Insights from Macroscopic Models of Urban Transportation Systems

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Approaches to City-Scale Modeling

- **Disaggregate Model**
  - Unavailable Inputs
  - Untestable Theories

- **Aggregate Model**
  - Observable Inputs
  - Testable Theories

At the aggregate level, we can find testable laws of behavior.
Aggregate Models of Traffic & Transit

Traffic Network

Transit Network
Hypothesis

If vehicles (i.e., congestion) are uniformly distributed in space

Then

(a) VKT (i.e., average network flow) and VHT (i.e., average number of vehicles in network, average density or average occupancy) are related by MFD.
(b) Trip completion rate/network flow(or VKT) $\approx$ constant
### Real World Experiment: Yokohama, Japan

#### Taxi ID: 1087    Date: 12/14/2001

**Direction:**

\[ A_1 \rightarrow A_2 \rightarrow A_3 \rightarrow A_4 \rightarrow A_5 \rightarrow A_6 \rightarrow A_7 \rightarrow A_8 \]

<table>
<thead>
<tr>
<th>Time</th>
<th>Position</th>
<th>Trip</th>
</tr>
</thead>
<tbody>
<tr>
<td>17:11.30</td>
<td>A_1</td>
<td>FULL</td>
</tr>
<tr>
<td>17:22.00</td>
<td>A_2</td>
<td>EMPTY</td>
</tr>
<tr>
<td>17:26.00</td>
<td>A_3</td>
<td>FULL</td>
</tr>
<tr>
<td>17:48.00</td>
<td>A_4</td>
<td>EMPTY</td>
</tr>
<tr>
<td>19:00.30</td>
<td>A_5</td>
<td>FULL</td>
</tr>
<tr>
<td>19:34.30</td>
<td>A_6</td>
<td>EMPTY</td>
</tr>
<tr>
<td>19:40.00</td>
<td>A_7</td>
<td>FULL</td>
</tr>
<tr>
<td>19:57.00</td>
<td>A_8</td>
<td></td>
</tr>
</tbody>
</table>

**Area of Analysis**

- FULL
- EMPTY

---

**1km**

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(geroliminis & daganzo, 2008)
Experiment Result: Conjecture (a) MFD

(Geroliminis & Daganzo, 2008)
Experiment Result:
Conjecture (b) Completion Rate Ratio

(Geroliminis & Daganzo, 2008)
Application:
Trips in progress vs. trips leaving

\[ e = G(n) \]

\( e \) = trip completion rate
\( n \) = vehicles in circulation (trips in progress)

(Daganzo, 2007)
1-Bin Model: Aggregate Dynamics

Given: inflow $q_{in}$

Output: $e = G(n)$

\[ \frac{dn(t)}{dt} = q_{in}(t) - G(n(t)) \]
1-Bin Solution: Graphical Interpretation

\[ \frac{dn(t)}{dt} = O(t) - G(n(t)) \]

(Daganzo, 2007)
1-Bin Model: Control Strategy

\[ n^* = G(n) \]

\[ q_{in} \rightarrow n^* \]

\[ e = G(n) \]

(Daganzo, 2007)
Application: Perimeter Control

No Control

With Control

Restrict vehicles from entering

(Geroliminis & Daganzo, 2007)
1-Bin Model: Caveats

• Conditions favoring an even distribution of traffic
  – Uniform demand
  – Homogeneous networks
  – Adaptive drivers
  – Redundant networks
  – Neighborhoods big but not too big

• Are there forces working against an even distribution?
  – Yes: congestion attracts congestion
    But: Driver adaptation mitigates this effect

(Daganzo, 2007, Daganzo et al, 2010)
2-Ring Simulation

- [http://www.ce.berkeley.edu/~daganzo/Simulations/two_ring_sim.html](http://www.ce.berkeley.edu/~daganzo/Simulations/two_ring_sim.html) (Gayah and Daganzo 2010a)
Explanation: 2-Bin Model
MFDs of 2-Bin Model

Non-adaptive drivers

Adaptive drivers
Recent Findings

- Endogenous trip completion rates exacerbate effect and produce hysteresis loops beneath MFD.
- Hysteresis has been observed in reality (Buisson and Ladier, *JTRB* 2124, 127-136, 2009)
- Yokohama’s empirical evidence suggests that adaptation can overcome these problems for moderate congestion.

