Empirical Research on the Occurrence Mechanism of Congested Regime in a Macroscopic Fundamental Diagram

20th Hongkong Society for Transportation Studies
Dec.12th ~ 14th, 2015, Hongkong

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Limitations of current traffic forecasting models
- Require too many inputs (e.g., dynamic OD matrices)
- Driver navigation is an unpredictable gaming activity
- Congested networks behave chaotically

It is difficult to put these forecasting models into practice

Daganzo (2007) [Theoretical study]
- Proposed a macroscopic observation-based model called *Macroscopic Fundamental Diagram (MFD)*
- The MFD relates the number of vehicles (accumulation) in an area to the area’s traffic production
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
Background (3)

Analysis on MFD features (e.g., hysteresis loops)

- Analyzed the relationship between the MFD features and the spatial distribution of link density

It is still difficult to understand the mechanism of the MFD features, especially the occurrence of the congested regime in an MFD

[Geroliminis and Sun (2011b)]
Previous empirical studies on MFD

- Urban road networks
  - Geroliminis and Daganzo (2008): Yokohama
  - Tsubota et al. (2014): Brisbane
  - He et al. (2014): Beijing
  - Saeedmanesh and Geroliminis (2015): Sydney
  - Wang et al. (2015): Sendai

- Expressway networks
  - Buisson and Ladier (2009): Toulouse
  - Geroliminis and Sun (2011a, b): Minnesota
  - Saberi and Mahmassani (2012), (2013): Portland, Chicago
  - Knoop and Hoogendoorn (2013): Amsterdam

It is much less than the number of theoretical and simulation studies
Purpose of this study

Limitations of previous empirical studies on MFD

- Use data for only several days at most, which may be insufficient to investigate the robust features of the MFD
- Do not explore the mechanism of the MFD features (e.g., relationship between MFD features and congestion pattern)

This study

- Use a long-term detector data to analyze the robust features of the MFD for an urban road networks
- Explore the mechanism by investigating the relationship between the MFD features and the congestion pattern
Contents

- Basic information of the detector data
  - Data record
  - MFD definition

- Characterization of MFDs
  - Different demand condition (weekday/weekend)
  - Different supply condition (sunny/rainy)

- Mechanism analysis
  - MFD features v.s congestion pattern
  - Evolution process of congestion pattern
Contents

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Basic information of detector data (1)

- Analysis area
  - CBD road networks in Naha (Okinawa Pref., Japan)
  - Number of detectors: 122

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

Road network structure in analysis area
Basic information of detector data (2)

- **Analysis period**
  - 5/1/2012 ~ 4/30/2013 (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:
  \[ N_t = \sum_{i=1}^{[l]} k^i l^i = \sum_{i=1}^{[l]} \left( q^i_t / v^i_t \right) l^i \]

- Traffic production: \[ P_t = \sum_{i=1}^{[l]} q^i_t l^i \] \( l^i \): length of link \( i \)
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The congested regime occurs in an MFD for Naha CBD road networks on some weekdays and only several Saturdays.
MFDs for different demand condition

- MFDs on sunny weekdays and weekends

The congested regime occurs on **12.0%** of sunny weekdays and **do not** occur on sunny weekends (including Saturdays, Sundays, and holidays)

![Graph of MFDs for different demand conditions]
MFDs for different supply condition

- MFDs on rainy weekday and weekend

The congested regime occurs on 31.1% of rainy weekdays and 4.2% of rainy weekends.
On sunny weekdays

MFDs with congested regime (Example 1)

- 6/26/2012 (Tue)
- 12/6/2012 (Thu)
- 12/25/2012 (Tue)
MFDs with congested regime (Example 2)

- On rainy weekdays

8/8/2012 (Wed) 12/5/2012 (Wed) 2/12/2013 (Tue)

Production (veh·km/5min)

Accumulation (veh)

Accumulation (veh)

Accumulation (veh)

