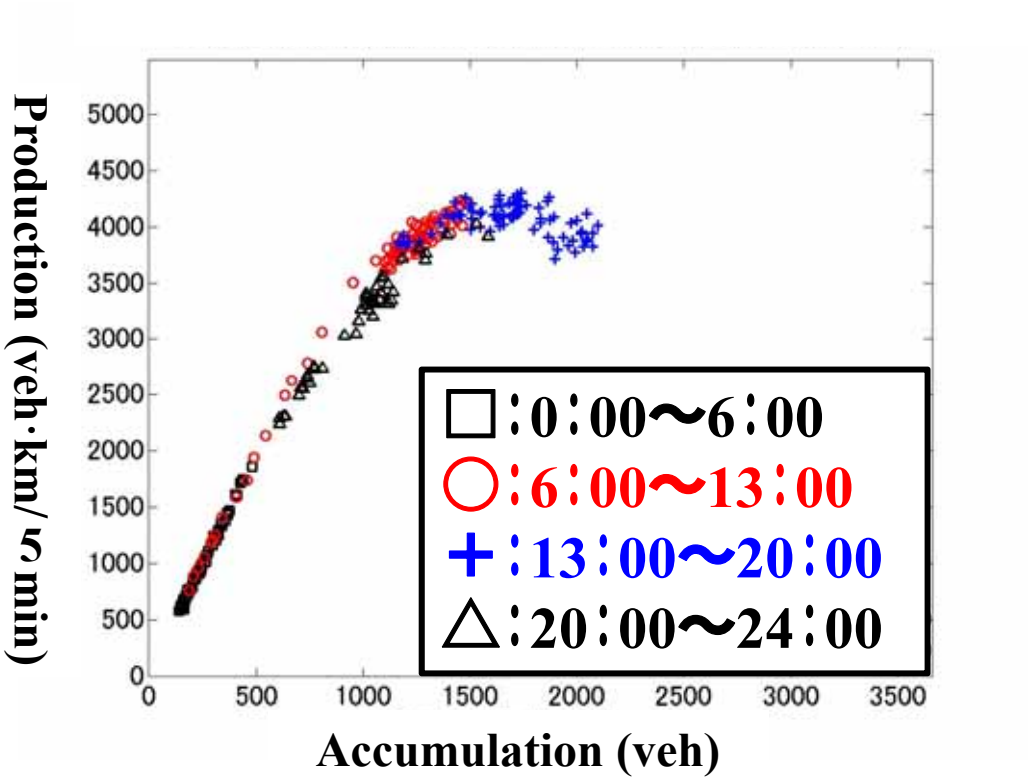
Basic information of detectors data (2)

- Analysis period
  - 5/1/2012 ~ 4/30/2013 (353 days, about 96.7% of days)
  - 5-min period during each 24-h day (T=288)

- Data records of detector *i* during *t* (5-min period)
  - Traffic flow: q_t^i
  - Vehicle speed: v_t^i
  - Traffic density: $k_t^i = q_t^i / v_t^i$

MFD definition

- The calculation of coordinates for each plot
  - Accumulation: $N_t = \sum_{i=1}^{|I|} k_t^i l^i = \sum_{i=1}^{|I|} \left(q_t^i / v_t^i \right) l^i$
  - Traffic production: $P_t = \sum_{i=1}^{|I|} q_t^i l^i$ l^i:length of link i



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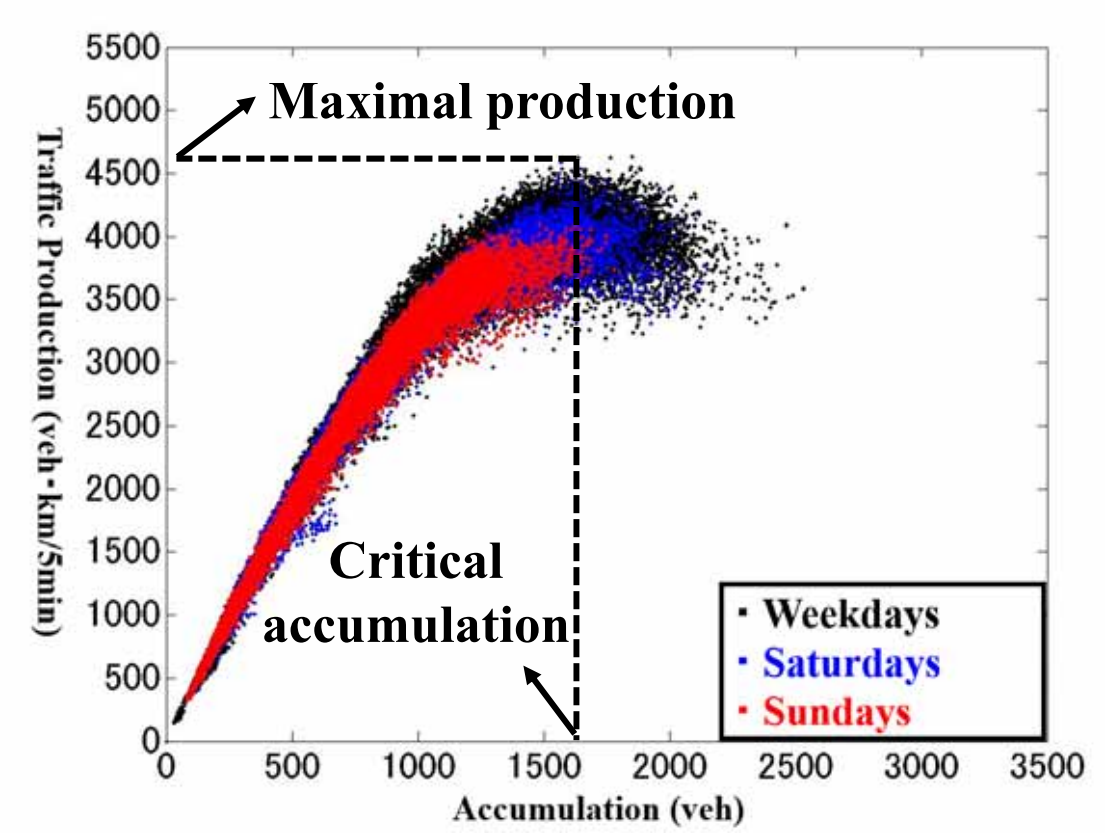
MFD classification

- MFDs for the entire year

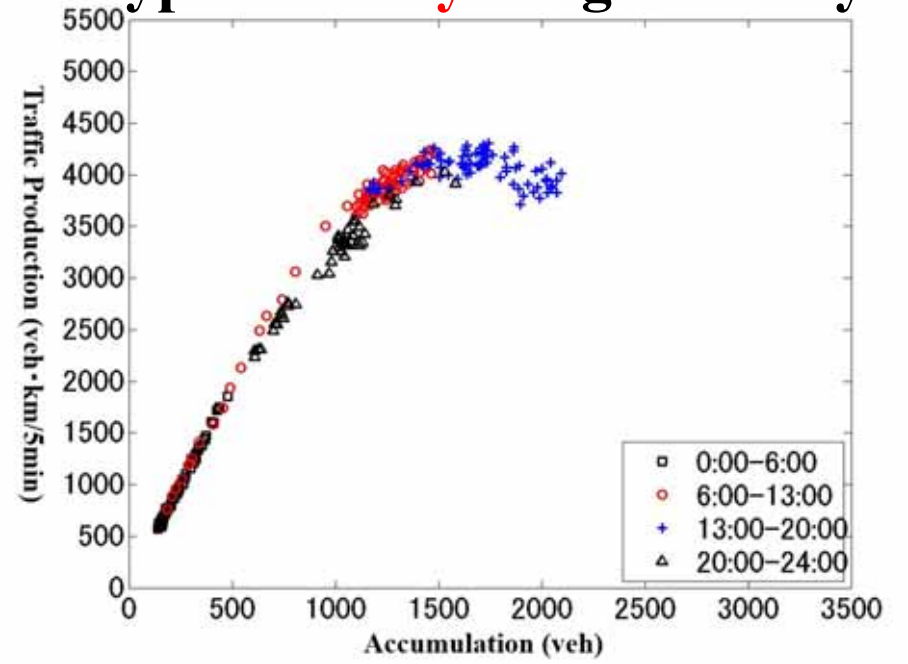


- Congested regime occurs on some weekdays and only several Saturdays

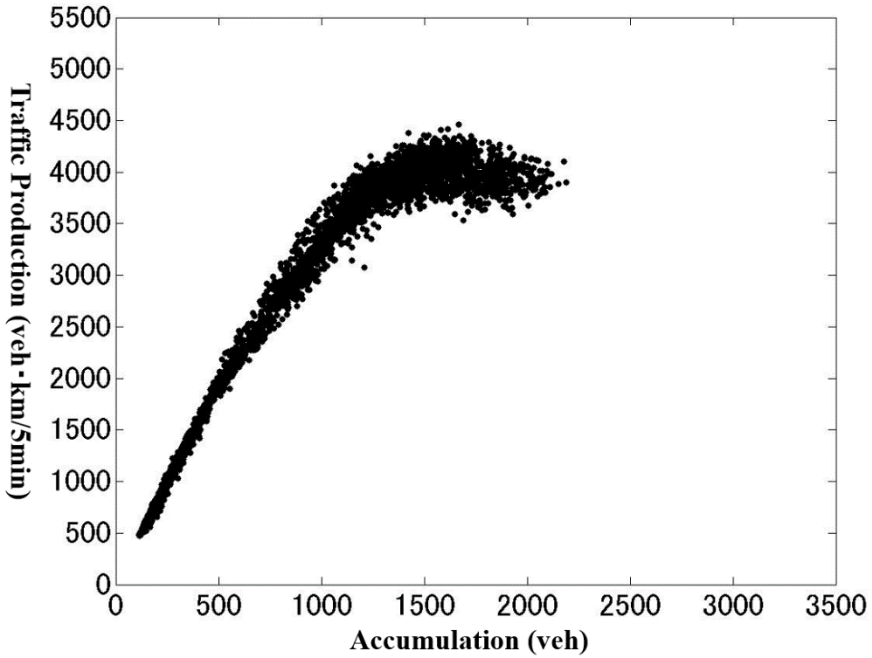
MFDs for different demand condition (1)

- MFDs on sunny weekdays

Typical sunny congested day



All sunny congested days

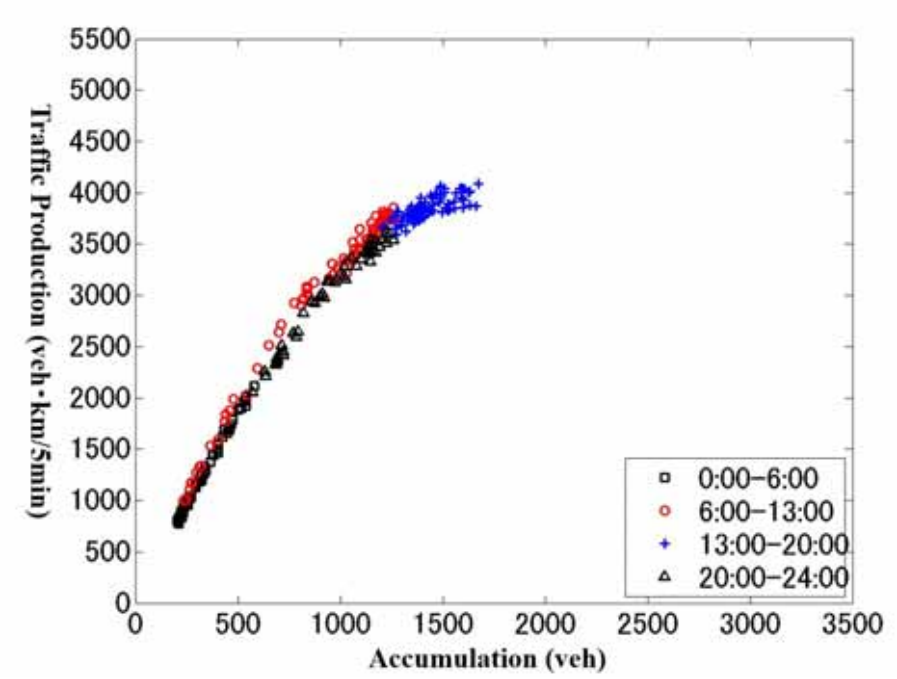


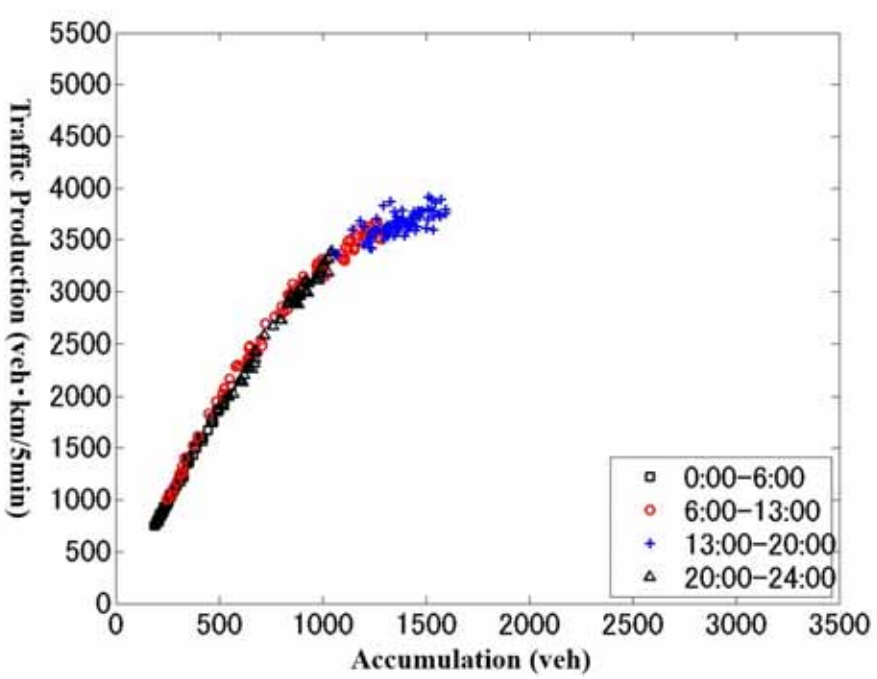
- The congested regime occurs on 12.0% of sunny weekdays
- The hysteresis loop does not form in unloading process

Except filed experiment of downtown Yokohama, ***no empirical study*** has reported that such well-defined MFD exist in real street networks!

MFDs for different demand condition (2)

- MFDs on sunny weekends





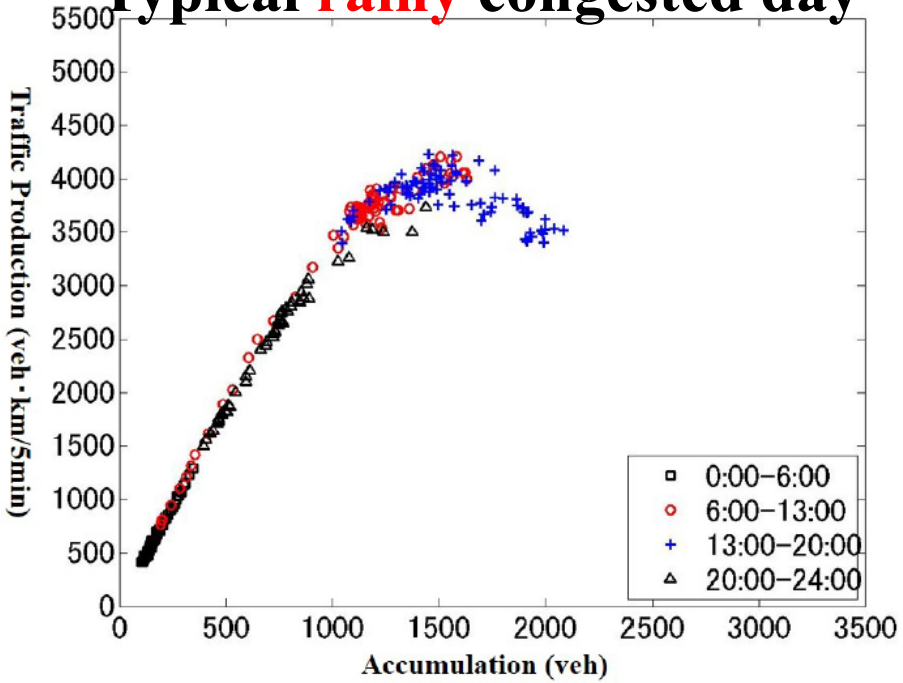
- Congested regime does not occur on sunny weekends (including Saturdays, Sundays, and holidays)

The high traffic demand level is ***a necessary condition*** for the occurrence of congested regime in the MFD

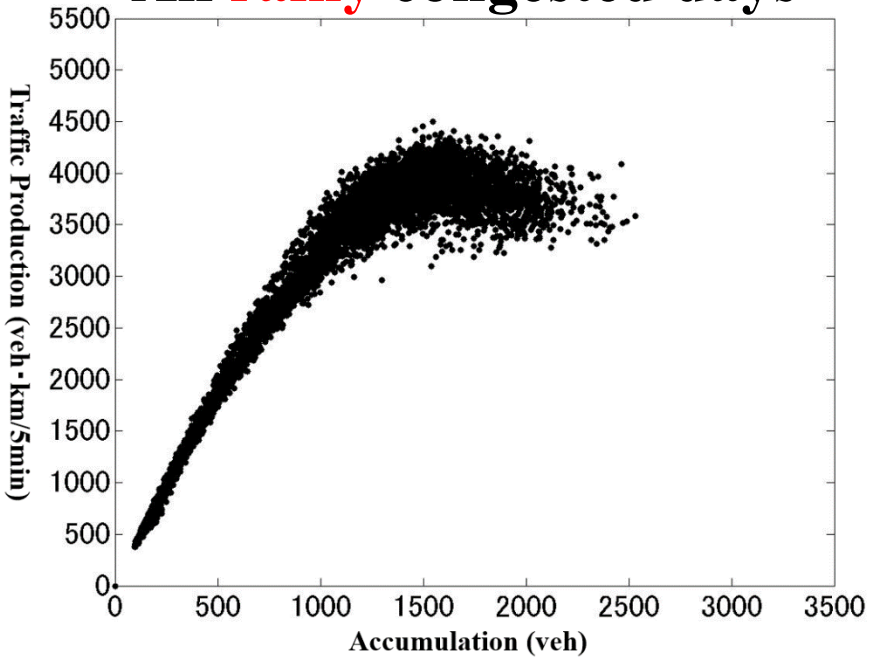
MFDs for different supply condition (1)

- MFDs on rainy weekdays

Typical rainy congested day



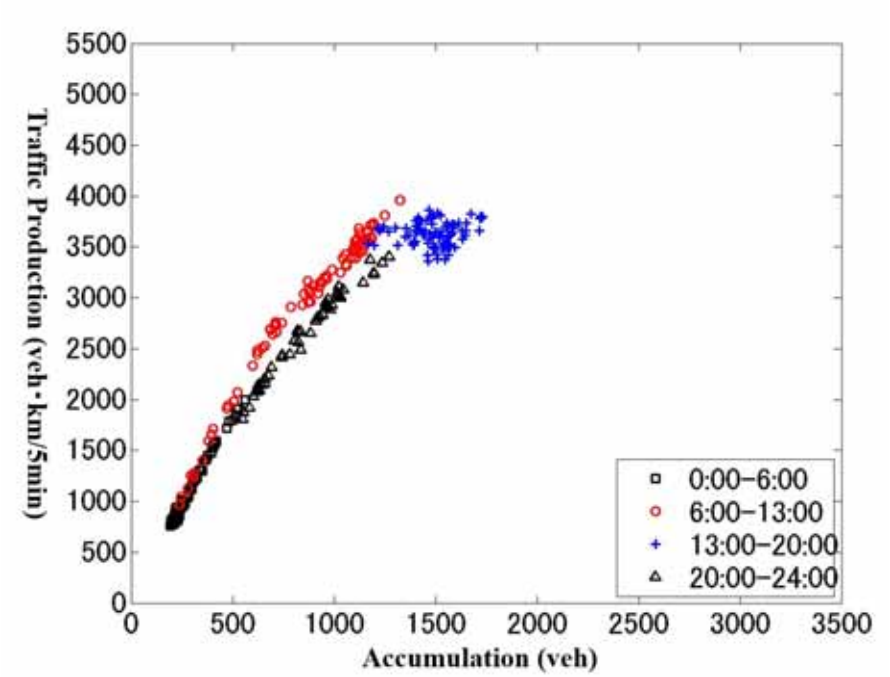
All rainy congested days

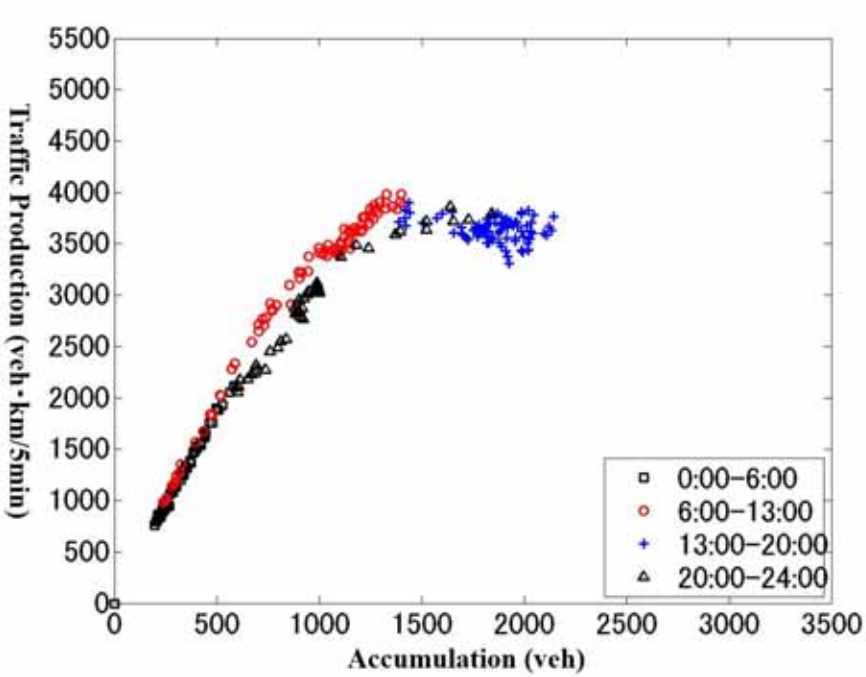


- The congested regime occurs on 31.1% of rainy weekdays
- The hysteresis loop does not form in unloading process

MFDs for different supply condition (2)

- MFDs on rainy weekends (only two days)

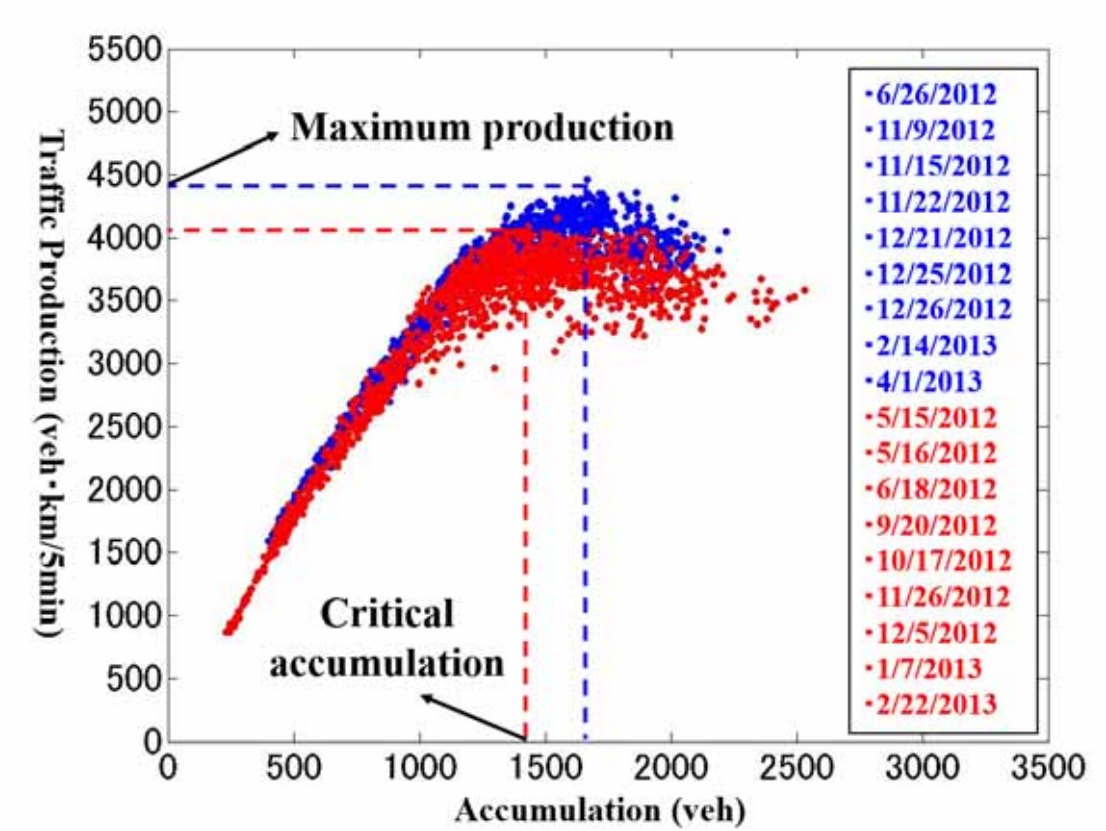




- The congested regime occurs on 4.2% of rainy weekends (only two examples are shown in these two figures above)