(Source: Buisson & Ladier, 2009)
URBAN TRAFFIC: Summary

- Macroscopic models possible if vehicles distribute themselves evenly.

- Robust traffic management strategies are then possible.

- Homogeneous demand and driver adaptation even out the vehicular distribution.

- Too much congestion can destroy evenness, reducing flow.

- Control strategies to redistribute traffic favorably should be considered.
Aggregate Models of Transit

Traffic Network

Transit Network
## URBAN TRANSIT: Goal of Design Method

<table>
<thead>
<tr>
<th></th>
<th>When you want it?</th>
<th>Where you want it?</th>
<th>Quick?</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>STATUS QUO</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Individual Transportation (Auto)</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Public Transportation (Metro)</td>
<td>YES</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>Public Transportation (Bus)</td>
<td>NO</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td><strong>VISION</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Public Transportation (Next-gen Bus)</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
</tbody>
</table>
The Spatial Distribution of Buses

4 Buses Uncontrolled

4 Buses Controlled

(Daganzo and Pilachowski, 2010)
1-Bin Design Method

1. Define 2 decision variables for the network shape and the network density (i.e., the vehicular distribution inside the bin)

2. Define 1 decision variable for the headway or equivalently the fleet size (i.e., the number of buses in the bin)

3. Express society’s welfare (combining passenger travel times and the agency costs) in terms of the 3 decision variables; and optimize.

4. Adapt the macroscopic 1-bin solution to the microscopic city details.

(Daganzo, 2010)
Network Shapes

Grid
(Holroyd, 1965)

Radial
(Air Transport 1980’s)

Hybrid
(Daganzo, 2010)
Decision Variable Definitions: Basic Concept

Headway (H)

Stop separation (s) = Line separation

Ratio of central area, $\alpha = \frac{d}{D}$

The hybrid concept can represent varied public transportation structures:

$\alpha = 0$, radial

$\alpha = 1$, grid
Generalized Concept

Additional variable
Line separation (S)

- Ordinary stop (no transfer)
  - Transfer stop

Full

S=s

Semi-alternating

S=s

Alternating

S=2s

(Estrada et al, 2010)
1-Bin Model Formulation: Objective function and decision variables

\[
\min \left\{ Z = \left[ \pi_v V + \pi_M M + \pi_L L \right] + \left[ A + W + T + \left( \delta/v_w \right) e_T \right] : s \geq 0, H \geq 0, 0 \leq \alpha \leq 1, O \leq C \right\}
\]

Agency time cost  \quad User time cost

Agency costs (depend on \( \alpha, s, H \))

\begin{tabular}{|l|l|}
\hline
\( V \) & [veh-km/h] \quad Bus distance traveled per hour \\
\( M \) & [veh-h/h] \quad Fleet size \\
\( L \) & [km] \quad Length of two-way infrastructure \\
\( O \) & [pax/veh] \quad Maximum vehicle occupancy \\
\hline
\end{tabular}

User costs (depend on \( \alpha, s, H \))

\begin{tabular}{|l|l|}
\hline
\( A \) & [h] \quad Mean walking time \\
\( W \) & [h] \quad Mean waiting time \\
\( T \) & [h] \quad Mean riding time \\
\( e_T \) & [-] \quad Mean number of transfers \\
\( \delta / v_w \) & [h] \quad Transfer Time \\
\hline
\end{tabular}
Optimal Design: Large City Results

Typical parameter values for: Bus, BRT and Metro.