The evening peak hours

Summary

- Congested regime occurs in an MFD is not a rare phenomenon
- The occurrence times are always during the evening peak hours on sunny or rainy weekdays (16:30~19:30)
The MFDs with congested regime which is due to the demand increase or supply decrease can be clearly classified into two groups.
Analysis on the congested regime (2)

Comparison of MFD shapes

The MFDs with congested regime which is due to the demand increase exhibits higher critical accumulation and maximum traffic production.
Contents

- Basic information of the detector data
  - Data record
  - MFD definition

- Characterization of MFDs
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  - Different supply condition (sunny/rainy)

- Mechanism analysis
  - MFD features v.s congestion pattern
  - Evolution process of congestion pattern
Aggregated analysis on congested pattern

- Hypothesis
  - If the number of queue-spillbacks become large to a high value, the congested regime may occur in an MFD

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

<table>
<thead>
<tr>
<th>Case-1</th>
<th>Case-2</th>
<th>Case-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_t = 0$</td>
<td>$S_t = 1$</td>
<td>$S_t = 3$</td>
</tr>
</tbody>
</table>

$\rightarrow$: Congested link ($v_t^i \leq 20[\text{km/h}]$)
$\rightarrow$: Uncongested link
Comparison of queue-spillbacks

- Time series of the number of queue-spillbacks

Congested regime occurs in an MFD when the number of queue-spillbacks become large to a high value during the evening peak hours.
Congestion pattern during the entire year

- **No.1-No.4**: congested frequencies for each link and the spatial distribution of congested links are extremely different between the two kinds of days.

For the Naha CBD road networks, if the congestion spreads in Nos.1-4, the congested regime occurs in an MFD.
MFD v.s Congestion pattern (Example 1)

6/26/2012 (Congested day, sunny)

Congestion pattern

MFD

Congested link
MFD v.s Congestion pattern (Example 1)

6/26/2012 (Congested day, sunny)

Congestion pattern

<table>
<thead>
<tr>
<th>Latitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>26.205</td>
</tr>
<tr>
<td>26.21</td>
</tr>
<tr>
<td>26.215</td>
</tr>
<tr>
<td>26.22</td>
</tr>
<tr>
<td>26.225</td>
</tr>
<tr>
<td>26.23</td>
</tr>
<tr>
<td>26.235</td>
</tr>
<tr>
<td>26.24</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Longitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>127.68</td>
</tr>
<tr>
<td>127.685</td>
</tr>
<tr>
<td>127.69</td>
</tr>
<tr>
<td>127.695</td>
</tr>
<tr>
<td>127.7</td>
</tr>
<tr>
<td>127.705</td>
</tr>
</tbody>
</table>

Production (veh·km/min)

Accumulation (veh)

MFD

Maximum production

17:35
MFD v.s Congestion pattern (Example 1)

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

Congestion pattern

<table>
<thead>
<tr>
<th>Latitude</th>
<th>Longitude</th>
<th>Production (veh·km/5 min)</th>
<th>Accumulation (veh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>26.24</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26.23</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26.22</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26.21</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26.205</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26.205</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

MFD

17:55

Congested regime
MFD v.s Congestion pattern (Example 1)

6/26/2012 (Congested day, sunny)
MFD v.s Congestion pattern (Example 1)

6/26/2012 (Congested day, sunny)

The congested regime occurs gradually as the congestion spreads in cluster Nos.1-4
MFD v.s Congestion pattern (Example 2)

5/8/2012 (Uncongested day, sunny)

**Congestion pattern**

**MFD**

![Congestion pattern and MFD chart](image-url)
MFD v.s Congestion pattern (Example 2)

5/8/2012 (Uncongested day, sunny)

Uncongested regime
MFD v.s Congestion pattern (Example 2)

5/8/2012 (Uncongested day, sunny)

Congestion pattern

Production (veh.km/10 min)

Accumulation (veh)

Latitude

Longitude

MFD

18:20

Maximum production
MFD v.s Congestion pattern (Example 2)