Congested sunny and rainy weekdays

- Comparison of MFD shapes



The MFDs with congested regime on sunny days exhibit higher critical accumulation and maximum traffic production

Summary of MFD features in Naha

- Occurrence frequency and time of congested reimage

	Sunny weekday	Rainy weekday	Sunny weekend	Rainy weekend	Total
Days	16	32	0	2	50
Total days	133	103	69	48	353
Rate	12.0%	31.1%	0%	4.2%	14.2%

Occurrence of congested regime in the MFD is ***not a rare phenomenon***

	A.M/Sunny	P.M/Sunny	A.M/Rainy	P.M/Rainy	Total
Days	0	16	1	31	48
Total days	133	133	103	103	236
Rate	0%	12.0%	0.97%	30.1%	20.3%

The occurrence times are always during the ***evening peak hours*** **(16:30~19:30)**

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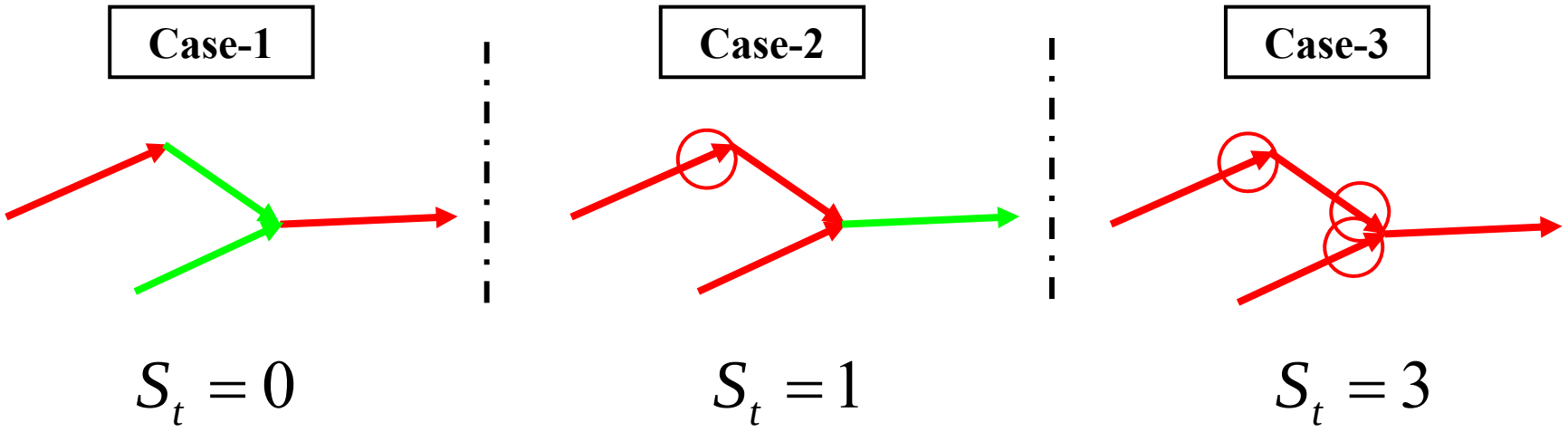
  - Discussion for the relationship

Aggregated analysis on congested pattern

- Definition of queue-spillbacks during time period *t*

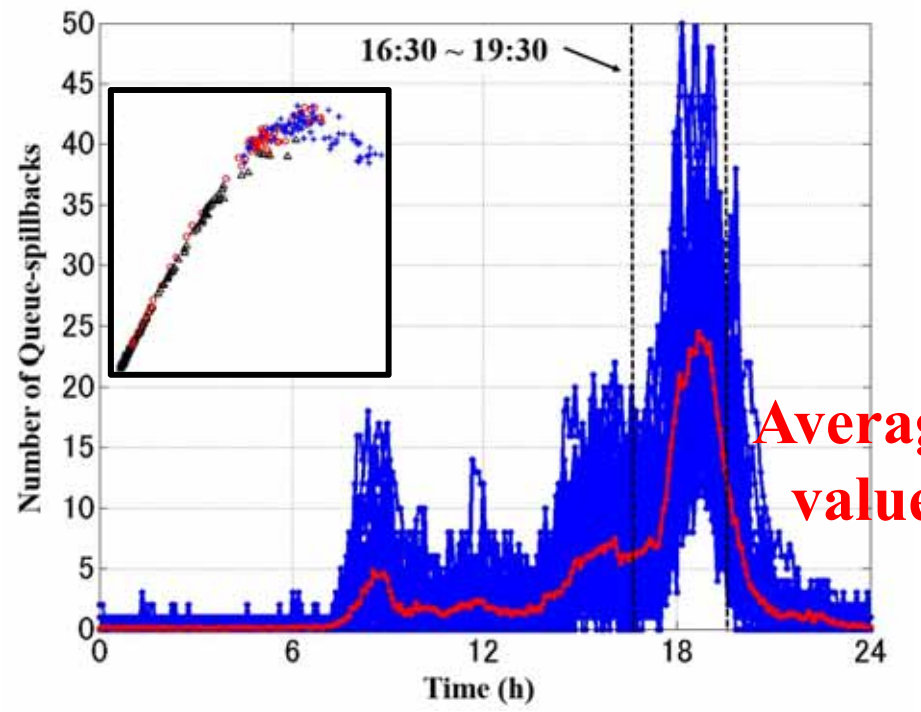


- Hypothesis
  - If the number of queue-spillbacks exceeds its critical value, the congested regime occurs gradually with the significant increase of the number of queue-spillbacks

Comparison of queue-spillbacks (1)

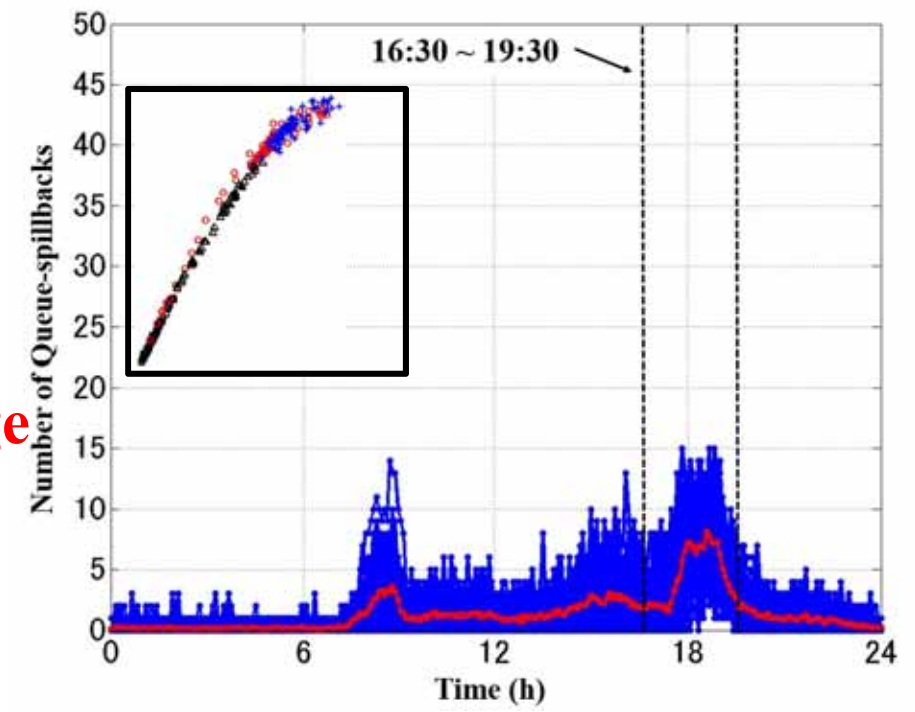
- Congested days vs. Uncongested days

Congested days for one year



Average value

Uncongested days for one year

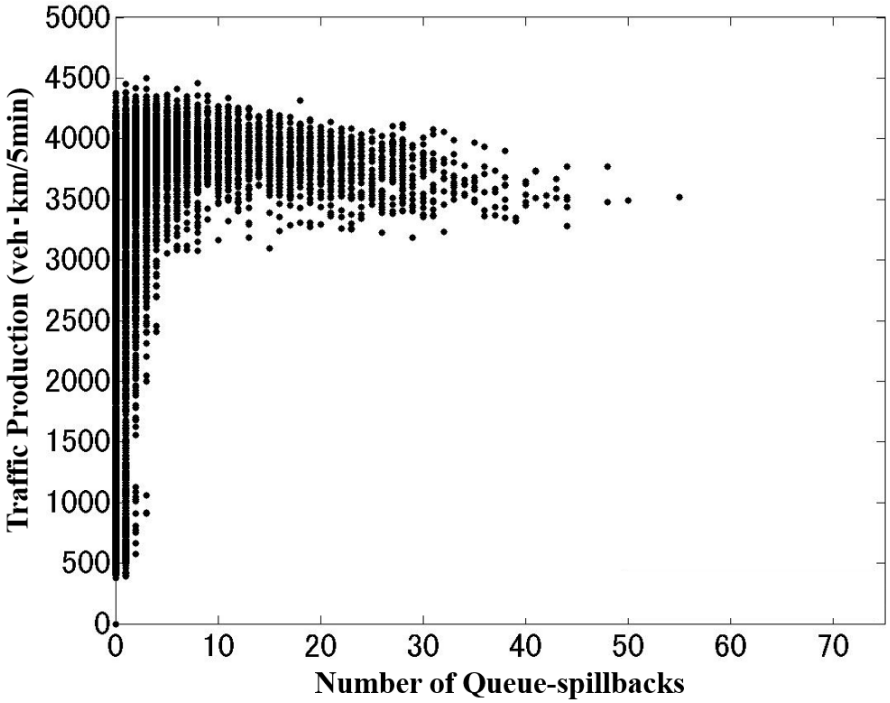


The occurrence of congested regime in an MFD is corresponding to ***the high number of queue-spillbacks*** during evening peak hours

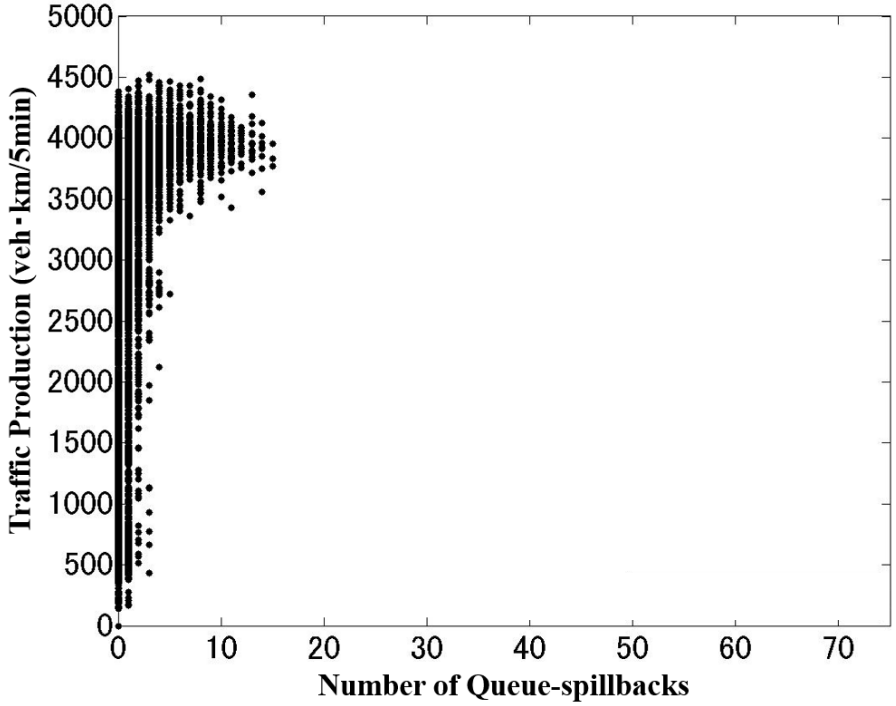
Comparison of queue-spillbacks (2)

- Congested days vs. Uncongested days

Congested days for one year



Uncongested days for one year

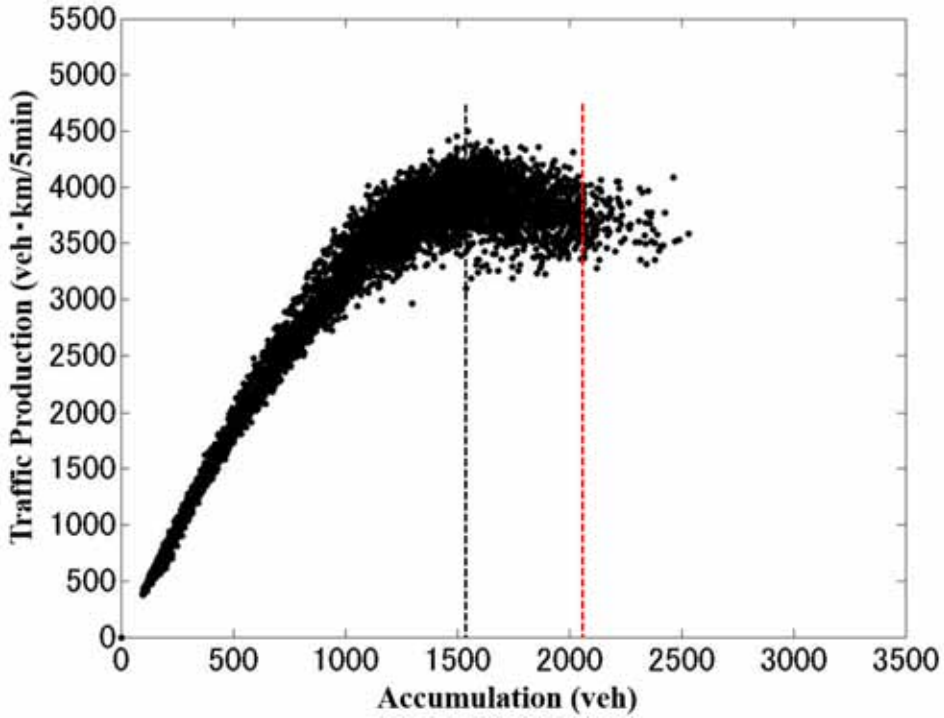


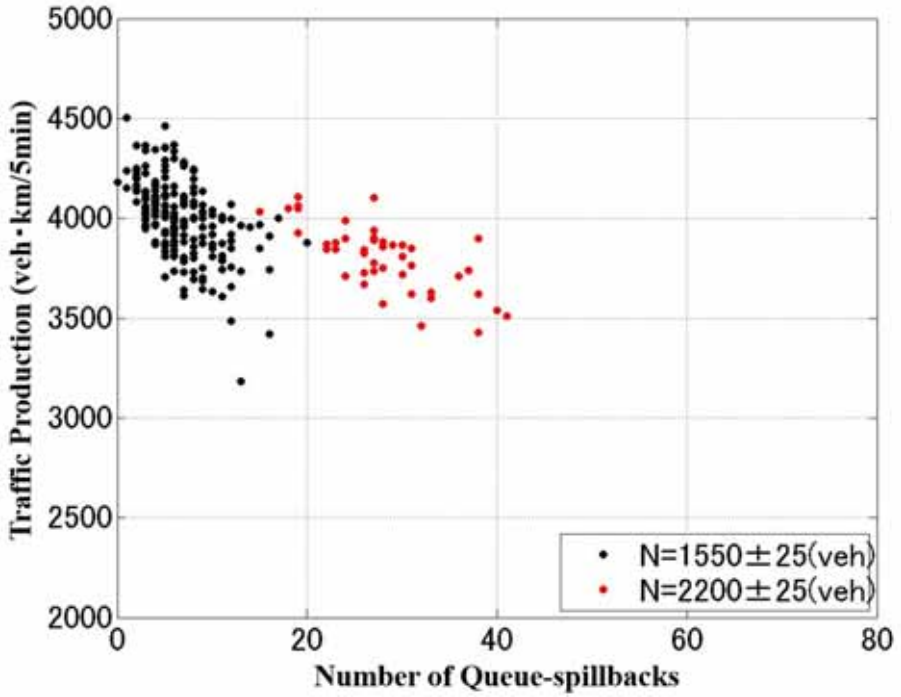
If the number of queue-spillbacks exceeds its critical value, the congested regime occurs with ***the increase of number of queue-spillbacks***

It also ***verified the robustness*** of a conclusion from simulation studies!

Comparison of queue-spillbacks (3)

- Traffic production vs. Number of queue-spillbacks





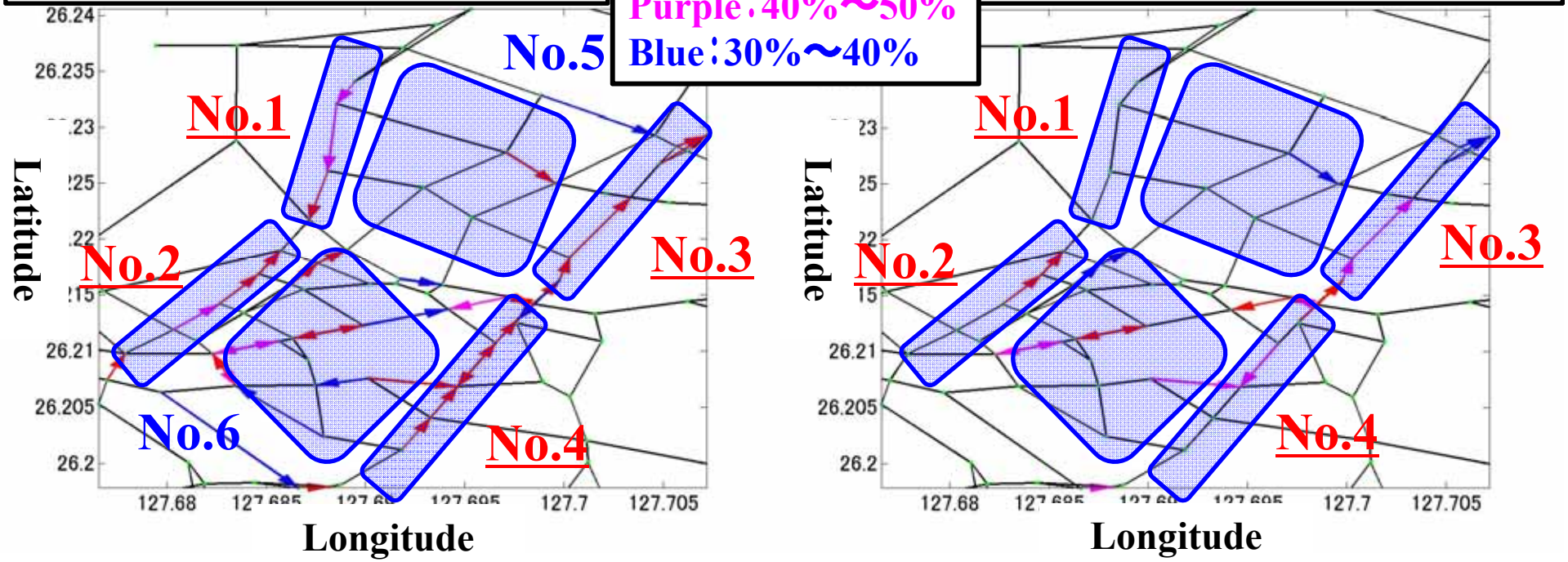
The relationship between the traffic production and the number of queue-spillbacks under the same accumulation level is ***almost negative linear***

Congestion pattern during the entire year

All Congested days

Red：50%～
Purple：40%～50%
Blue：30%～40%

All Uncongested days

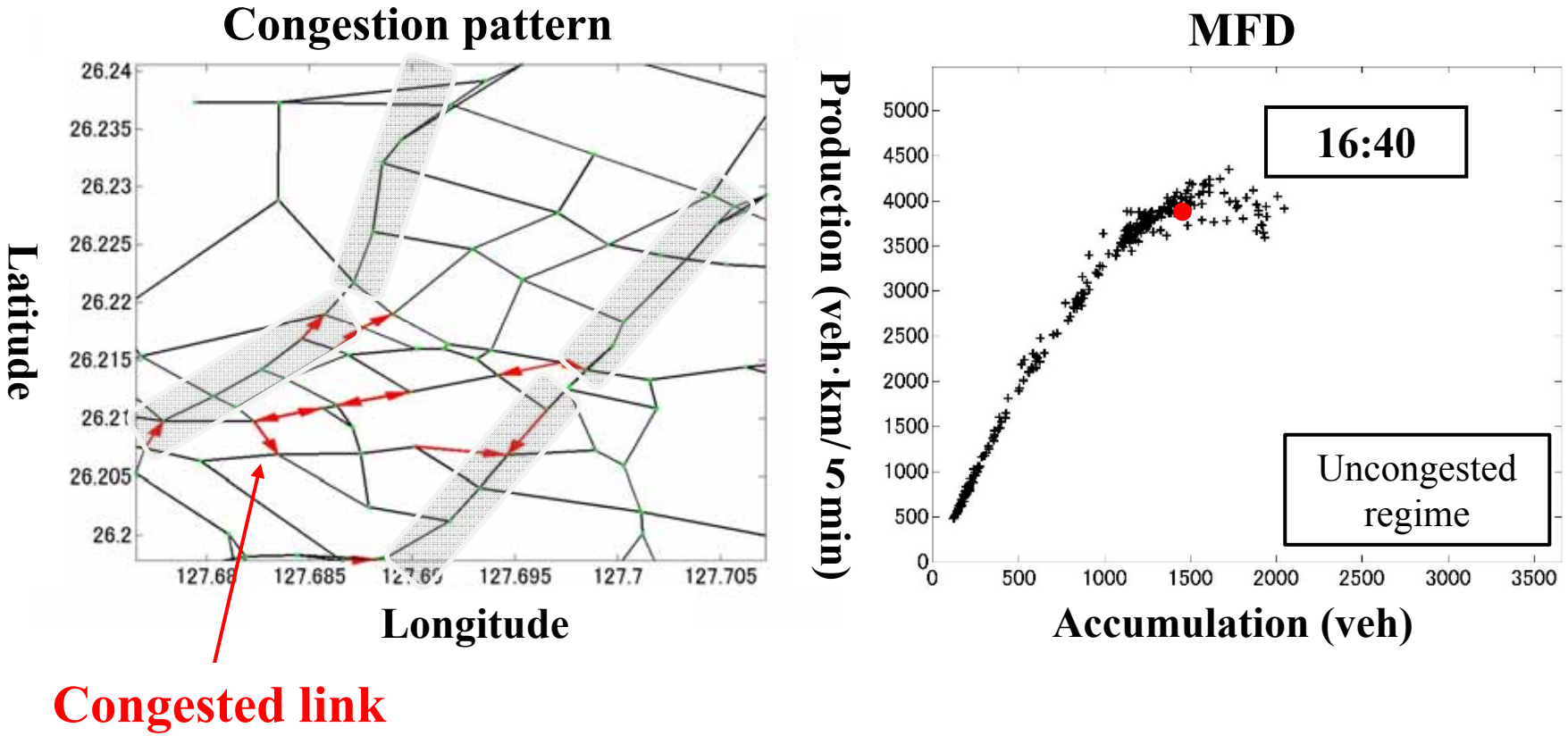


- **Nos.1-4**: congested frequencies for each link are extremely different between the two kinds of days (especially, for cluster No.1 and No.4)

For Naha CBD street networks, if the congestion spreads in cluster Nos.1-4, the congested regime occurs in the MFD

MFD vs. Congestion pattern (Example 1)

- 6/26/2012 (Congested day, sunny)