<table>
<thead>
<tr>
<th></th>
<th>$C$ (p)</th>
<th>$v$ (km/h)</th>
<th>$L$ ($/km\cdot h$)</th>
<th>$V$ ($/veh\cdot km$)</th>
<th>$M$ ($/veh\cdot h$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus</td>
<td>120</td>
<td>25</td>
<td>9</td>
<td>1</td>
<td>30</td>
</tr>
<tr>
<td>BRT</td>
<td>150</td>
<td>40</td>
<td>90</td>
<td>1</td>
<td>30</td>
</tr>
<tr>
<td>Metro</td>
<td>1000</td>
<td>60</td>
<td>900</td>
<td>3</td>
<td>40</td>
</tr>
</tbody>
</table>

Application to a large city (e.g., London, $l=80,000$ pax/h; $D=20$ km)

<table>
<thead>
<tr>
<th></th>
<th>$\alpha$</th>
<th>$s$ (km)</th>
<th>$H$ (min)</th>
<th>$O$ (pax)</th>
<th>$M$ (veh)</th>
<th>$v_c$ (km/h)</th>
<th>$Z$ (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus</td>
<td>0.92</td>
<td>0.56</td>
<td>3.5</td>
<td>110</td>
<td>2627</td>
<td>17.8</td>
<td>71</td>
</tr>
<tr>
<td>BRT</td>
<td>0.83</td>
<td>0.61</td>
<td>3</td>
<td>150*</td>
<td>1882</td>
<td>25.1</td>
<td>62</td>
</tr>
<tr>
<td>Metro</td>
<td>0.57</td>
<td>1.05</td>
<td>2.5</td>
<td>396</td>
<td>724</td>
<td>35</td>
<td>88</td>
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London Metro
Optimal Design: Medium City Results

Application to a medium city
(e.g., Philadelphia  \( l=20,000 \) pax/h; \( D=10 \) km)

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<th>( H ) (min)</th>
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<td>0.94</td>
<td>0.47</td>
<td>5.0</td>
<td>65</td>
<td>599</td>
<td>16.5</td>
<td>51</td>
</tr>
<tr>
<td>BRT</td>
<td>0.81</td>
<td>0.53</td>
<td>4.0</td>
<td>95</td>
<td>437</td>
<td>23.0</td>
<td>49</td>
</tr>
<tr>
<td>Metro</td>
<td>0.38</td>
<td>0.97</td>
<td>3.0</td>
<td>314</td>
<td>121</td>
<td>33.8</td>
<td>75</td>
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Philadelphia
Stockholm
Tokyo
Optimal Design: Medium City Results

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(e.g., Philadelphia  \(l=20,000\) pax/h; \(D=10\) km)

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South Chicago: Buses and Metro
Numerical Results for Barcelona: a 10x5 km rectangle

<table>
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<tr>
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<th>Current bus system</th>
<th>Semi-alternating (no BRT, ( v = 21 \text{ km/h} ))</th>
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<tbody>
<tr>
<td>Door-to-door travel time (min)</td>
<td>57,9</td>
<td>50,3</td>
</tr>
<tr>
<td>Commercial speed (km/h)</td>
<td>11,9</td>
<td>15,1</td>
</tr>
<tr>
<td>Number of Buses</td>
<td>890</td>
<td>272</td>
</tr>
<tr>
<td>Stop separations (m)</td>
<td>300</td>
<td>650 (430 in the center)</td>
</tr>
<tr>
<td>Network shape ( \alpha = a/A = b/B )</td>
<td>N.A.</td>
<td>0,80</td>
</tr>
<tr>
<td>Headway (min)</td>
<td>13</td>
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(Estrada et al, 2010)
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Model predicts lower user and agency costs!

(Estrada et al, 2010)
Final Design Step: From Macro to Micro

Simulations
• confirm the predicted savings
• match predictions to within 5%

Barcelona (2010-2011)
References