5/8/2012 (Uncongested day, sunny)

Congestion pattern

MFD

Accumulation (veh)

Production (veh·km/5 min)

Latitude

Longitude

Maximum accumulation

18:35
5/8/2012 (Uncongested day, sunny)

We do not observe the congestion spreading in cluster Nos. 1-4 during the entire traffic evolution, even if at the maximum accumulation!
Summary and future plans

Throughout the observation during the entire year,
- Congested regime occurs in an MFD
  - (Sunny & Rainy) weekdays: 20.3%
  - (Rainy) weekends: 4.2%
  - The MFDs with congested regime on sunny weekdays exhibits higher critical accumulation and higher production

- Relationship between MFD and congestion pattern
  - The number of queue-spillbacks is large
  - Congestion spreading in cluster Nos.1-4 of the network

Future plans
- Establish a model to explore the occurrence mechanism of the congested regime in an MFD
Thank you very much for your attention!


Appendix (1)

- The condition of the existence of well-defined MFD
- The statistical distribution of link density is the same for two different time intervals with the same average density

\[ \{sd(t_1) \sim sd(t_2) \text{ and } O(t_1) = O(t_2) \} \implies Q(t_1) = Q(t_2) \]

[Geroliminis and Sun (2011a)]
Appendix (2)

Geroliminis and Skabardonis (2011)

- San Francisco CBD road networks
- Investigated the relationship between the number of vehicles in spillovers and the output using simulation

If the number of vehicles in spillovers become larger than the critical value, the output of an area decrease
Appendix (3)

- MFDs on **rainy weekdays (evening peak hours)**

### 10/17/2012 (Wed)

The **variation of MFD** (the range of traffic production observed for each accumulation) is larger than that on sunny weekdays.
Because of the large rainfall (27mm/h), the congested regime occurs during the morning peak hours.
## Appendix (5)

### Occurrence frequency and time of congested reimage

<table>
<thead>
<tr>
<th></th>
<th>Sunny weekday</th>
<th>Rainy weekday</th>
<th>Sunny weekend</th>
<th>Rainy weekend</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Days</strong></td>
<td>16</td>
<td>32</td>
<td>0</td>
<td>2</td>
<td>50</td>
</tr>
<tr>
<td><strong>Total days</strong></td>
<td>133</td>
<td>103</td>
<td>69</td>
<td>48</td>
<td>353</td>
</tr>
<tr>
<td><strong>Rate</strong></td>
<td>12.0%</td>
<td>31.1%</td>
<td>0%</td>
<td>4.2%</td>
<td>14.2%</td>
</tr>
</tbody>
</table>

Congested regime occurs in an MFD is not a rare phenomenon

<table>
<thead>
<tr>
<th></th>
<th>A.M/Sunny</th>
<th>P.M/Sunny</th>
<th>A.M/Rainy</th>
<th>P.M/Rainy</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Days</strong></td>
<td>0</td>
<td>16</td>
<td>1</td>
<td>31</td>
<td>48</td>
</tr>
<tr>
<td><strong>Total days</strong></td>
<td>133</td>
<td>133</td>
<td>103</td>
<td>103</td>
<td>236</td>
</tr>
<tr>
<td><strong>Rate</strong></td>
<td>0%</td>
<td>12.0%</td>
<td>0.97%</td>
<td>30.1%</td>
<td>20.3%</td>
</tr>
</tbody>
</table>

The occurrence times are always during the evening peak hours (16:30~19:30)
Appendix (6)

- Example of **demand increase**

<table>
<thead>
<tr>
<th>Analysis area</th>
<th>Upstream</th>
<th>Downstream</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow (veh/5 min)</td>
<td>Time (h)</td>
<td>Flow (veh/5 min)</td>
</tr>
<tr>
<td>144</td>
<td>392</td>
<td>393</td>
</tr>
<tr>
<td>142</td>
<td>375</td>
<td>376</td>
</tr>
<tr>
<td>138</td>
<td>389</td>
<td>388</td>
</tr>
</tbody>
</table>