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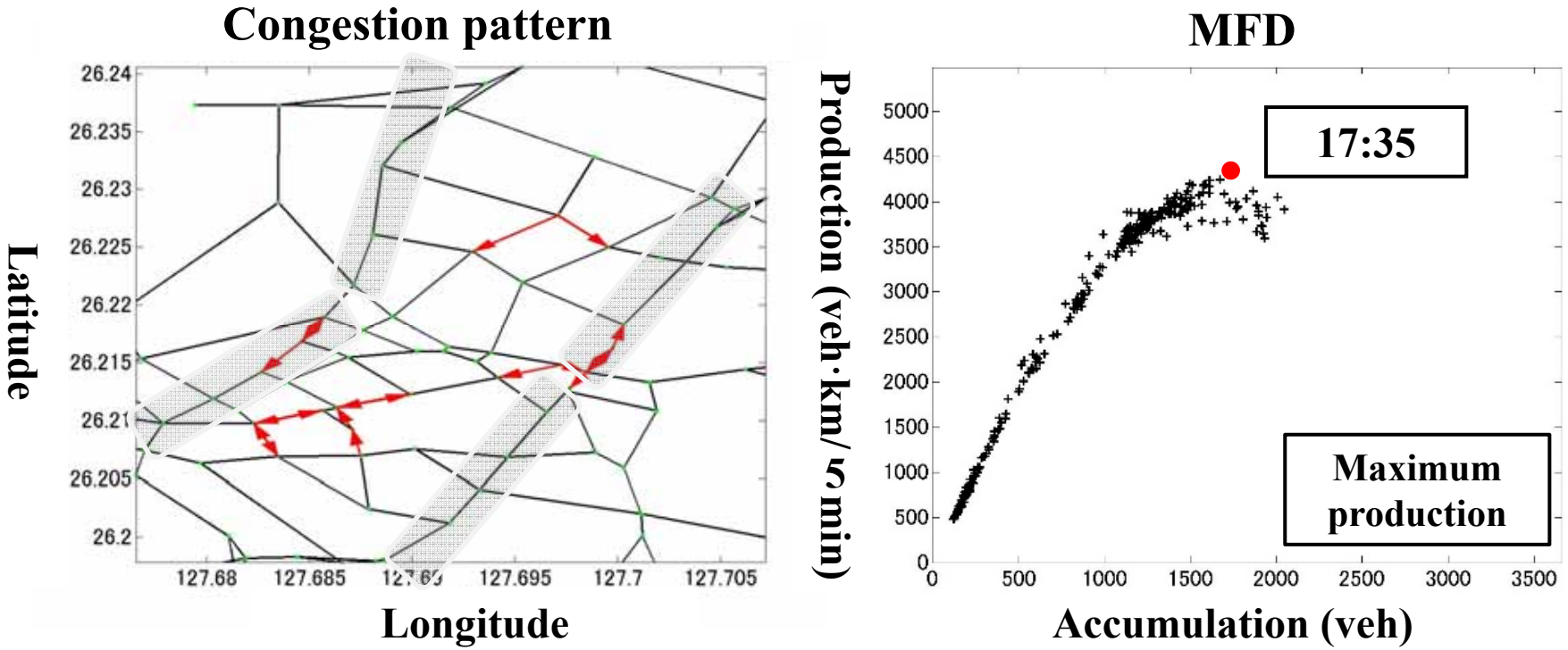

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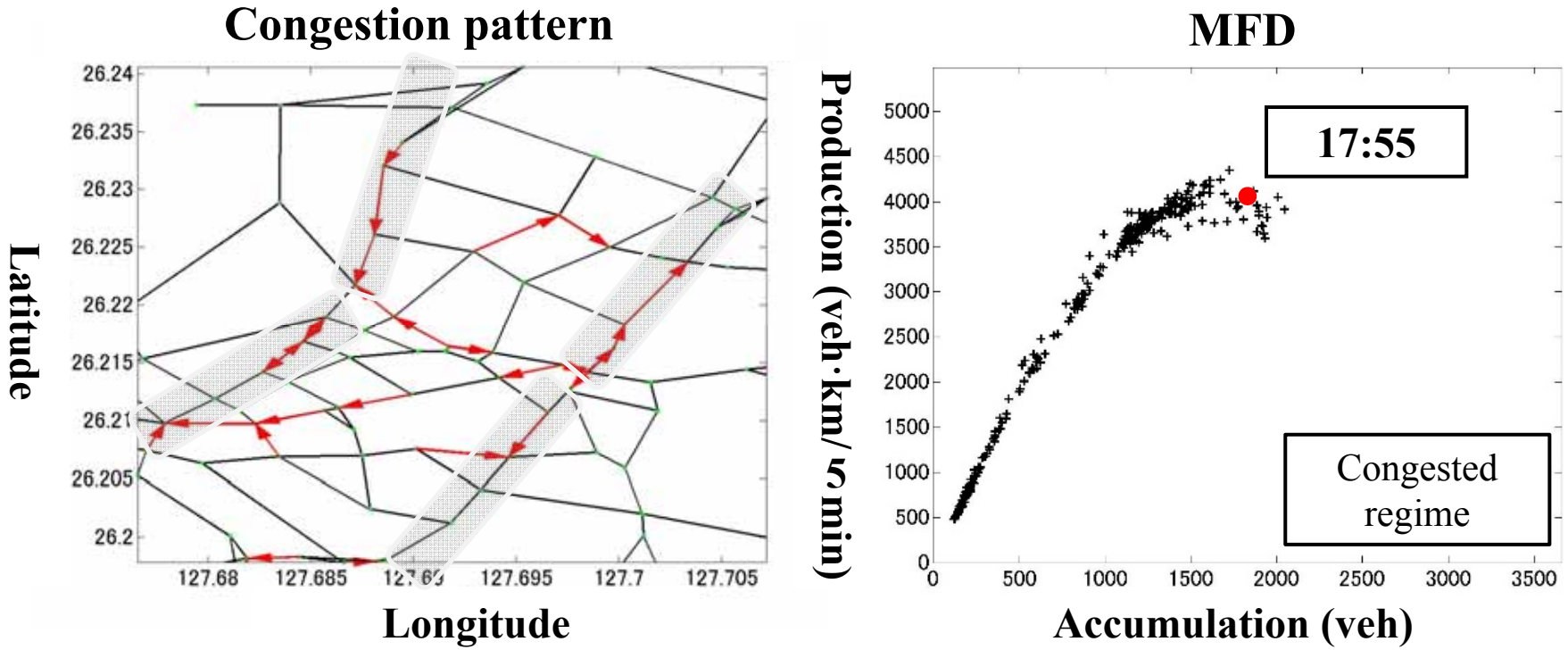

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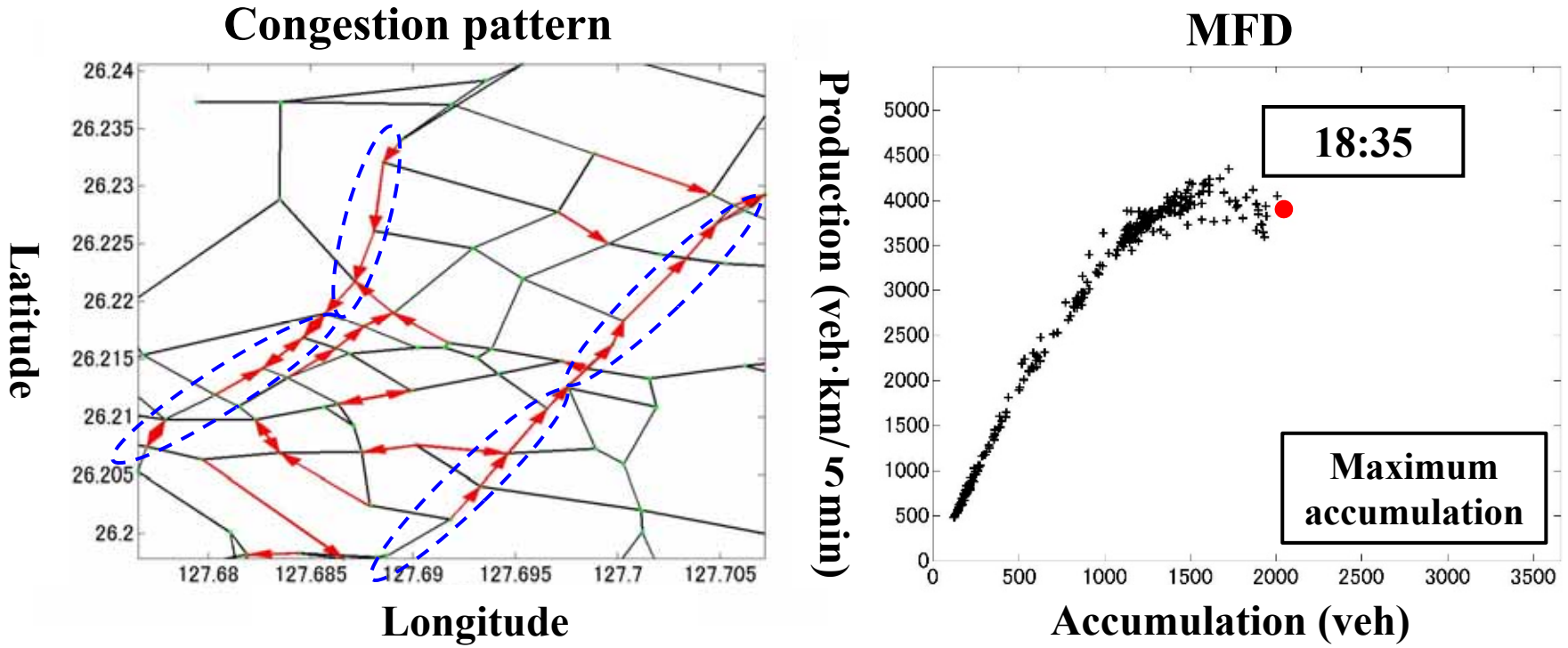

MFD vs. Congestion pattern (Example 1)

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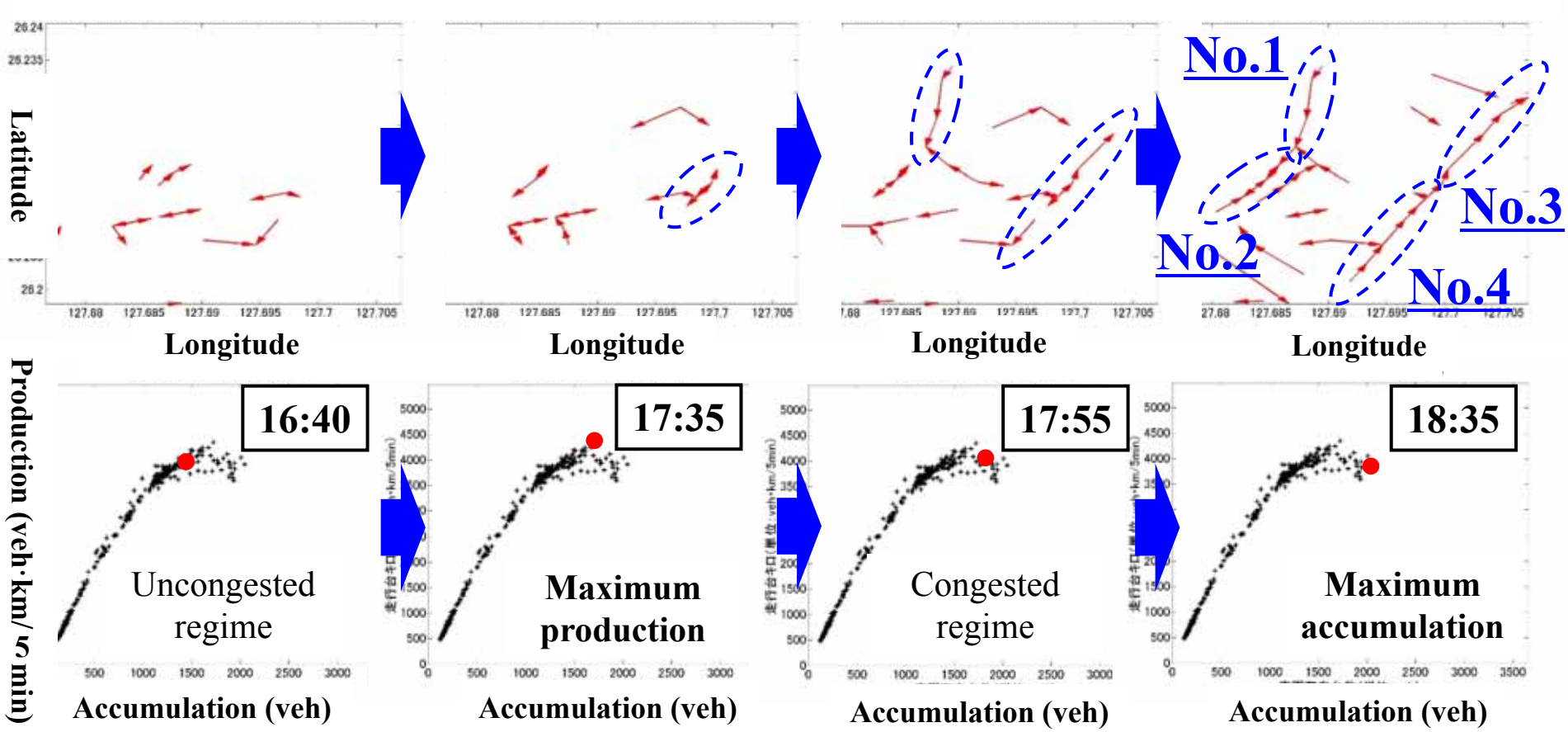
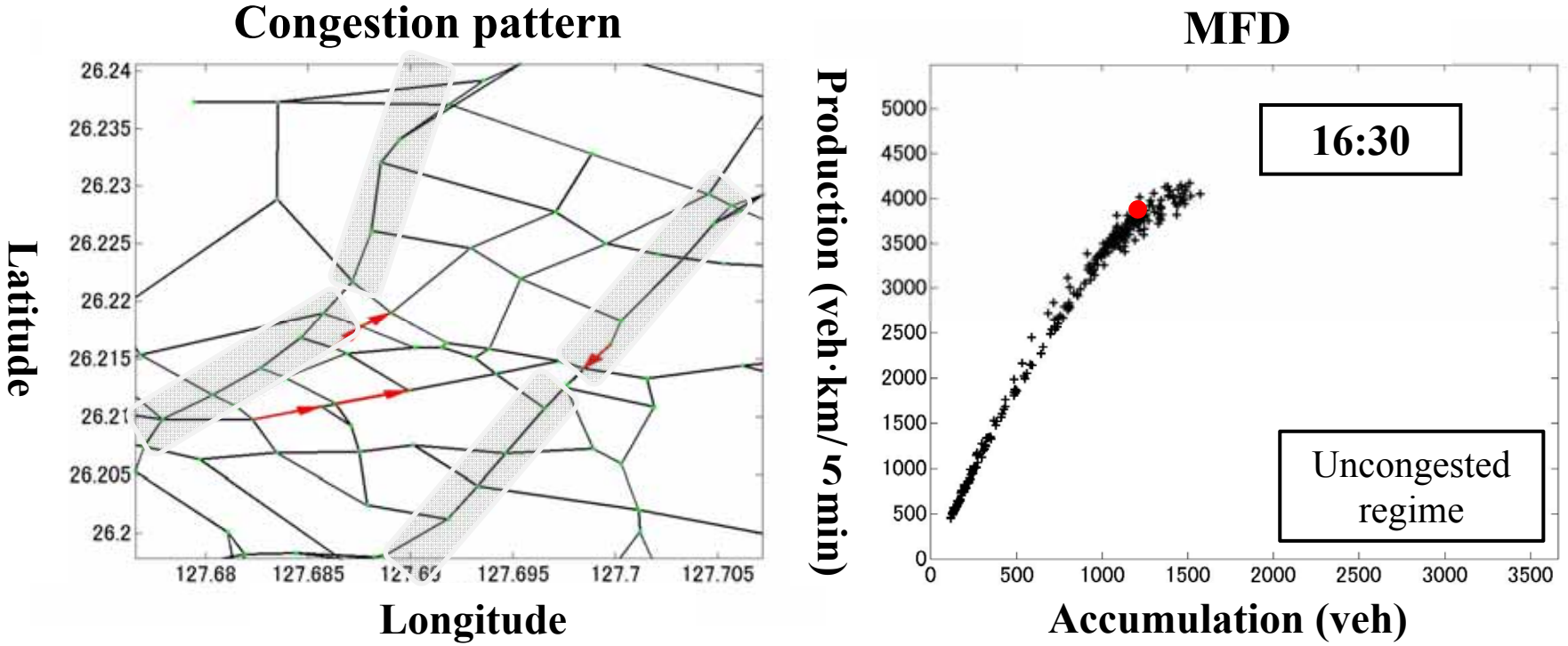


The congested regime occurs gradually as the congestion spreads in cluster Nos.1-4

MFD vs. Congestion pattern (Example 2)

- 5/8/2012 (Uncongested day, sunny)



MFD vs. Congestion pattern (Example 2)

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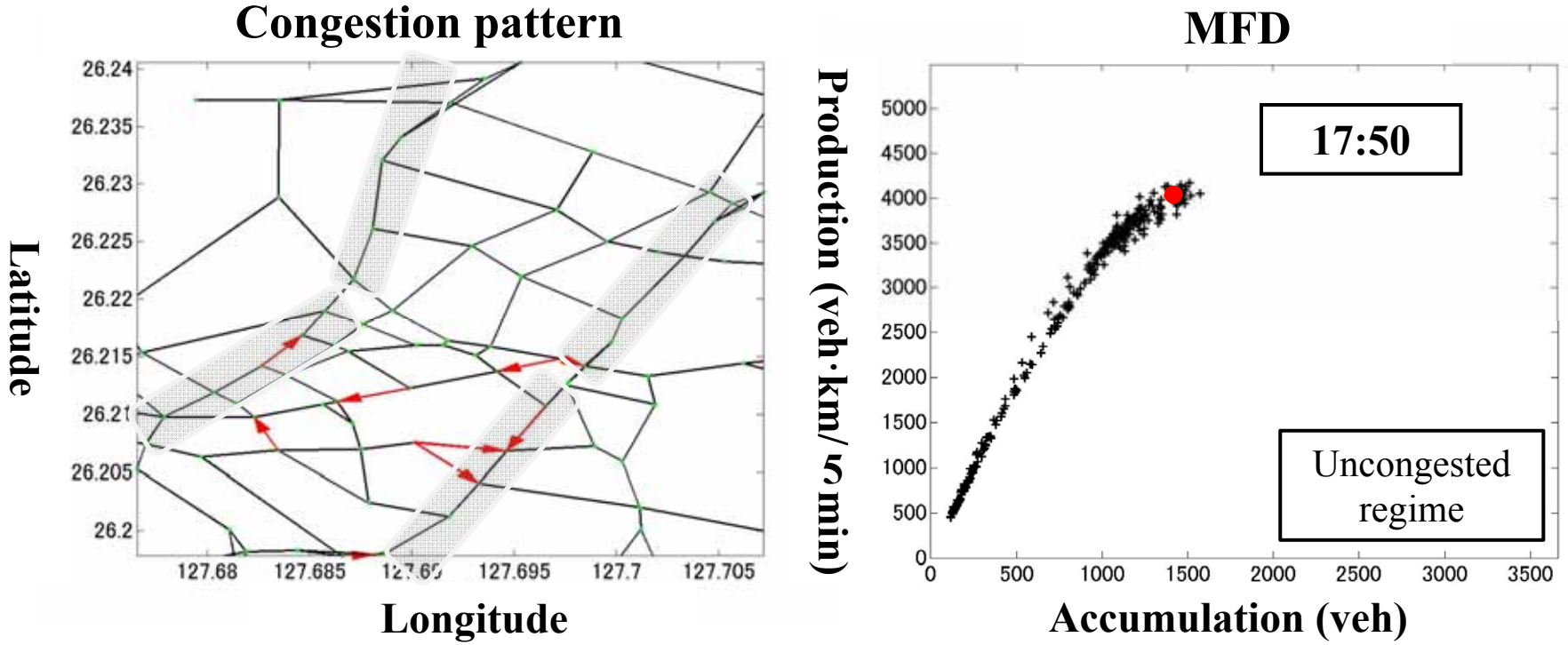
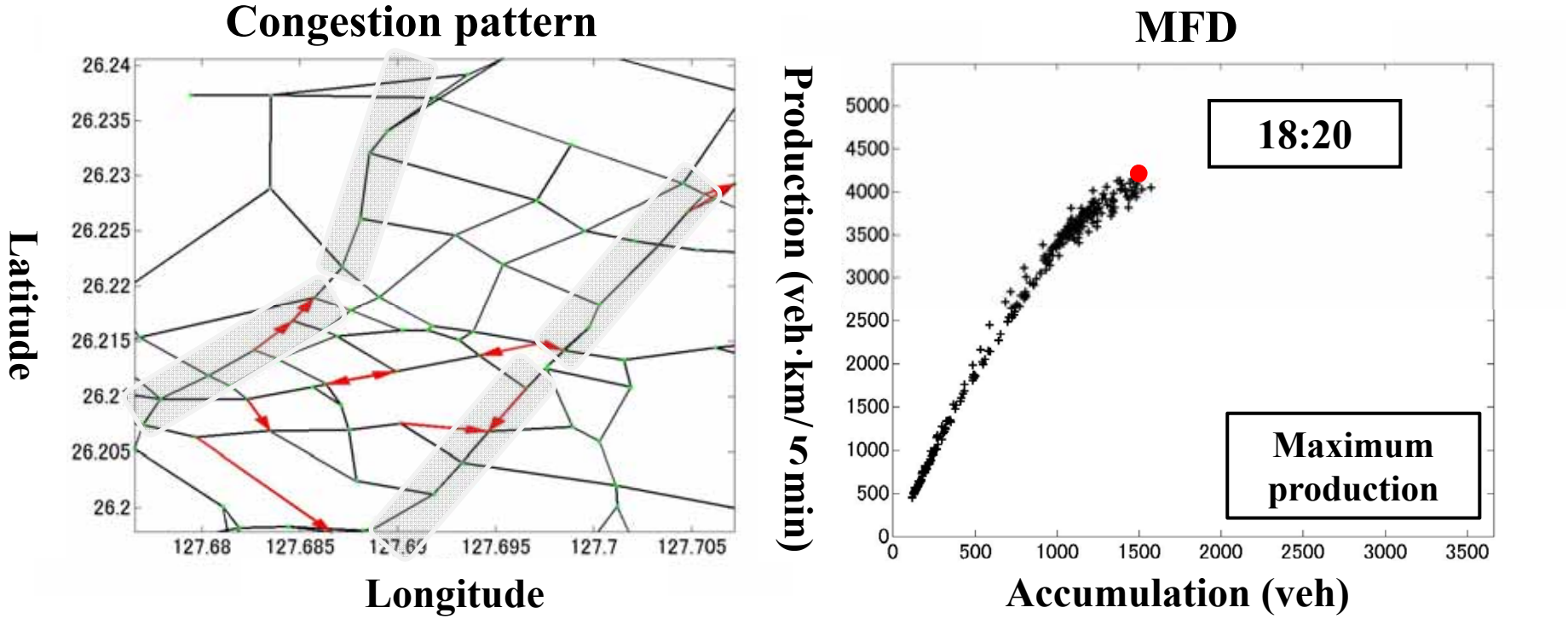


MFD vs. Congestion pattern (Example 2)

- 5/8/2012 (Uncongested day, sunny)



MFD vs. Congestion pattern (Example 2)

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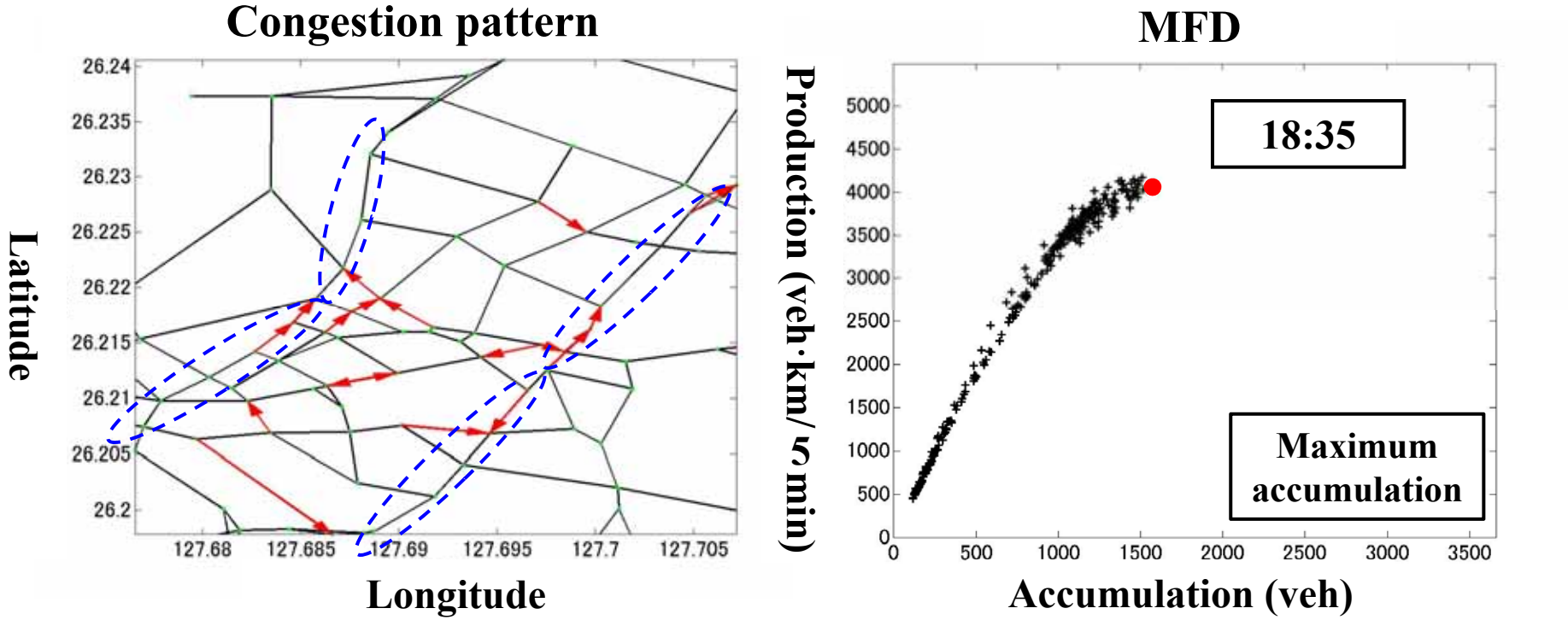
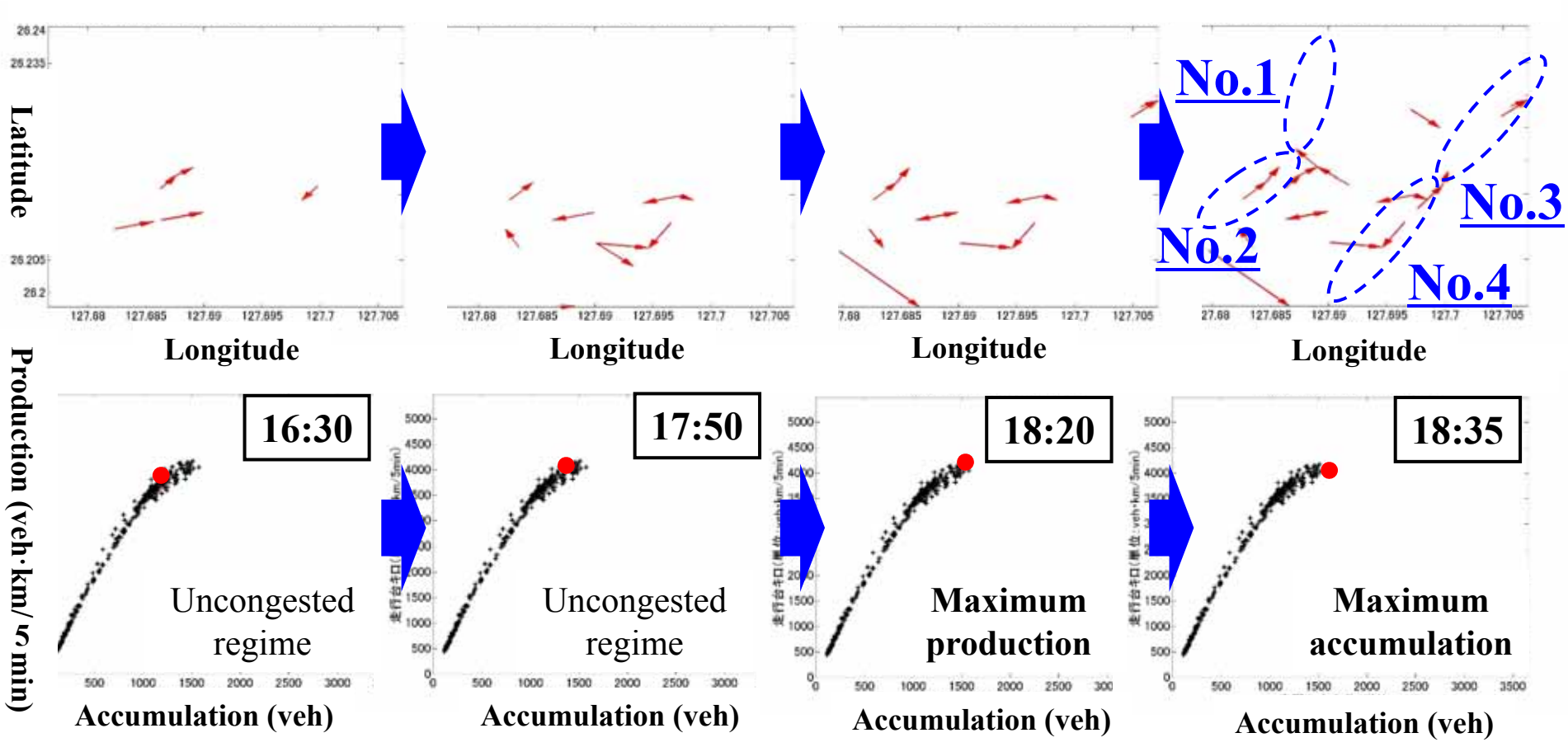


MFD vs. Congestion pattern (Example 2)

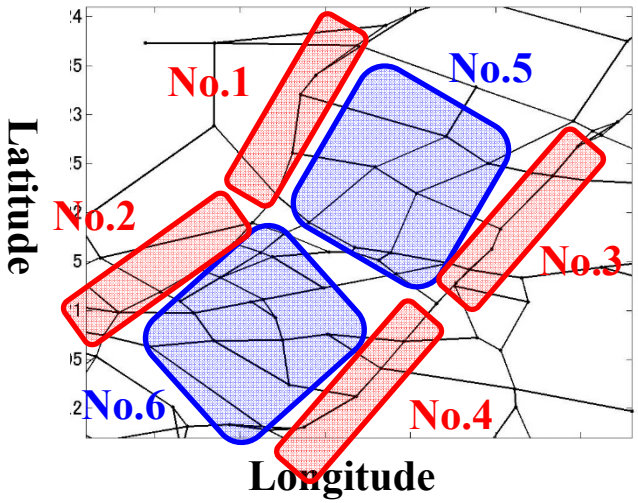
- 5/8/2012 (Uncongested day, sunny)



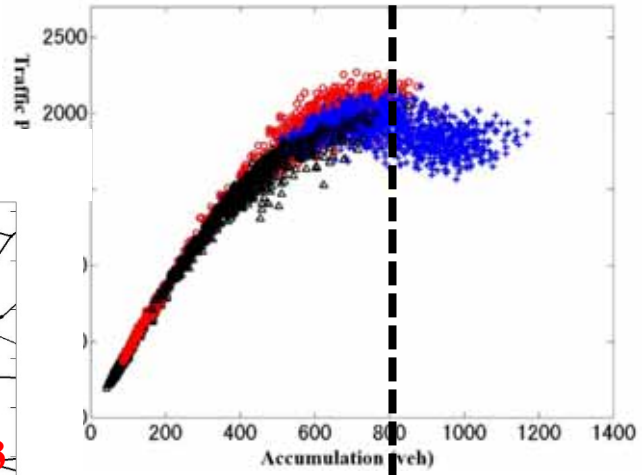
The congestion ***does not*** spread in cluster Nos.1-4 during the entire traffic evolution, even if at the maximum accumulation!

Discussion for the relationship (1)

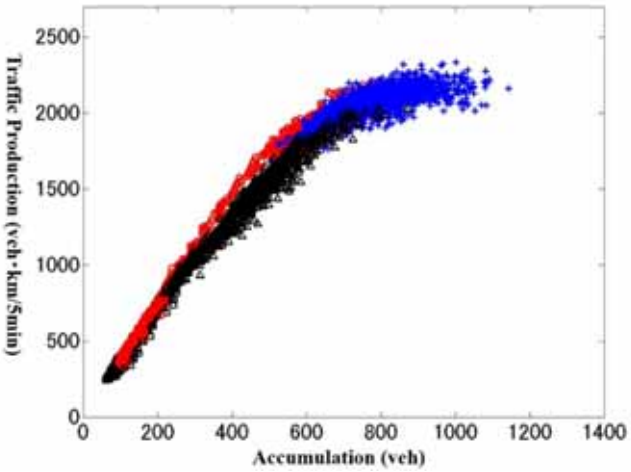
- MFDs for different clusters (Nos.1-4 and Nos.5-6)



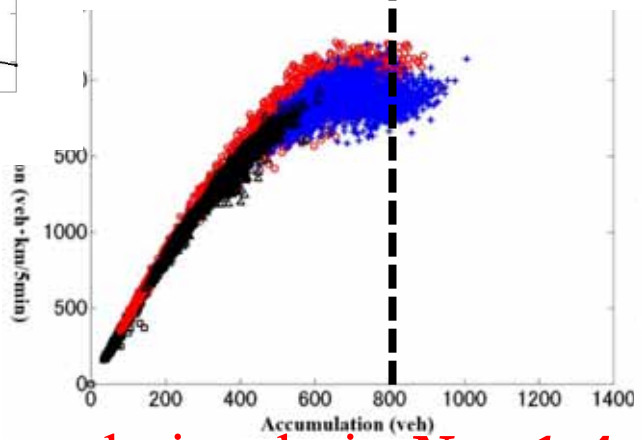
Congested No.7 (Nos.1-4)



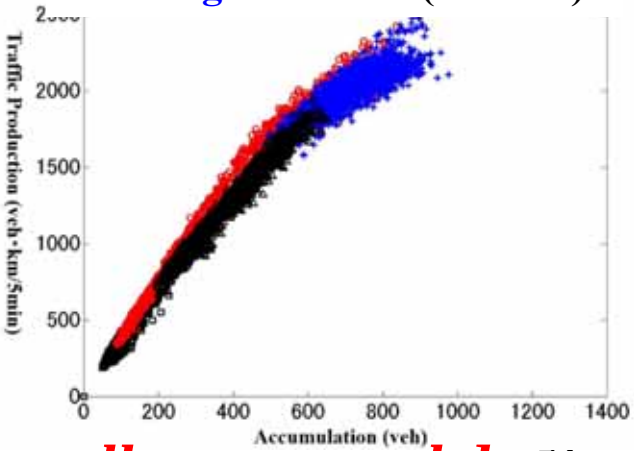
Congested No.8 (Nos.5-6)



Uncongested No.7 (Nos.1-4)



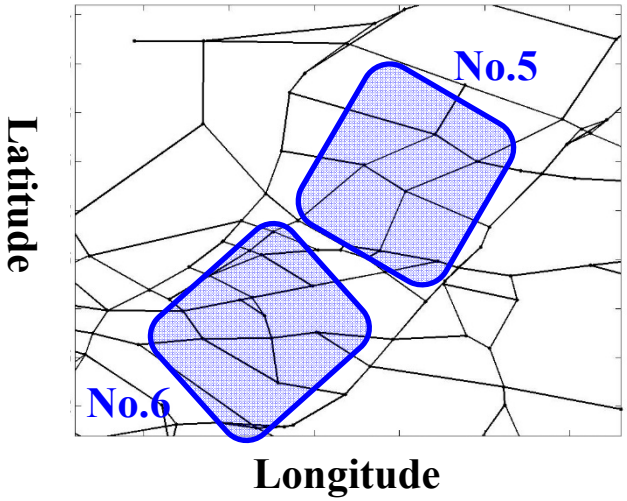
Uncongested No.8 (Nos.5-6)

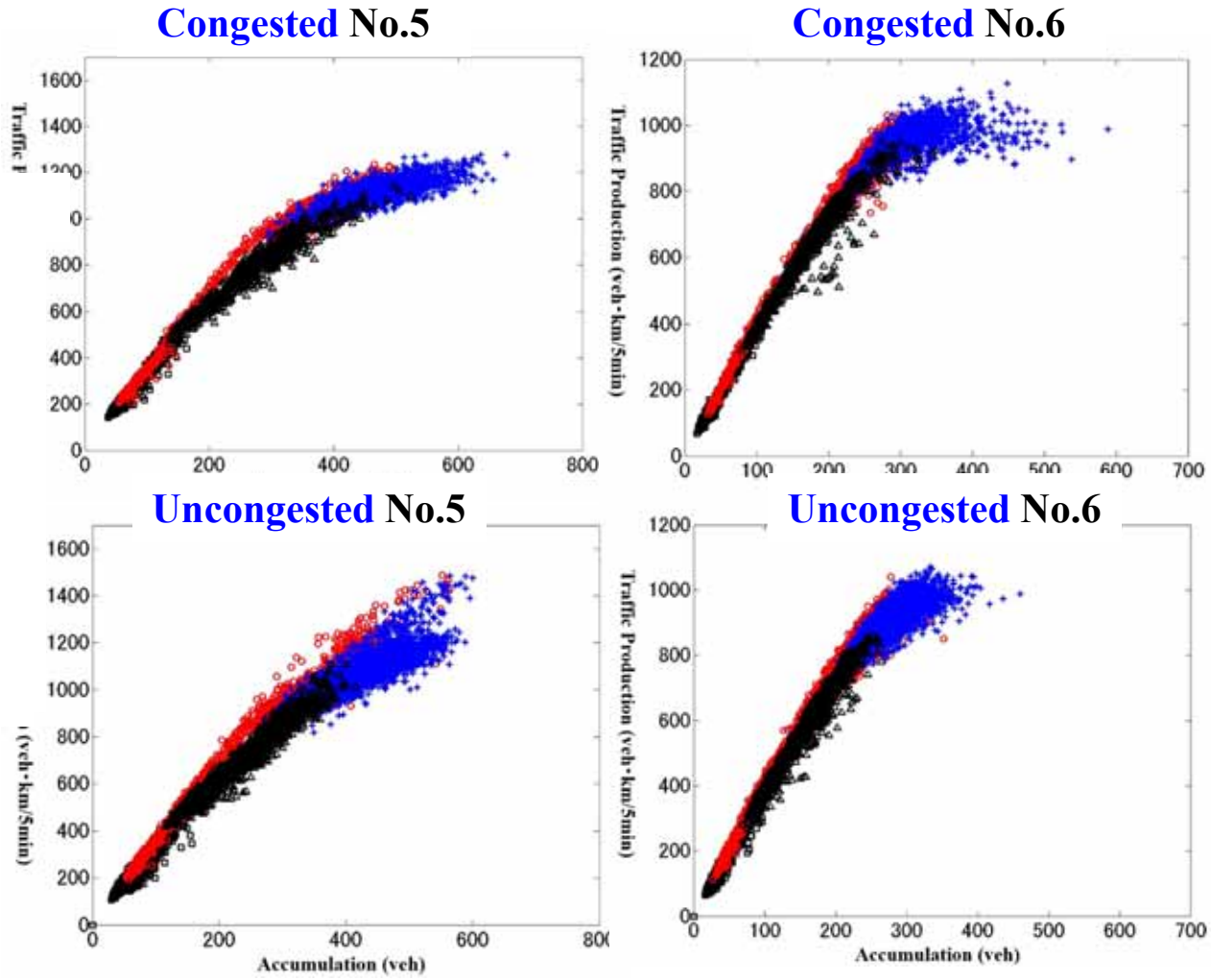


Congested regime occurs obviously in ***Nos.1-4 on all sunny weekdays***

Discussion for the relationship (2)

- MFDs for different clusters (No.5 and No.6)

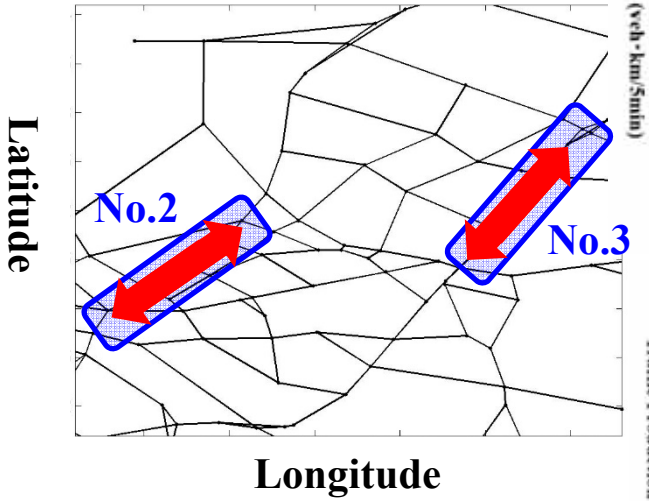


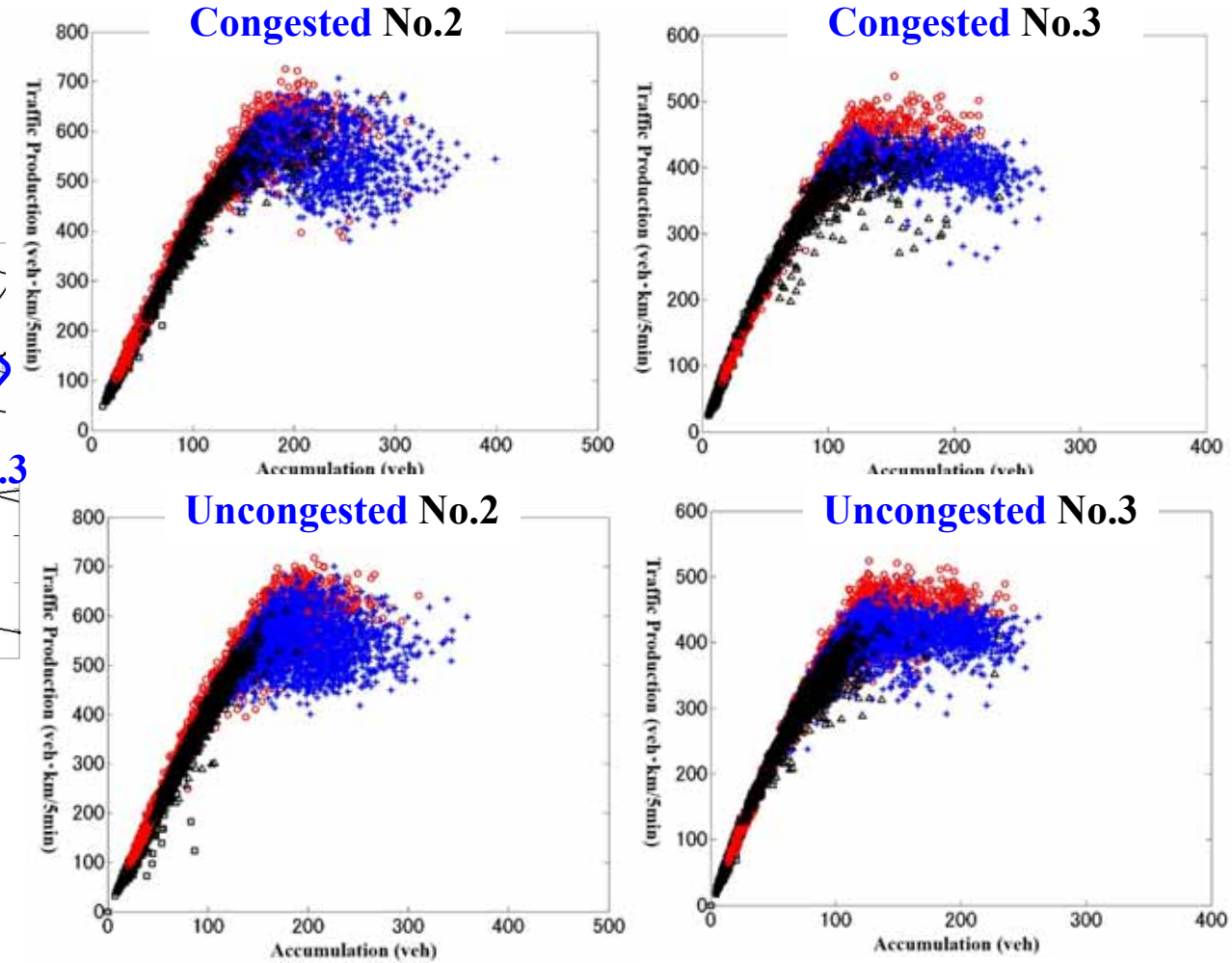


Congested regime does not occur in ***No.5 and No.6***

Discussion for the relationship (3)

- MFDs for different clusters (No.2 and No.3)

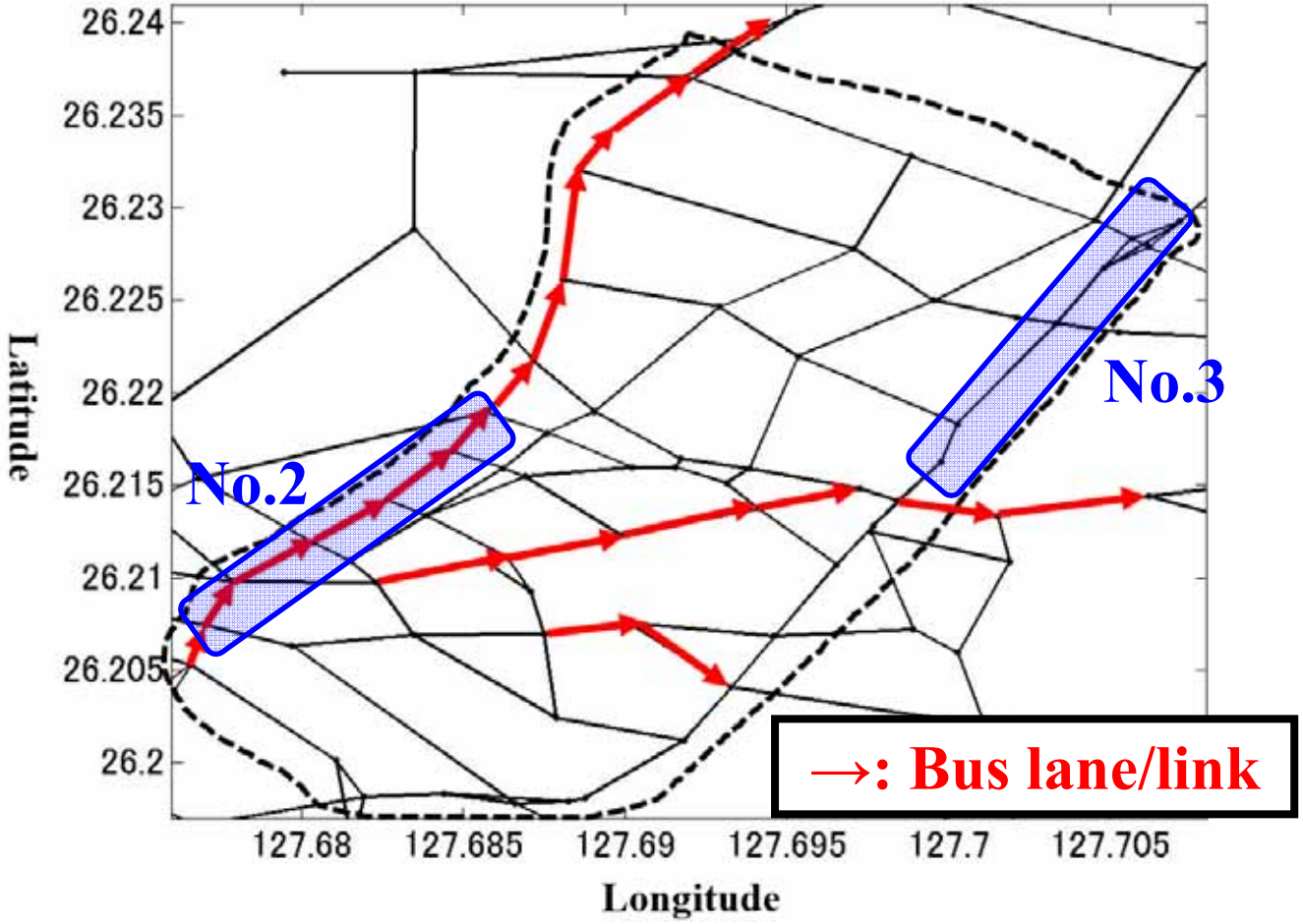




No difference exists between congested and uncongested days

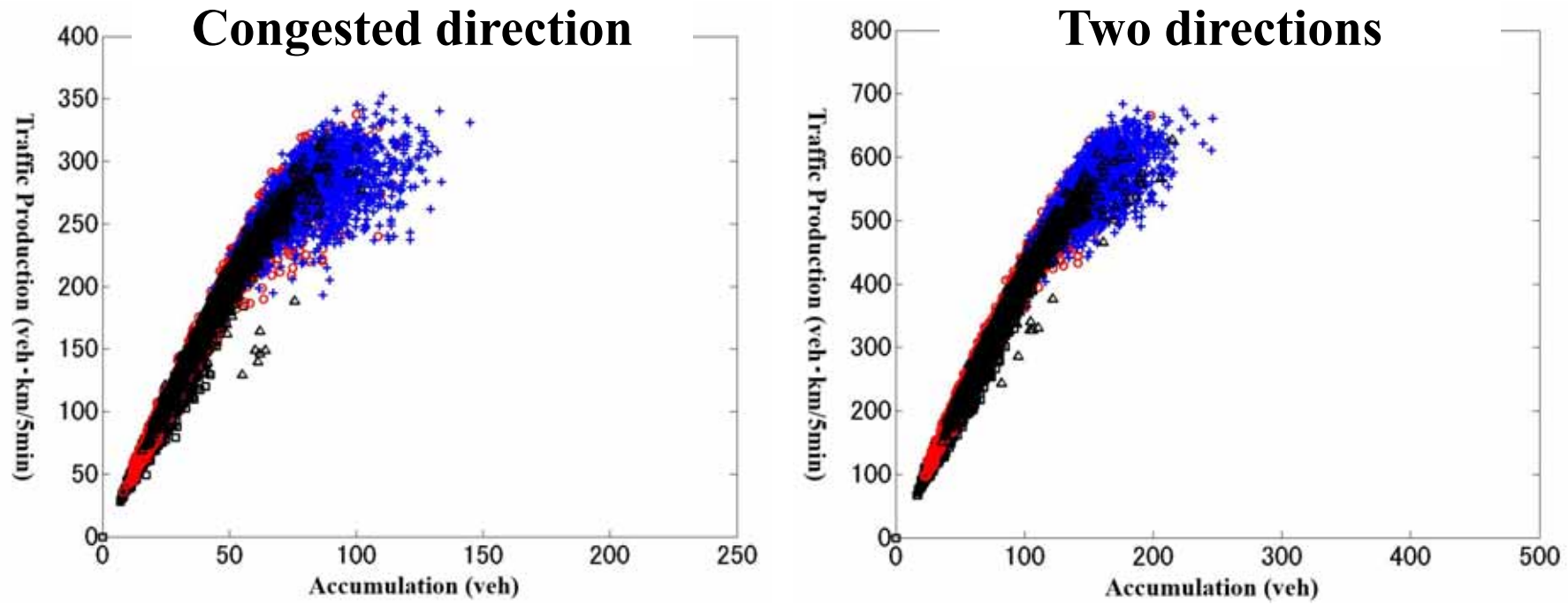
Discussion for the relationship (4)