**Flow for each link**

- Inflow is 1.3 times larger than that of uncongested days

[Graph showing flow and time for each link]
Example of supply decrease

Outflow is 50% lower than that of uncongested days

The flow decrease by about a factor of 50%
Appendix (8)

- Analysis on the rainfall during evening peak hours
  - The number of congested days: 47 days
  - The number of rainy days in congested days: 16 days

<table>
<thead>
<tr>
<th>Rainfall [mm/3h]</th>
<th>Date</th>
<th>Rate (*/47)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-10</td>
<td>***** (13)</td>
<td>27.7%</td>
</tr>
<tr>
<td>11-20</td>
<td>2012/10/17 (1)</td>
<td>2.1%</td>
</tr>
<tr>
<td>21-30</td>
<td>2012/12/5 (1)</td>
<td>2.1%</td>
</tr>
<tr>
<td>31-40</td>
<td>2013/2/22 (1)</td>
<td>2.1%</td>
</tr>
</tbody>
</table>

Summary

The rainfall (during the evening peak hours) is not an essential reason for the occurrence of the congested regime in an MFD, but the congested regime occurs more easily when the rain falls
Bus transit lane/link during 17:30-19:00

Summary
Bus transit lane is not an essential reason for the occurrence of the congested regime in an MFD

→: Bus transit lane
→: bus transit link
Appendix (10)

Distribution of the intersections with accidents

Summary
Traffic accidents may be an important reason for the occurrence of the congested regime, but it is not an essential reason.

- worst-1, Tomari
- worst-2, Matsushima
- worst-3, Uenoya
No.1-No.4: congested frequencies for each link and the spatial distribution of congested links are extremely different between the two kinds of days.

For the Naha CBD road networks, if the congestion spreads in Nos.1-4, the congested regime occurs in an MFD.
Appendix (12)

The basic information of Naha road networks (1)
- Famous tourist/largest city in Okinawa prefecture, Japan
- The public transport system is not developed
- Population: 316 thousand
- Links: have 1-3 lanes in each direction
- Average length of links: 350[m]
- Speed limit: 60[km/h]

Summary
The number of visitors is larger than the number of local commuters. Most visitors rent cars to travel, due to the undeveloped public transport.
The spatial distribution of the sight-seeing spots (the destinations of the most users) is dispersed. This is a very important reason for the users do not center in Naha CBD area during the morning peak hours.
The users cannot select a new route to avoid the congested links, especially in Route 58 and Route 330. For this reason, if the congestion occurs in any link, it can spread to the upstream quickly.
Appendix (15)

- Clustering classification method (1)
  - Represent the MFD shape of each day by a 0-1 matrix \( M \)
    \[
    M_{ij} = \begin{cases} 
    1 & \text{if } P_{ij} > 0 \\
    0 & \text{if } P_{ij} = 0 
    \end{cases}
    \]
  - \( P_{ij} \): the number of plots in the mesh
  - Example of meshed MFD

![Graphs showing Accumulation (veh) vs Production (veh·km/5min)]
Appendix (16)

- Clustering classification method (2)
  - The effective mesh number of day $a$, $b$ and the common effective mesh:
    \[
    N_a = \sum_{i=1}^{I} \sum_{j=1}^{J} M_{ij}^{a}
    \]
    \[
    N_b = \sum_{i=1}^{I} \sum_{j=1}^{J} M_{ij}^{b}
    \]
    \[
    N_{a \cap b} = \sum_{i=1}^{I} \sum_{j=1}^{J} M_{ij}^{a}M_{ij}^{b}
    \]
  - Calculate the distance between day $a$ and day $b$
    \[
    D_{ab} = \frac{N_a + N_b - 2N_{a \cap b}}{N_a + N_b - N_{a \cap b}}
    \]