- Implementation of dedicated bus lane/link (during 17:30-19:30 on all weekdays)



Discussion for the relationship (5)

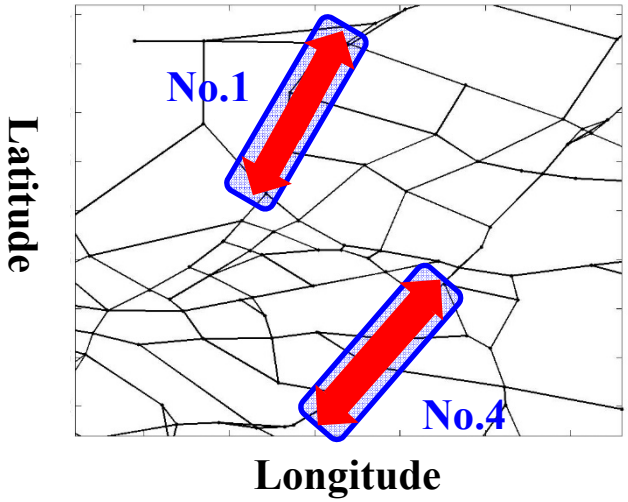
- MFDs for cluster No.2 on sunny ***weekends***

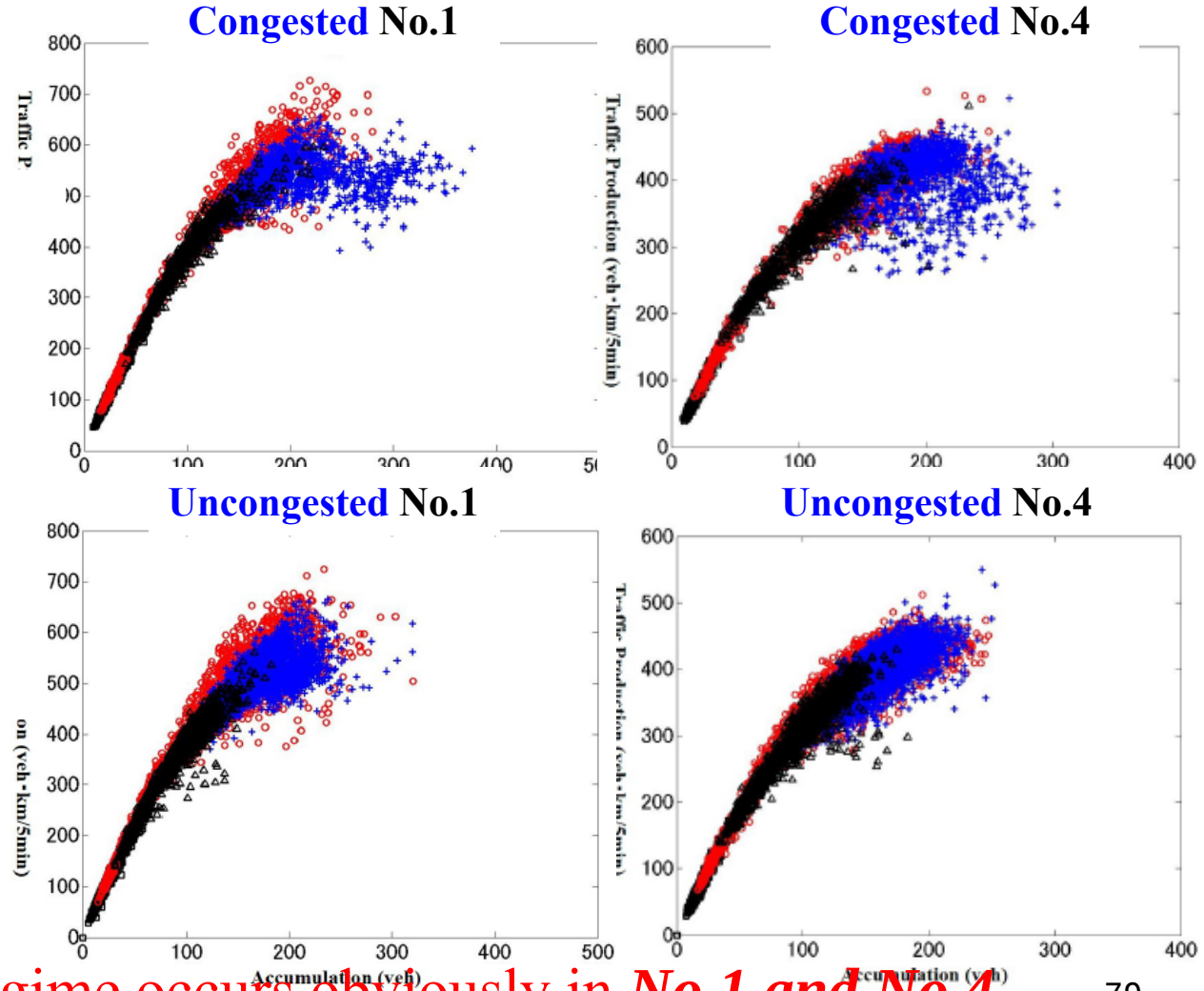


- The congested regime does not occur (for congested direction) in cluster No.2 on sunny ***weekends***
- It means that the occurrence of congested regime is strongly related to the setting of dedicated bus lanes

Discussion for the relationship (6)

- MFDs for different clusters (No.1 and No.4)

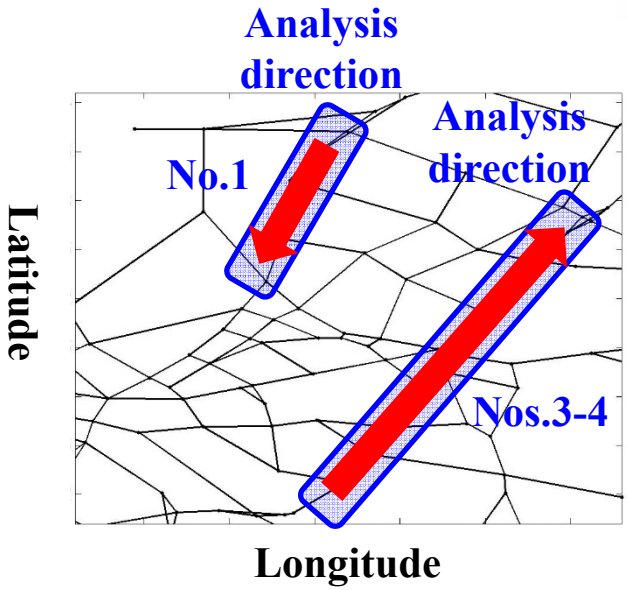


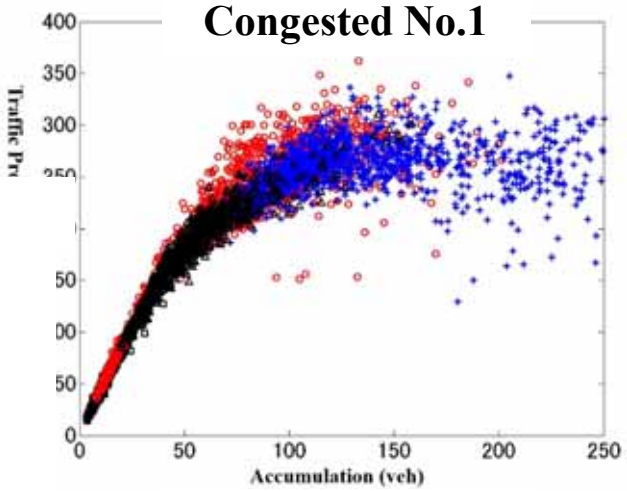


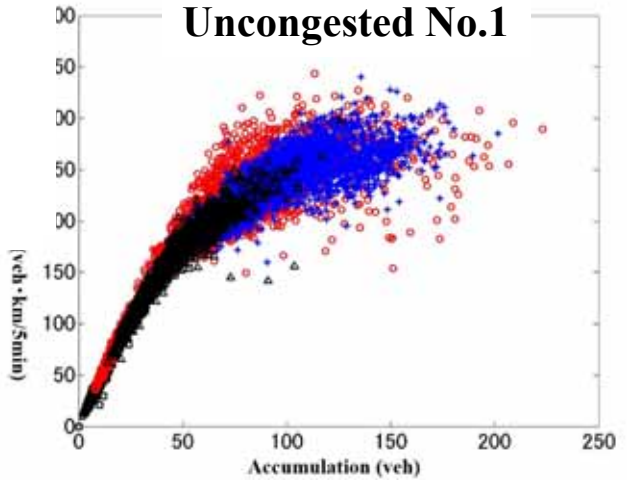
The congested regime occurs obviously in ***No.1 and No.4***

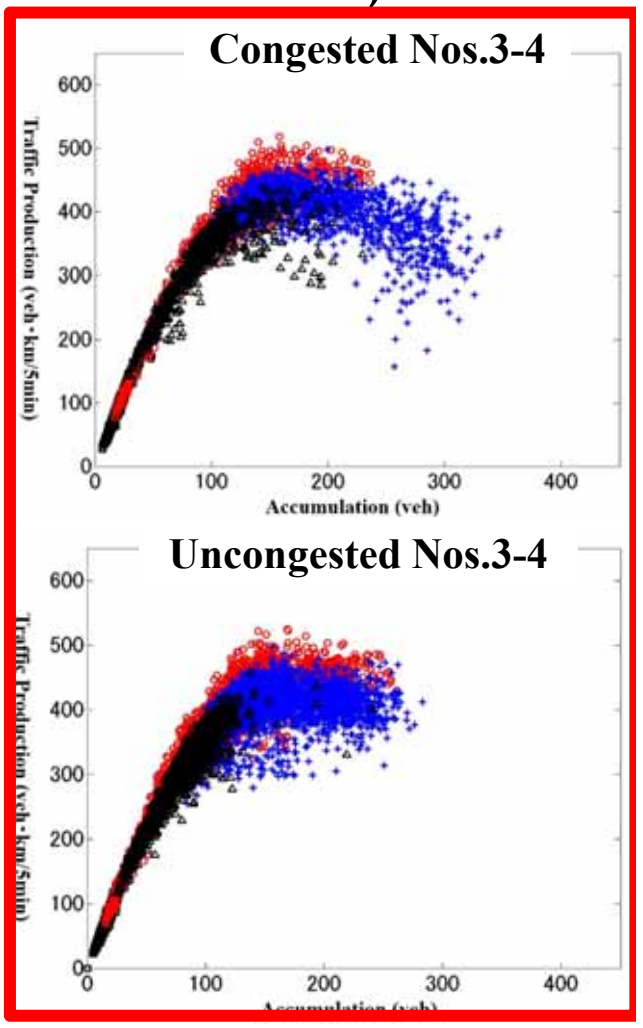
Discussion for the relationship (7)

- MFDs for different clusters (No.1 and Nos.3-4)





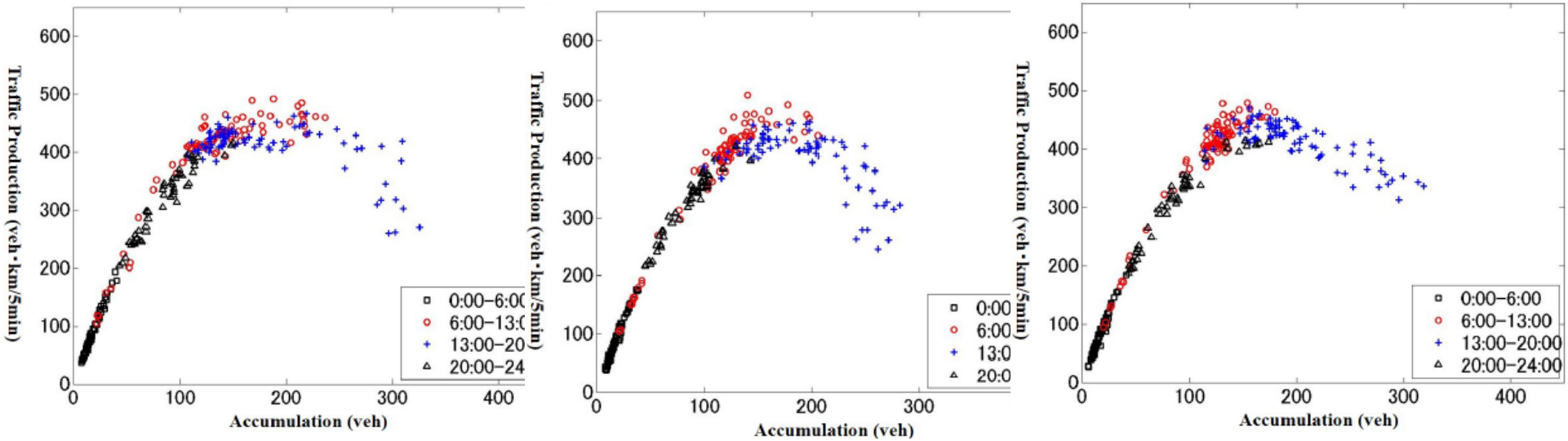




Well-defined MFDs with congested regime ***mainly exist in Nos.3-4***

Discussion for the relationship (8)

- MFD for cluster Nos.3-4 (typical days)

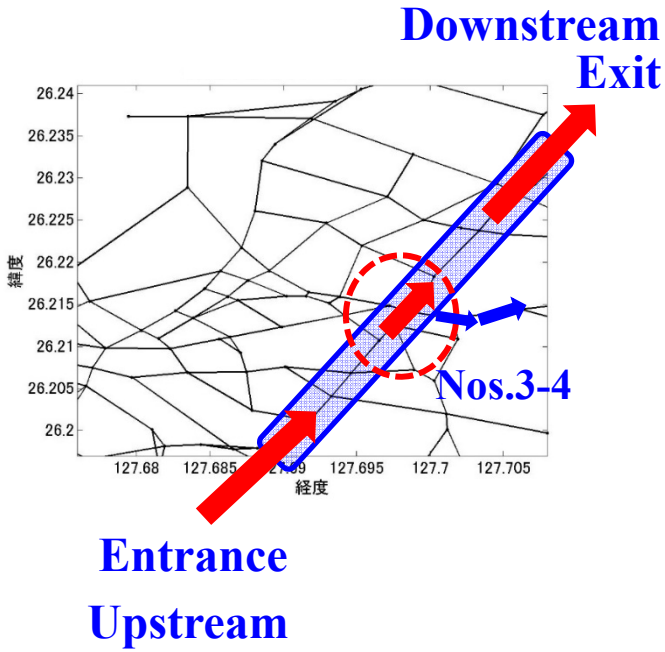


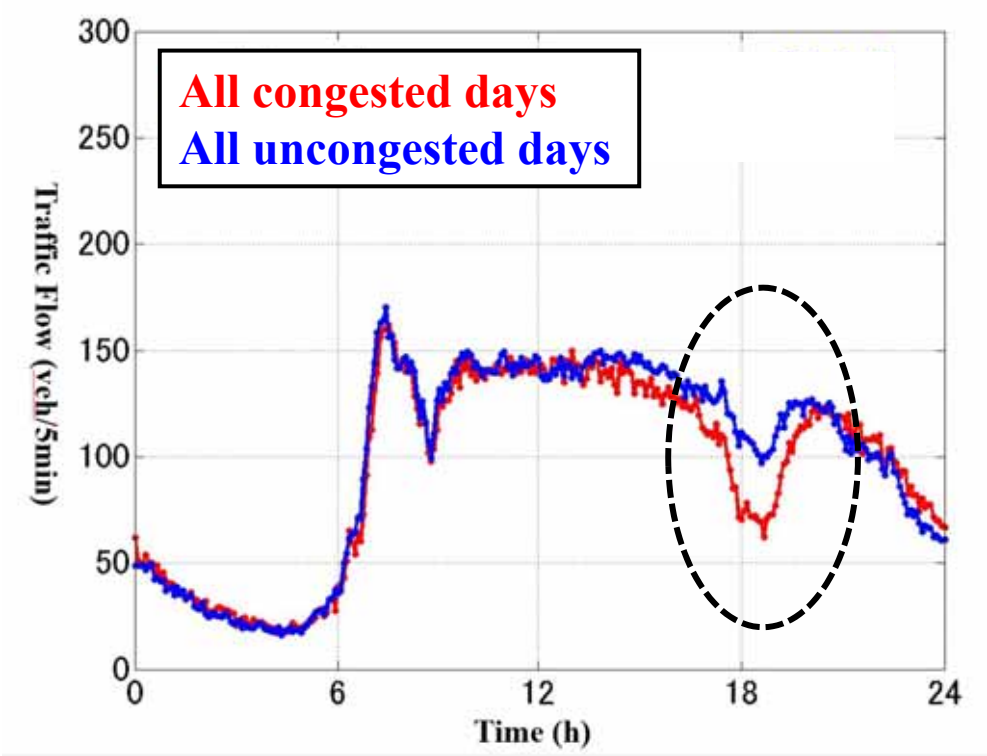
6/26/2012 11/16/2012 12/21/2012

Well-defined MFDs with congested regime (***without hysteresis loop***) exists

Discussion for the relationship (9)

- Entrance and exit flow of cluster Nos.3-4

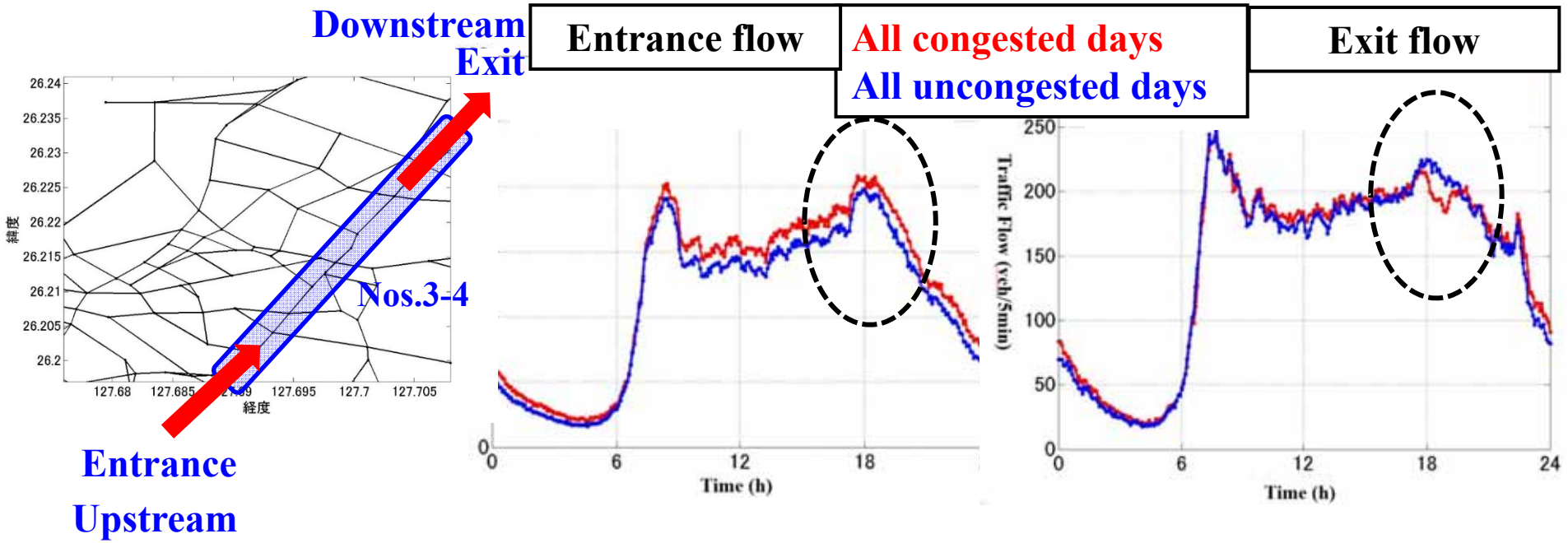




- The exit flow rate of a middle intersection (red dashed line) decreases from 17:30 and increases since 19:30 (the setting of the dedicated bus lane ***decreases*** the discharge rate of right-turn vehicles at this intersection)

Discussion for the relationship (10)

- Entrance and exit flow of cluster Nos.3-4



- Entrance flow rate (in the most upstream): it on congested day is higher than that on uncongested day
- Exit flow rate (in the most downstream): it on congested day is lower than that on uncongested day

Summary of **urban street networks** (1)

- Robust features of MFD (Sections 2.1-2.2)
  - Sendai: Formation of hysteresis loop
    - Morning peak hours: 100% of sunny weekdays
    - Evening peak hours: 64.2% of sunny weekdays
  - Kyoto: Formation of hysteresis loop
    - Sunny Saturdays: 66.7%
    - Sunny Sundays: 46.3%
  - Naha: Occurrence of congested regime
    - Sunny & rainy weekdays: 20.3%
    - Rainy weekends: 4.2%

(1) The formation of hysteresis loop is ***a common phenomenon***,
but the occurrence of congested regime is ***a rare phenomenon***.
(2) Especially, the ***well-defined MFD*** without hysteresis loop ***cannot be*** observed unless ***under the special condition*** (e.g., Dedicated Bus lane)

Summary of **urban street networks** (2)

- Relationship (Sections 2.1-2.2)
  - Under the same accumulation level, the relationship between the traffic production and the number of queue-spillbacks is almost negative linear
  - If the number of queue-spillbacks exceeds its critical value, the congested regime occurs gradually with the significant increase of the number of queue-spillbacks
  - The high number of queue-spillbacks (occurrence of congested regime) is corresponding to the congestion spreading in some specific parts of analysis networks

(1) The stable relationship between the MFD features and spatial congestion patterns ***exists robustly*** in different street networks!
(2) We can ***eliminate the queue-spillbacks in these important sub-networks*** to prevent the occurrence of congested regime in the MFD

Section 2.3

	Section 2.1	Section 2.2	Section 2.3
Country	Sendai Kyoto	Naha	**Tokyo**
Network Type	Street	Street	**Expressway**
MFD Features	Hysteresis Loop	Congested Regime	**Hysteresis Loop Congested Regime**

Contents of **Section 2.3**

- Basic information of detectors data
  - Road networks and detectors data
  - Traffic regulation information
- Characterization of MFDs
  - MFD features under different demand/supply conditions
  - Traffic production vs. Trip completion
- MFD features vs. Congestion pattern
  - Number of queue-spillbacks and congested destinations
  - Spatial distribution of congested links
  - Discussion for the relationship

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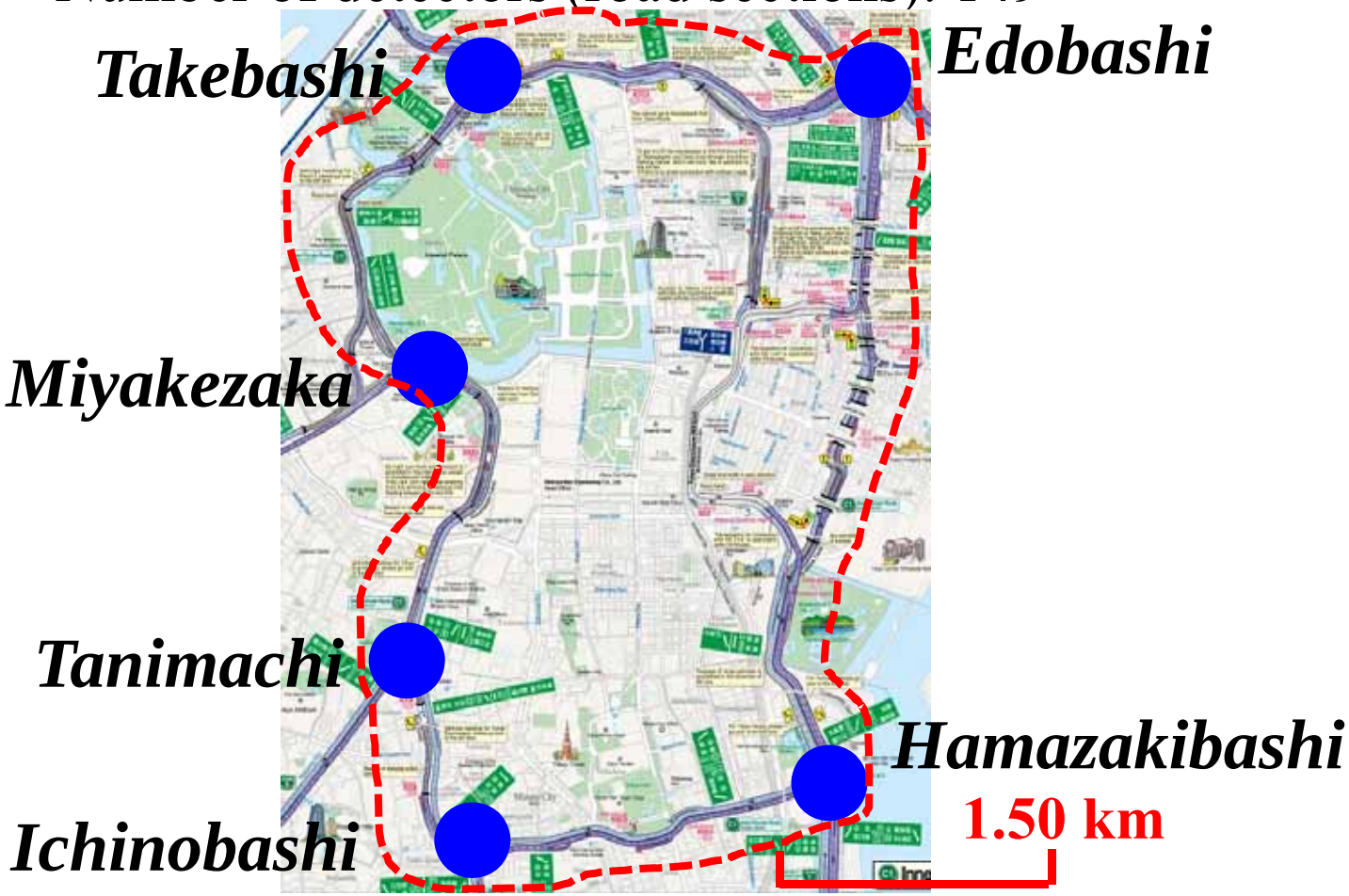
  - Discussion for the relationship

Basic information of detectors data (1)

- Analysis area
  - Inner Circular Route (approximate 9.6 km^2)
  - Number of detectors (road sections): 149



Basic information of detectors data (2)

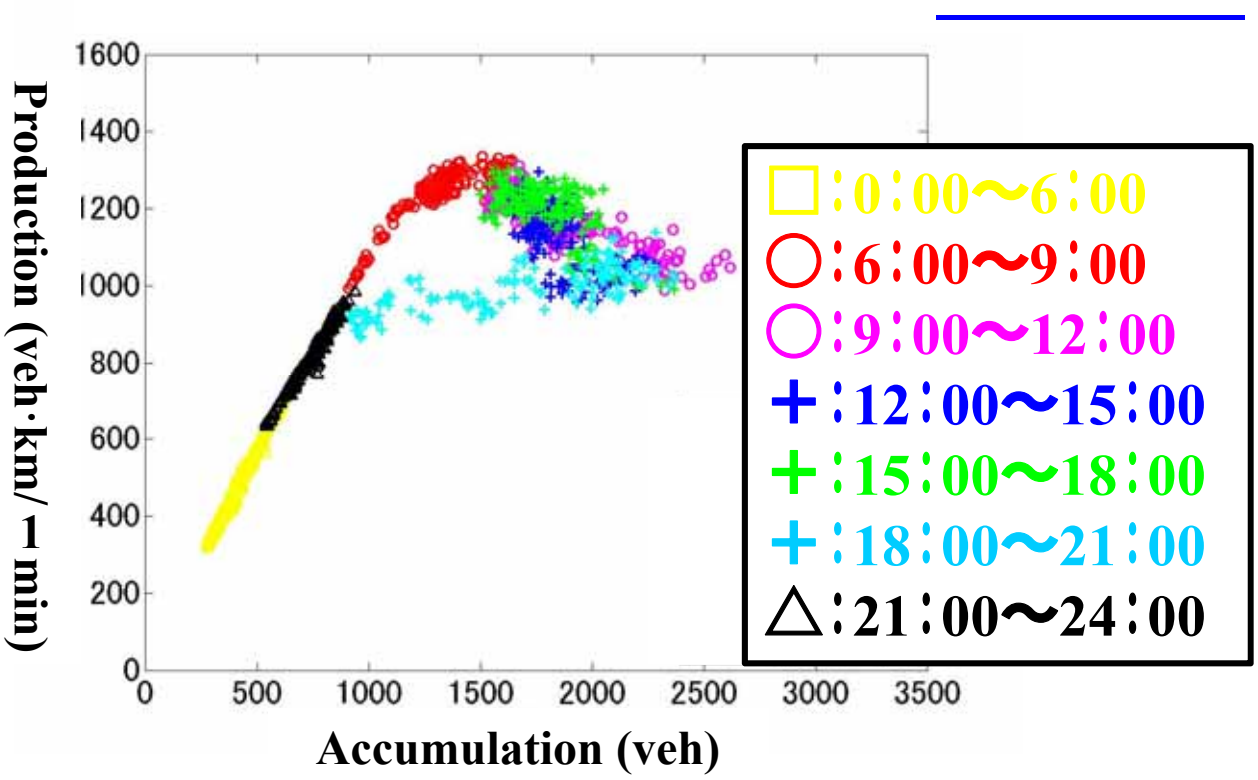
- Analysis period
  - 1/1/2014 ~ 12/31/2014 (365 days)
  - 1-min period during each 24-h day ($T = 1440$)

- Data records of detector i during t (1-min period)
  - Traffic flow: q_t^i
  - Vehicle speed: v_t^i
  - Traffic density: $k_t^i = q_t^i / v_t^i$

MFD definition

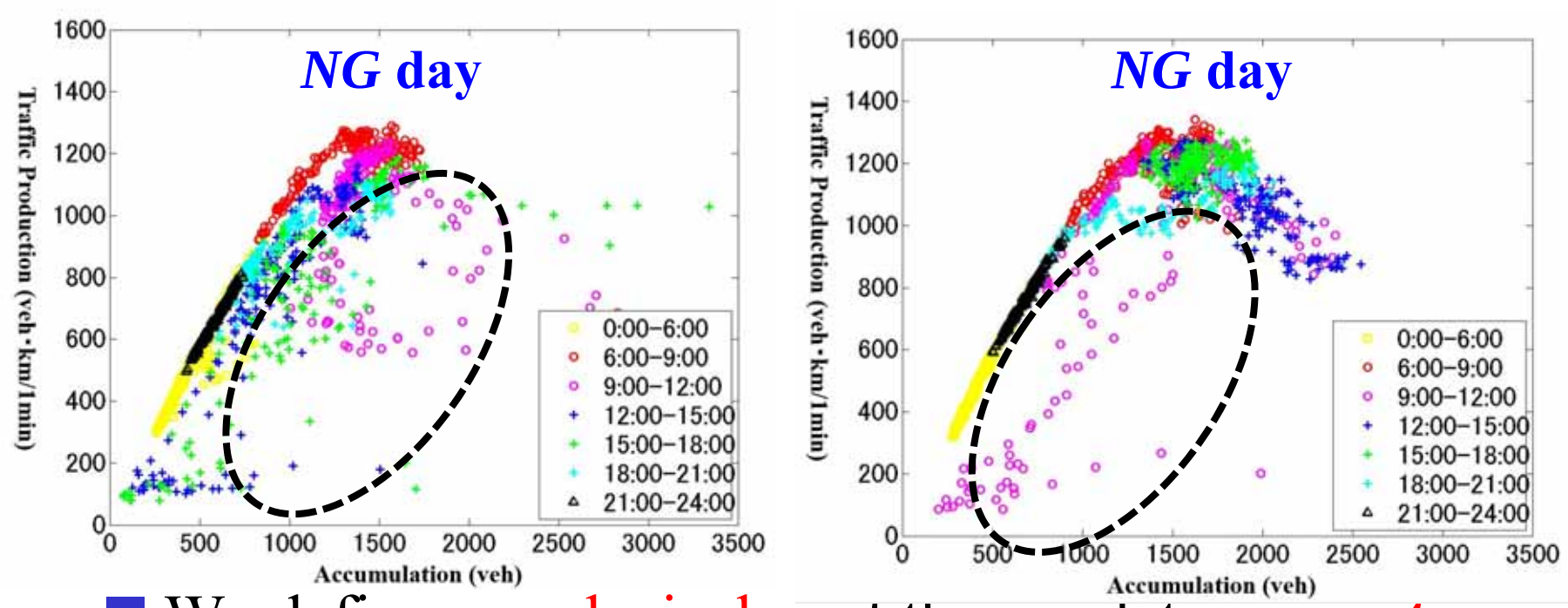
- The calculation of coordinates for each plot
  - Accumulation: $N_t = \sum_{i=1}^{|I|} k_t^i l^i = \sum_{i=1}^{|I|} \left(q_t^i / v_t^i \right) l^i$
  - Traffic production: $P_t = \sum_{i=1}^{|I|} q_t^i l^i$

l^i :length of road section i



Traffic regulation information

- Selection of analysis days for analysis



- We define a analysis day, if the regulation is ***not***
  - during the 7:00-21:00
  - on the main lanes in the analysis area

243 days (162 weekdays; 81 weekends) are selected for this analysis

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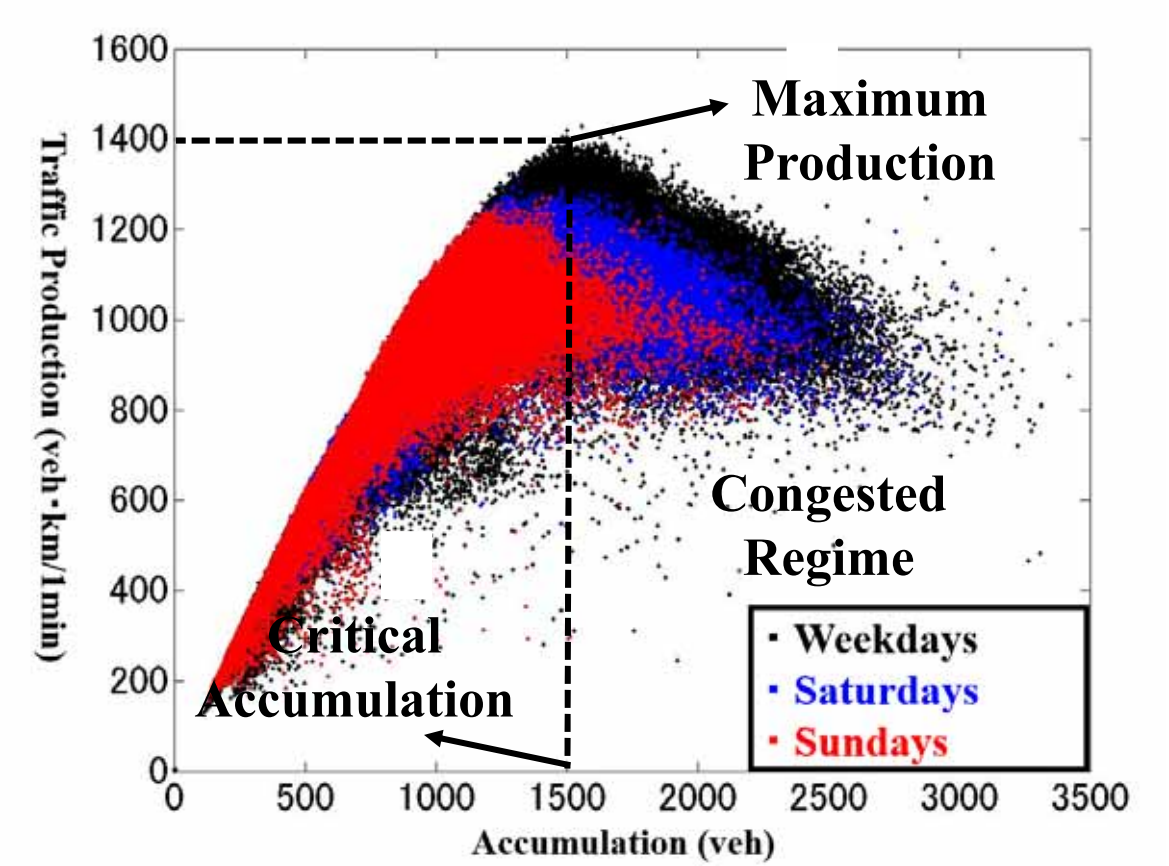
MFD classification

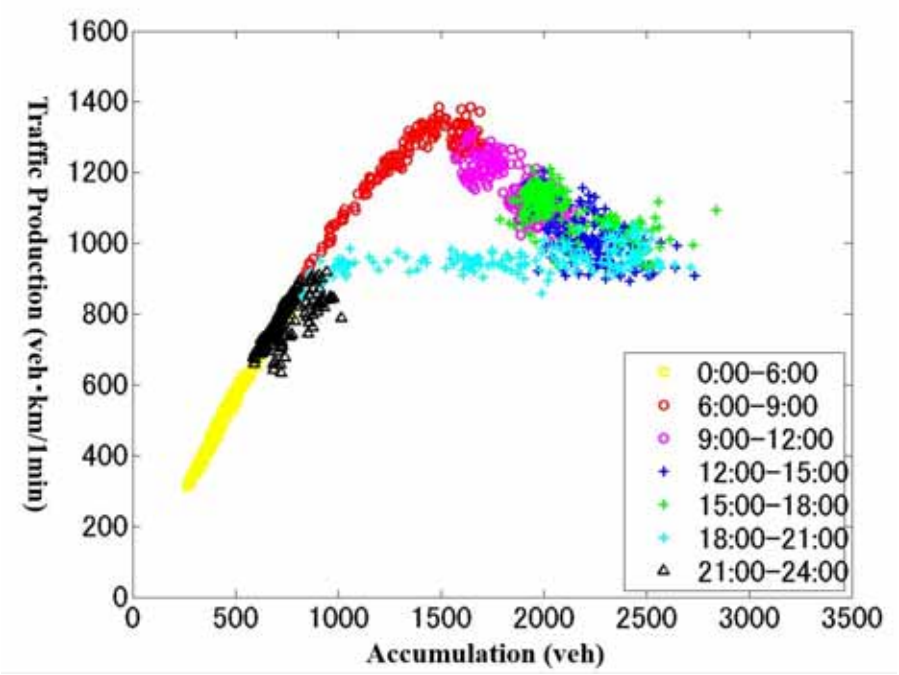
- MFDs for the entire year

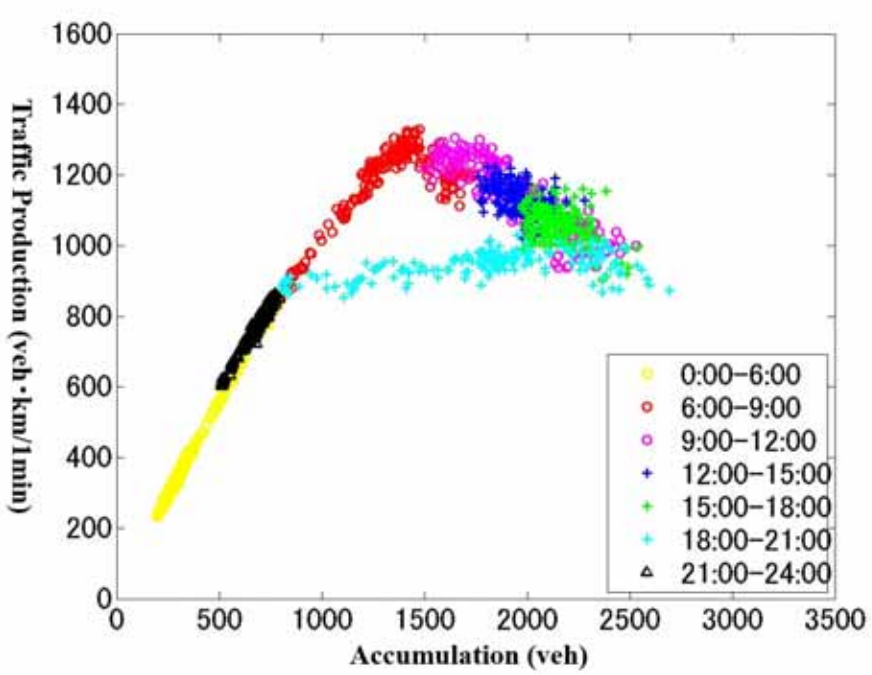


- Congested regime occurs on almost every weekdays and many weekends

MFDs for different demand condition (1)

- MFD features on sunny weekdays

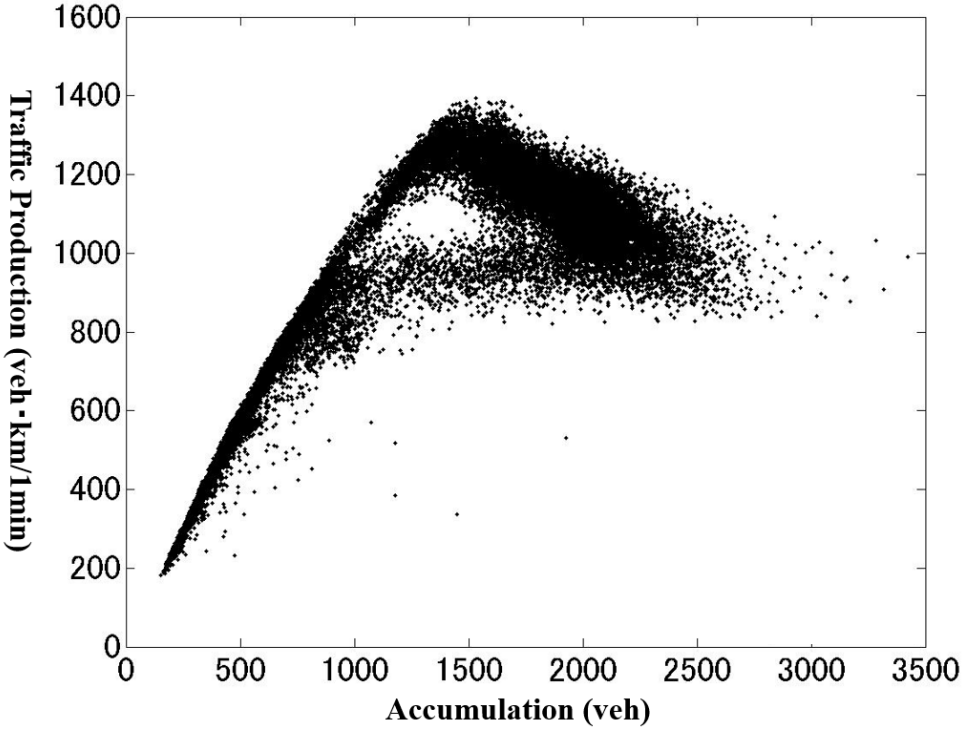




- Occurrence of congested regime is a common phenomenon for almost every sunny weekdays (95.6%)
- Formation of hysteresis loop can be often observed (66.7%)
- Triangular shaped MFDs with low scatters exist (40.5%)

MFDs for different demand condition (2)

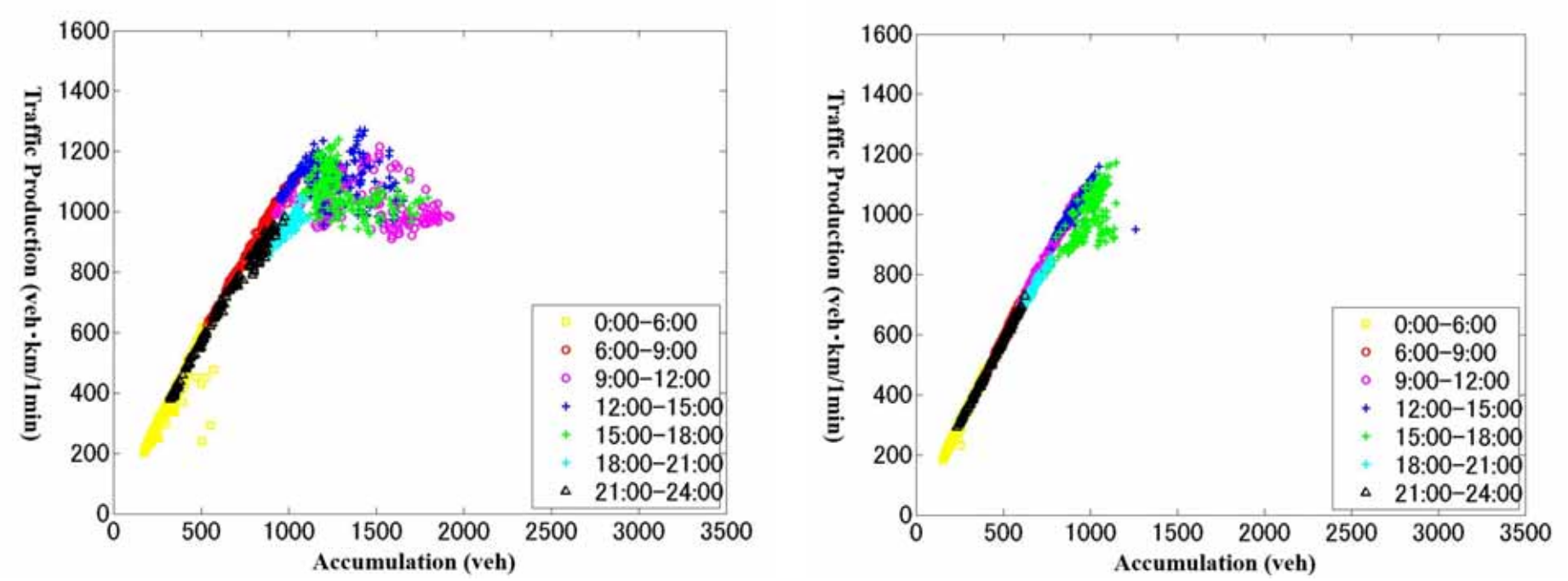
- Triangular shaped MFDs on sunny weekdays (30 days)



- The reproducible and invariant MFDs with congested regime and hysteresis loops exist on many sunny weekdays (congested regime and hysteresis loop have ***the same path***)

MFDs for different demand condition (3)

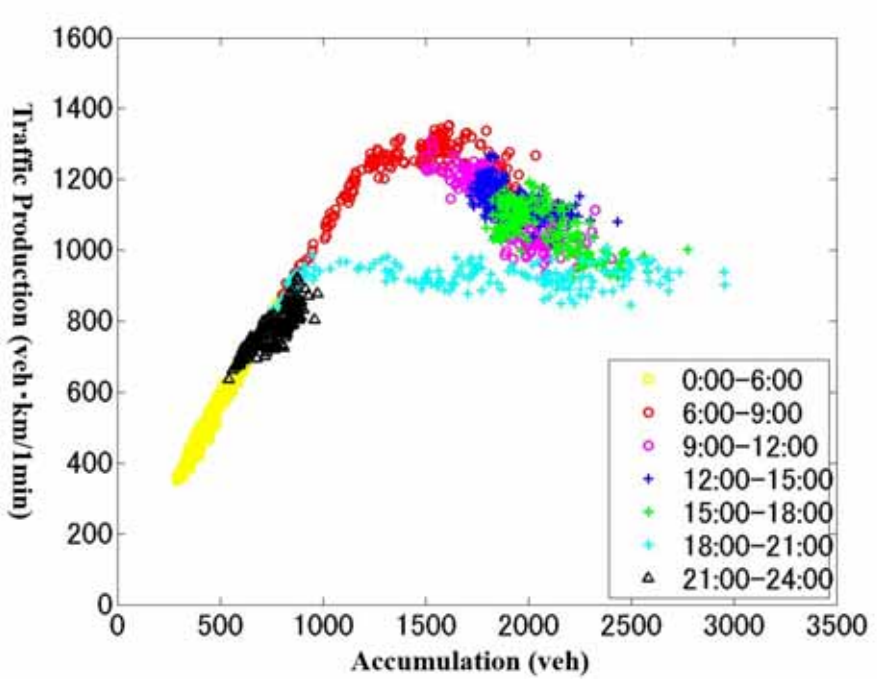
- MFD features on sunny weekends

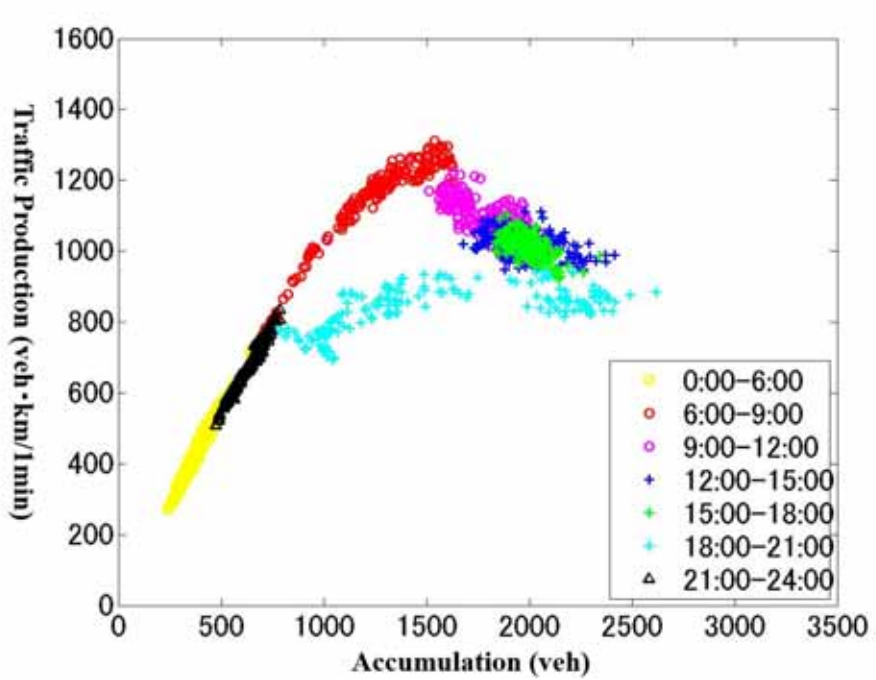


- The congested regime may occur (42.6%), or it may not
- The hysteresis loop is a rare phenomenon (4.8%)

MFDs for different supply condition

- MFD features on bad weather weekdays

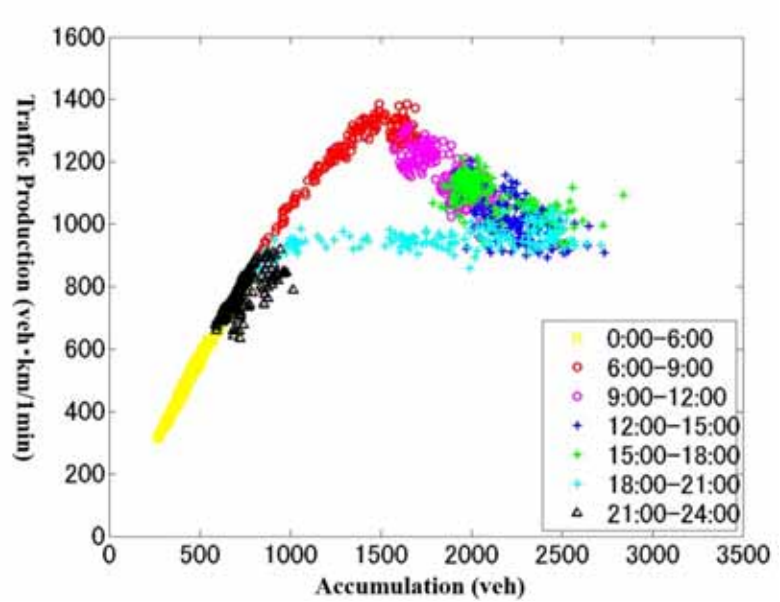




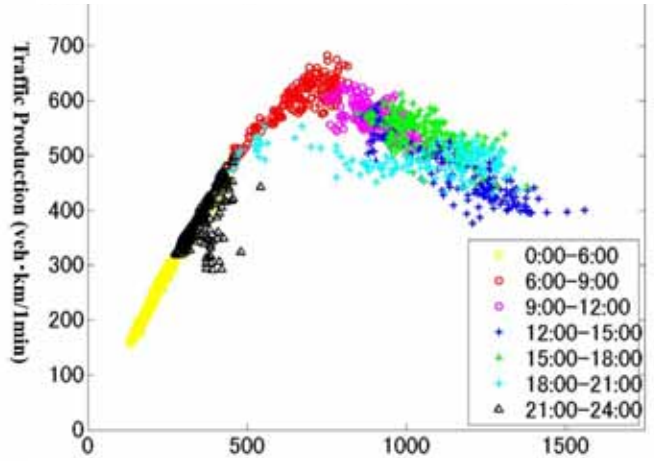
- Occurrence of congested regime is a common phenomenon for almost every bad weather weekdays (97.6%)
- Formation of hysteresis loop can be often observed (58.7%)

MFDs for different networks (1)

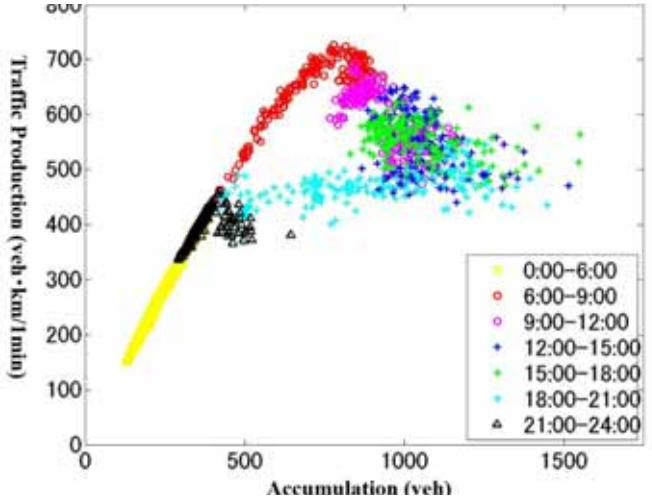
- MFDs for Anti-clockwise and Clockwise Route



Anti-clockwise Route



Clockwise Route

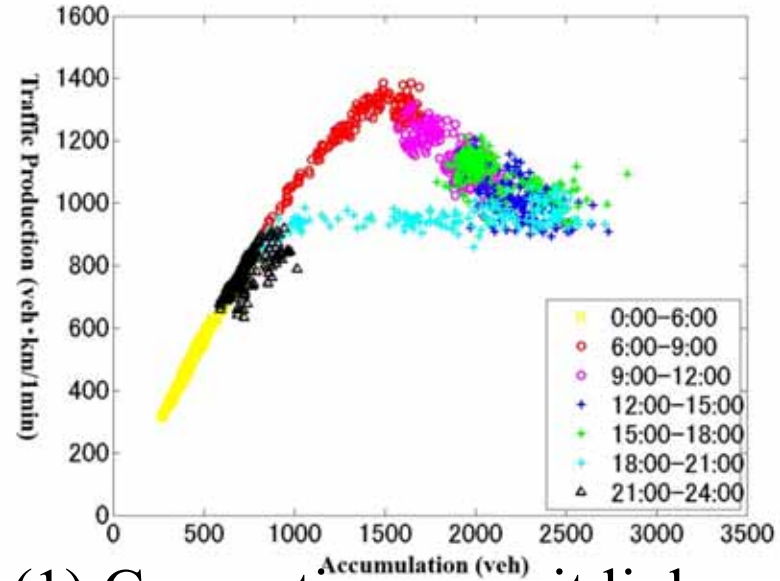


(1) Congested regime occurs both in these two routes

(2) Hysteresis loop only forms in Clockwise Route

MFDs for different networks (2)

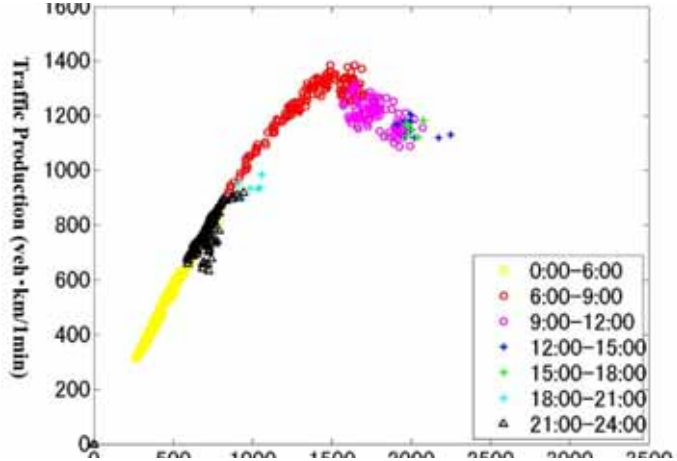
- MFDs for different congestion condition on JCTs



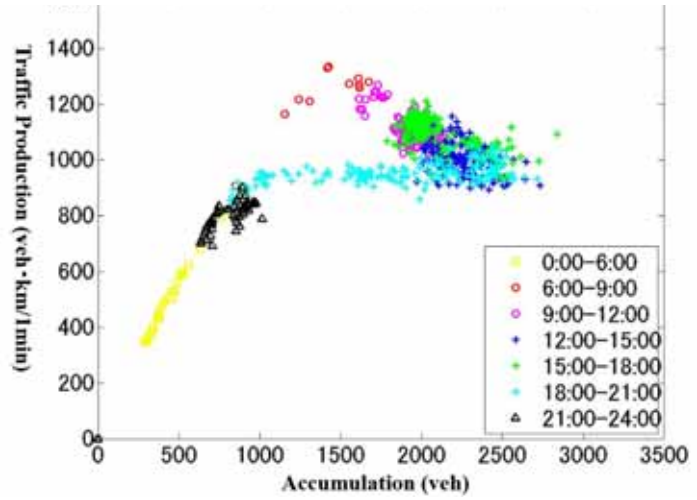
(1) Congestion on exit links of JCTs ***is not the basic reason*** for the occurrence of congested regime

(2) Congestion on exit links of JCTs increases the level of congested regime and causes the formation of hysteresis loop

No congestion exists on any JCTs

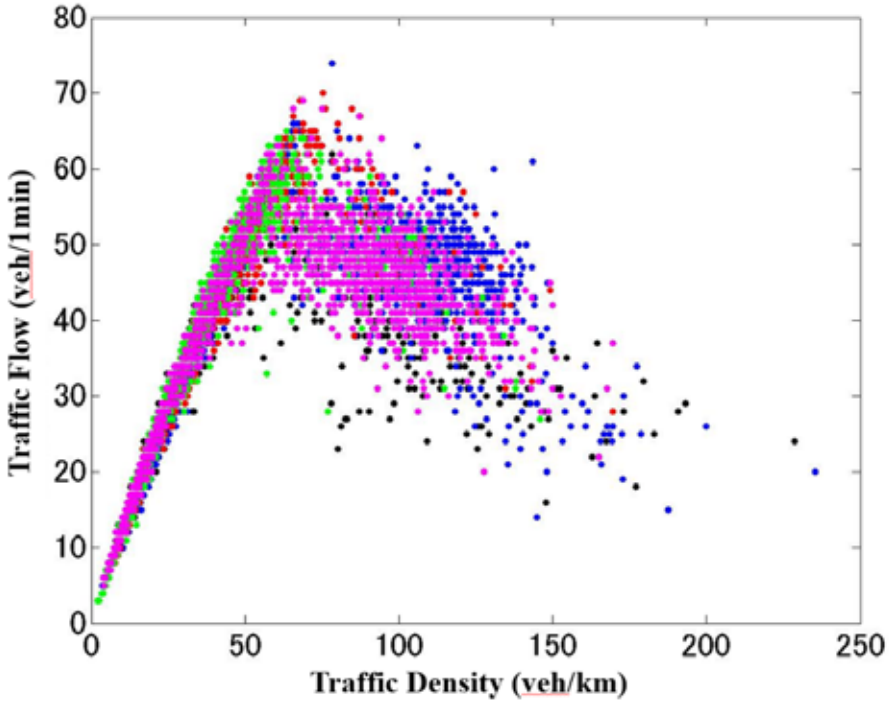


Congestion exists on any JCTs



Why the triangular shaped MFD exists?

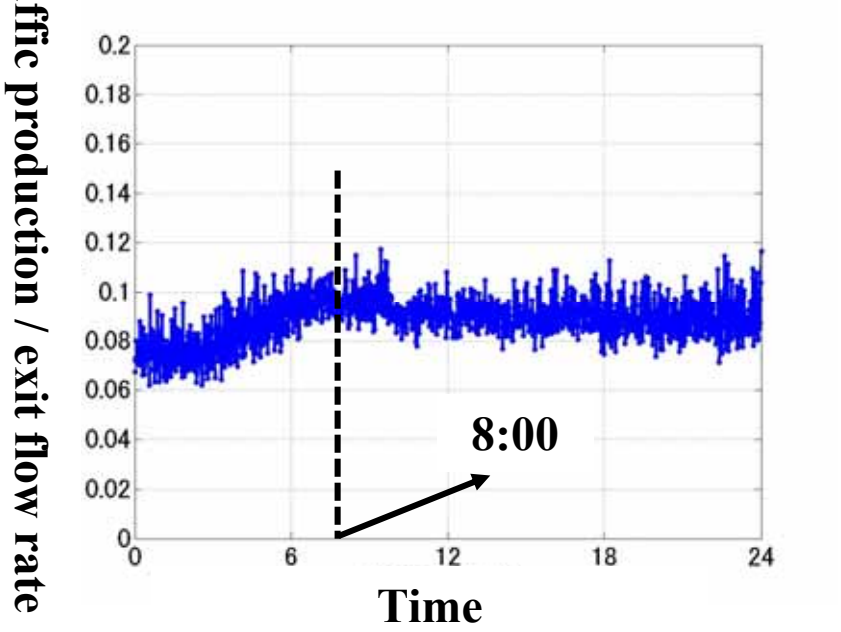
- Two reasons for this phenomenon

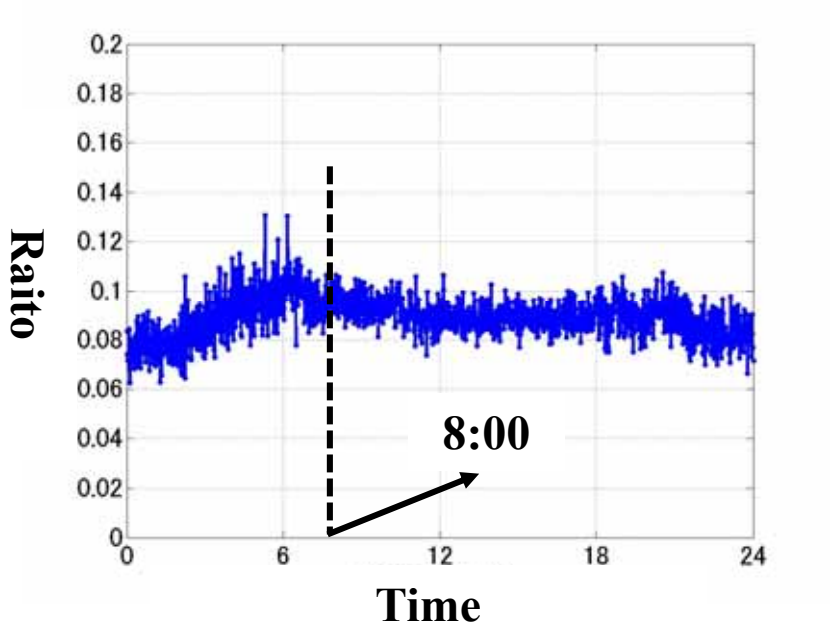


- Fundamental diagram for each road section is triangular
- There is no route choice for users to avoid the congestion

Traffic production / Trip completion (1)

- Using detectors data from some typical days



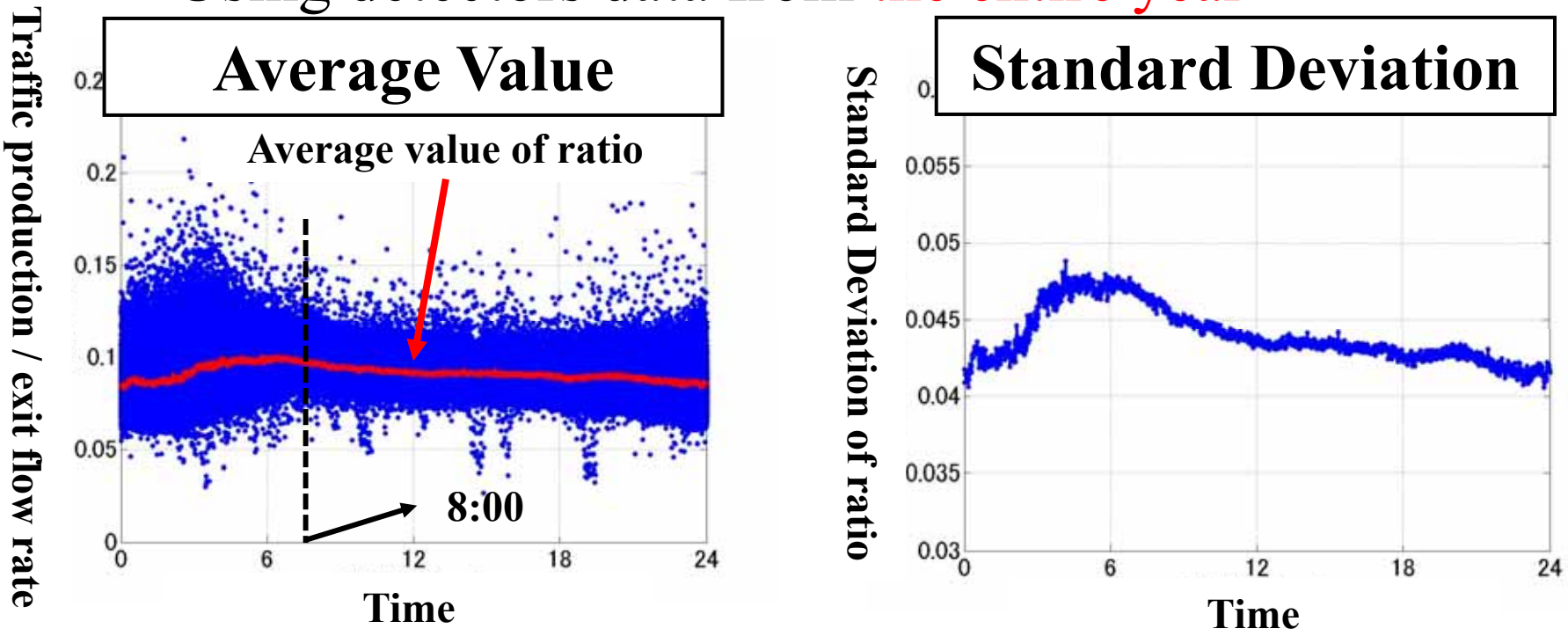


- We define the trip completion for each time period as the exit flow rate (from off-ramps and JCTs) of the networks
- The trip completion can be observed exactly

The ratio may change ***within-day***: it increases during 0:00-8:00 and holds a certain level during the daytime

Traffic production / Trip completion (2)

- Using detectors data from the entire year



- The average value increases during 0:00-8:00, holds a certain level during the day time (the average trip length of all users in nighttime is longer than that in the daytime)
- The standard deviation is high during 3:00-10:00 (value changes ***day-to-day***)

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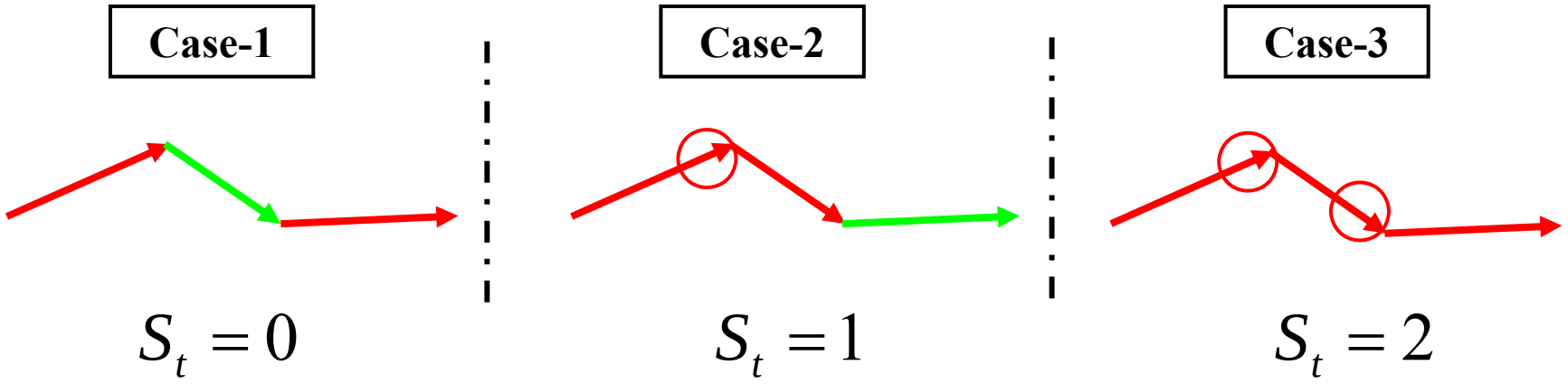
What shall we do in this part?

- Definition of two aggregated indexes
  - Number of queue-spillbacks
  - Number of congested destinations
- Aggregated value vs. MFD features
  - The formation of hysteresis loop
    - Upper curve vs. Lower curve
  - The occurrence of congested regime
    - Uncongested regime vs. Congested regime
- Spatial distribution of congested links
  - Compare the spatial distribution of congested links
    - Anti-clockwise Route vs. Clockwise Route
    - Where the massive queue-spillbacks always occurs?

Definition of aggregated indexes (1)

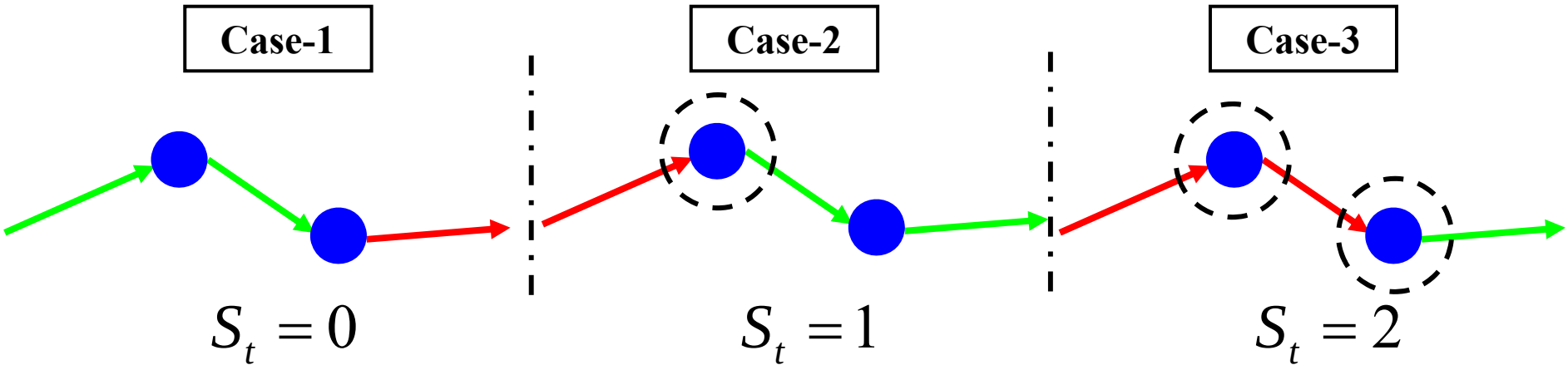
- The number of queue-spillbacks
  - It expresses the spatial connection relationship of congested links on the road networks



→: **Congested link** ($v_t^i \leq 40\ [km/h]$)
→: **Uncongested link**
○: **Queue-spillbacks**

Definition of aggregated indexes (2)

- The number of congested destinations
  - Destination means off-ramps and exit links on JCTs
  - It expresses the networks performance (congested destinations affect the exit flow rate of networks)

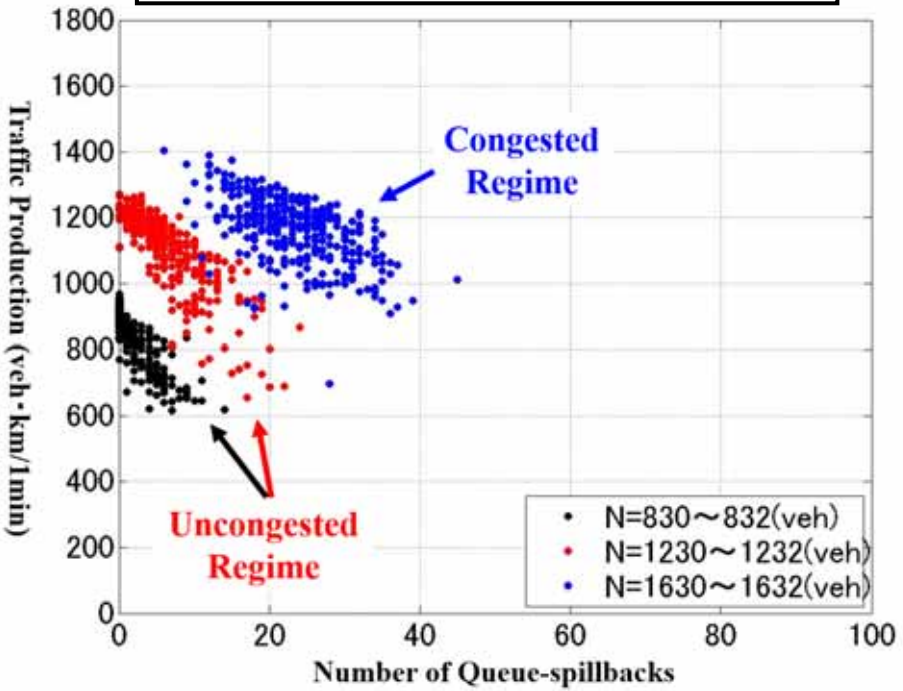


→: Congested link ($v_t^i \leq 40\ [km/h]$)
→: Uncongested link
●: Destinations

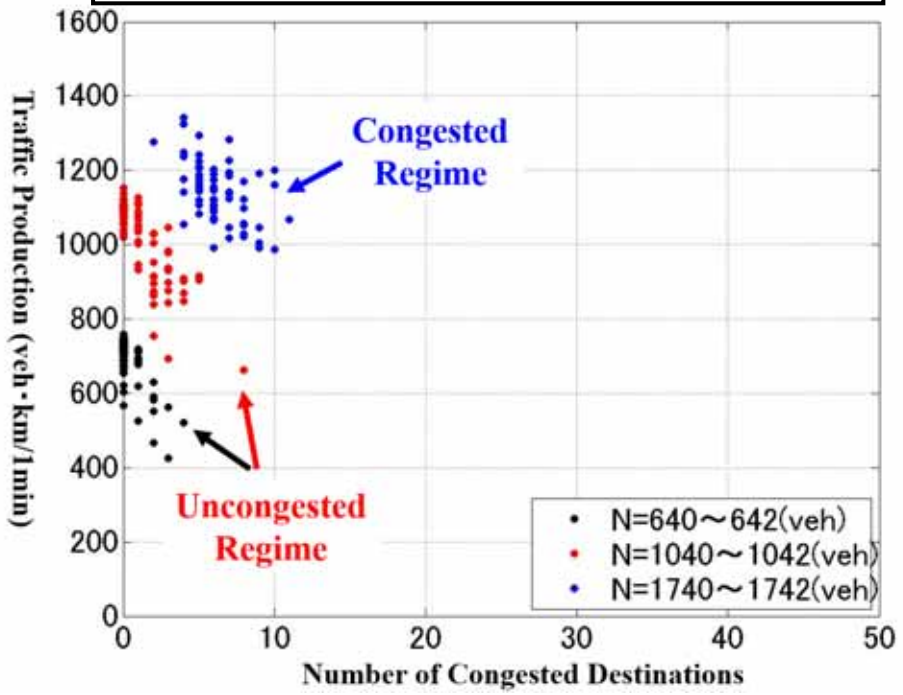
Aggregated index vs. Hysteresis loop

- Detectors data from all sunny weekdays

Queue-spillbacks



Congested Destinations

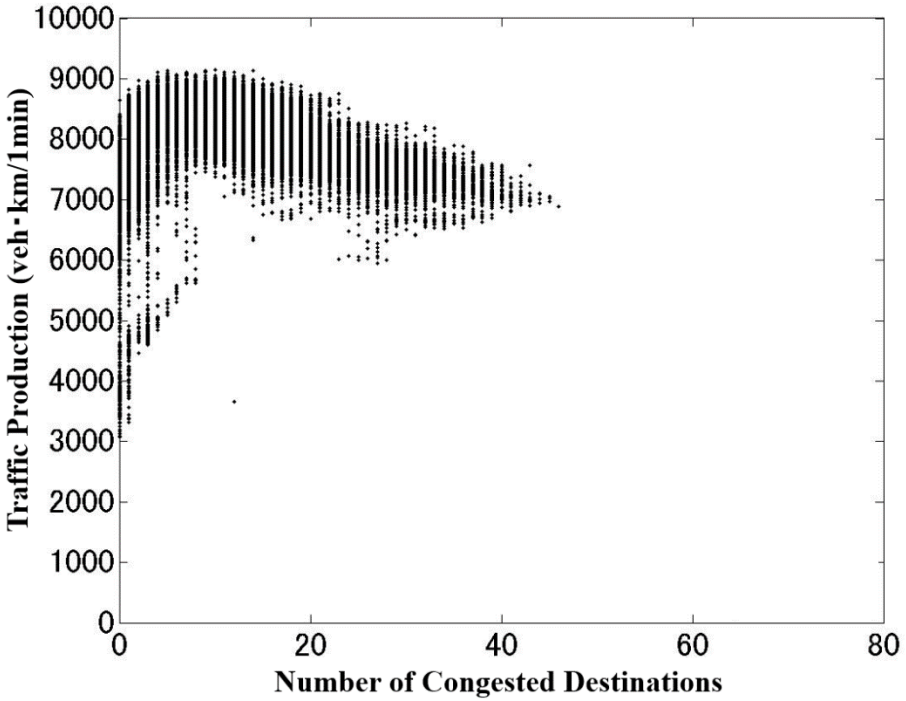


The relationship between the traffic production and the two aggregated indexes under the same accumulation level is ***almost negative linear***

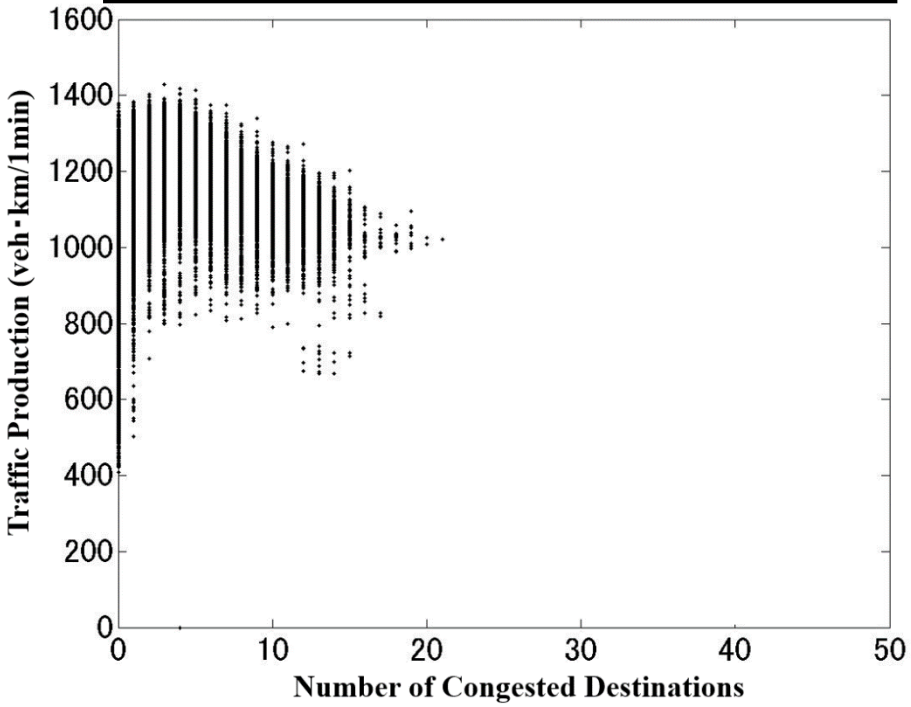
Aggregated index vs. Congested regime

- Detectors data from all sunny weekdays

Queue-spillbacks

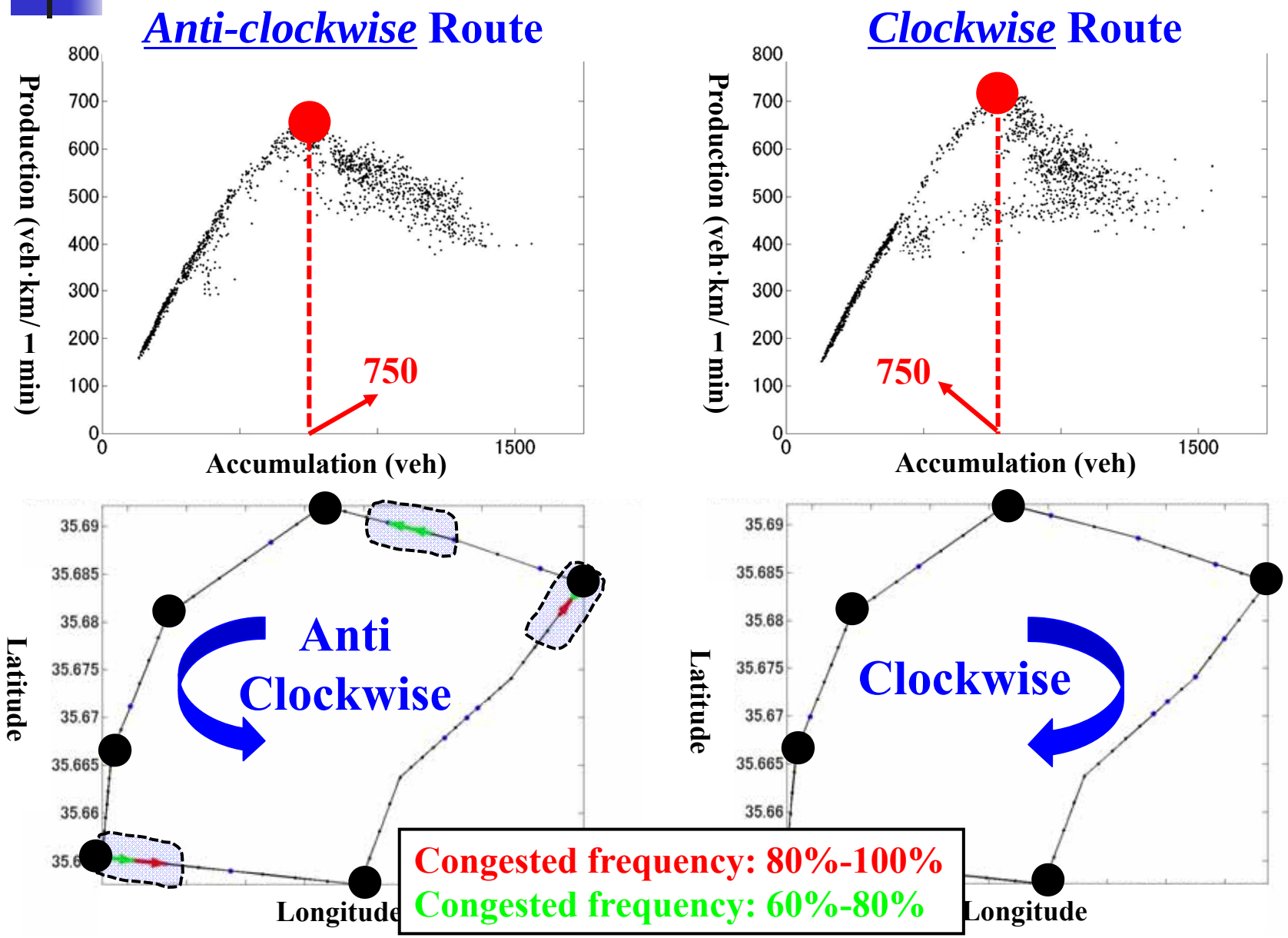


Congested Destinations

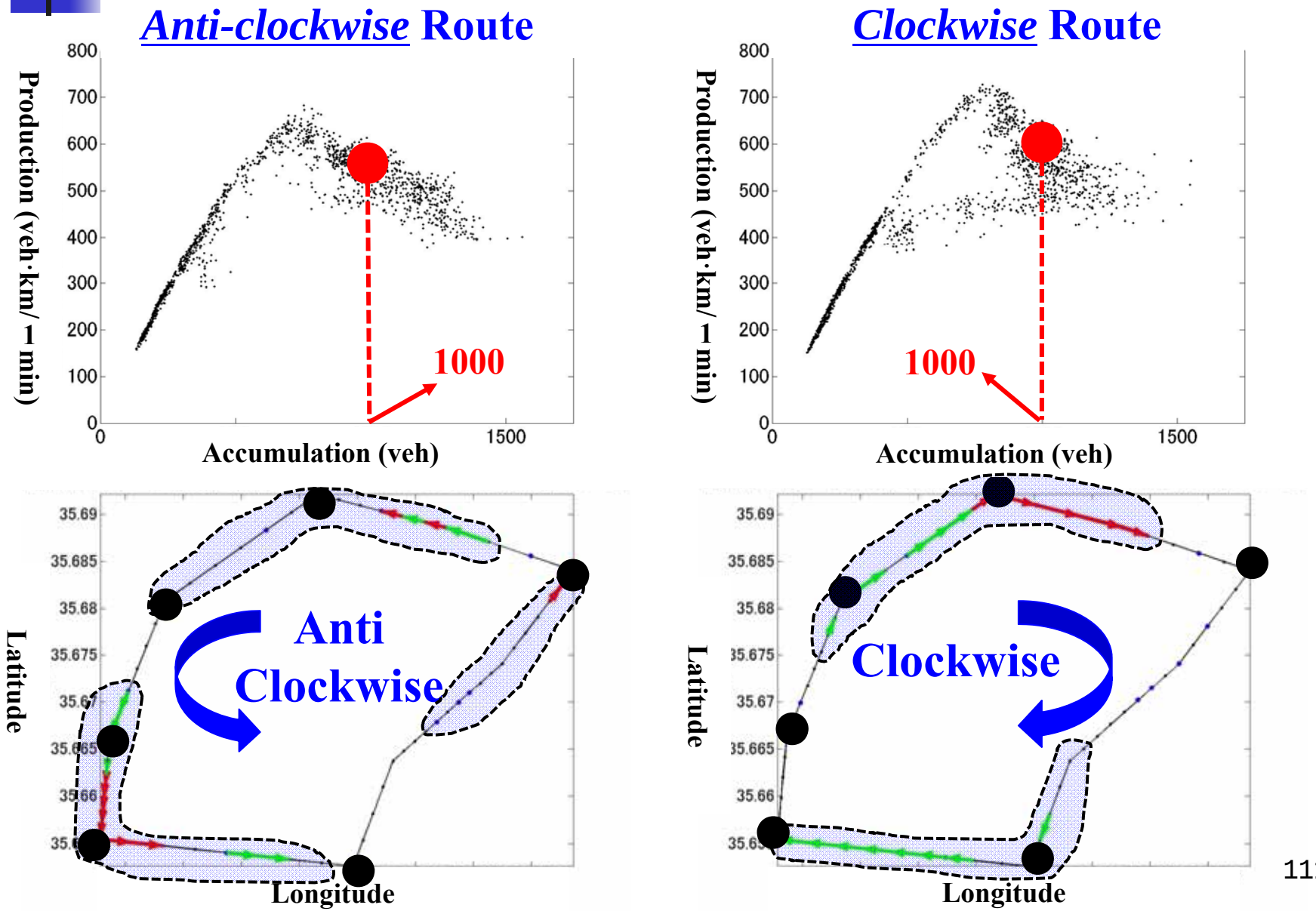


If the number of two aggregated indexes ***exceeds their critical value***, the congested regime occurs with the increase of the two aggregated indexes

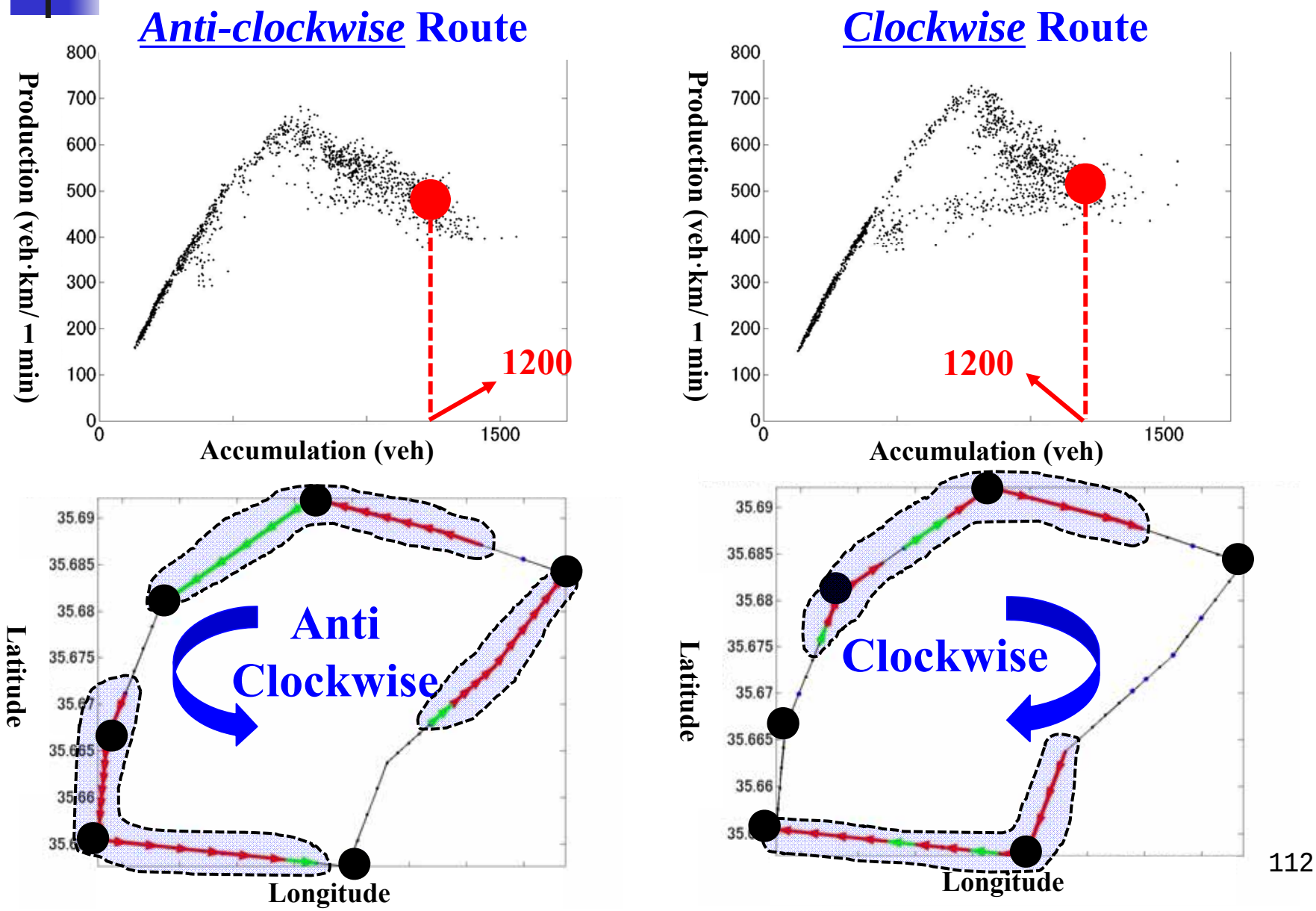
Evolution of congestion pattern (1)



Evolution of congestion pattern (2)

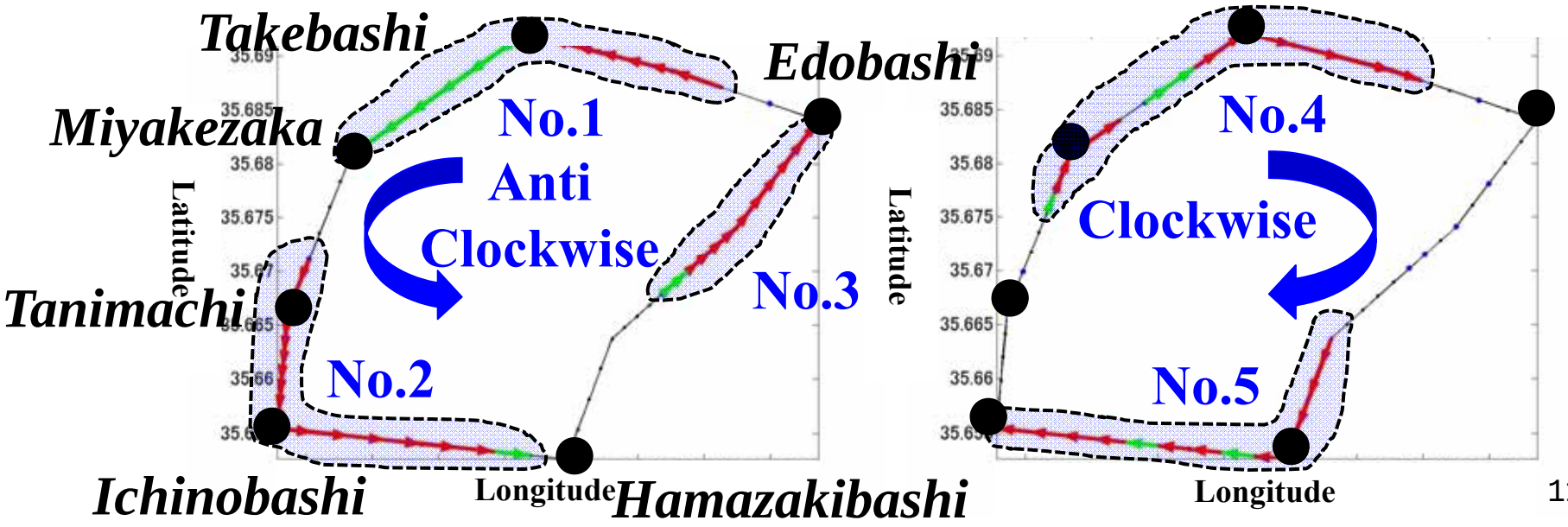


Evolution of congestion pattern (3)



Evolution of congestion pattern (4)

- Congested regime occurs in MFDs if
  - Anti-clockwise: the congestion spreads in cluster Nos.1-3
  - Clockwise: the congestion spreads in cluster Nos.4-5
- Such congestion pattern
  - is corresponding to the occurrence of congested regime
  - decreases the exit flow rate of off-ramps and JCTs



Summary of **Urban Road Networks** (1)

- Robust features of MFD
  - Sendai (Street): Hysteresis loop
  - Kyoto (Street): Hysteresis loop
  - Naha (Street): Congested regime
  - Tokyo (Expressway): Congested regime and hysteresis loop
    - Congested regime: 95.6% of sunny weekdays
    - Hysteresis loop: 66.7% of sunny weekdays

(1) The formation of hysteresis loop is ***a common phenomenon*** for both street and expressway networks, but the occurrence of congested regime in the MFD is ***a rare phenomenon*** for street networks

(2) Especially, the ***well-defined MFD*** without hysteresis loop ***cannot be*** observed unless ***under the special condition*** (e.g., Dedicated bus lane)

Summary of **Urban Road Networks** (2)

- MFD features vs. Congestion pattern
  - Under the same accumulation level, the relationship between the traffic production and the number of queue-spillbacks (or congested destinations) is almost negative linear
  - If the number of queue-spillbacks (or congested destinations) exceeds its critical value, the congested regime occurs gradually with the significant increase of the number of queue-spillbacks (or congested destinations)
  - The high number of queue-spillbacks (or congested regime) is corresponding to the congestion spreading in some specific parts of analysis networks

(1) The stable relationship between the MFD features and spatial congestion pattern exists robustly in ***street and expressway networks***!

(2) We can ***eliminate the queue-spillbacks which affect the destinations*** to prevent the occurrence of congested regime in the MFD

Exploring the Features of Macroscopic Fundamental Diagram and its Formation Mechanism Based on Long-term Detectors Data:

Empirical Studies on Urban Road Networks in Japan

Section 3

Future research directions

Important facts from these studies (1)

- MFD features
  - The not well-defined MFD (e.g., hysteresis loop, high scatters) is a common phenomenon for both urban street and expressway networks
  - The well-defined MFD (without hysteresis loop) with the congested regime actually exists in urban street networks
  - The MFD features for the whole analysis networks are mainly determined by the MFD features for some certain sub-networks
  - Under some certain (demand and supply) conditions, the reproducible and invariant MFD (MFDs have almost the same paths) exists

Important facts from these studies (2)

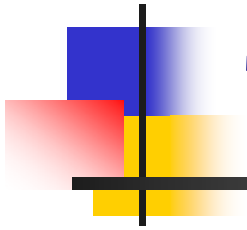
- MFD features vs. spatial congestion pattern
  - The stable relationship exists between the MFD features and the spatial congestion pattern
  - The occurrence of congested regime in the MFD is corresponding to the congestion spreading (increase of the number of queue-spillbacks) in some certain sub-networks which contains some main destinations of users

Future works (1)

- Analysis on the MFD features
  - Increase the number of the empirical studies on MFD features for other new urban street or expressway networks
  - Establish a model to conduct the quantitative analysis on the relationship between the MFD features and the spatial congestion pattern
  - Development of dynamic network partitioning method (e.g., for morning or evening peak hours)
  - Establish a model to fully capture the formation mechanism of MFD features

Future works (2)

- MFD application: boundary control strategy (should consider the following factors)
  - The not well-defined MFD
  - The evolution of congestion pattern on networks
  - The spatial distribution of users' destinations
  - Inner inflow and outflow of public off-street parking facilities
- MFD application: others (evaluation index)
  - Aggregated index to express the area traffic congestion state
  - Establish a measurement system of the traffic policy



Thank you very much for your attention!