Pareto-improving policies for an idealized two-zone city served by two congestible modes

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OUTLINE

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3. General properties
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6. Summary
Background

◆ Rapid urbanization (e.g., Beijing)

Expansion in city’s size — Longer travel distance — More serious traffic congestion
Background

Rapid developments of urban subways and railway networks (e.g., Beijing)

First-stage (2012.12.30)

Second-stage (2014.12.28)

These rapid and complex developments in cities raise challenging research questions, especially on the agenda of sustainable urban development.
**Background**

◆ Interplays between urban land use and transportation developments

- Population distribution and migration
- Changes in work place

Land use

Travel choices

Location choices

- Development of transport system
- Traffic management policies

Transportation

Therefore, understanding the interplays between urban economic activities and transportation developments, is important in shaping the city’s development.
**Literature review**—introduction to urban model

**Monocentric city**—only one workplace (Central Business District)

![Diagram](image1)

Fig. 2. Rail line configuration along a linear urban corridor with an integrated rail-property development.

- **Linear city**

- **Circular city**
  - ● represents CBD

- **Two zone city**

![Diagram](image2)

Fig. 1 A simple core-suburb city structure.
Literature review - introduction to urban model

- Single transportation mode + residential location choice
  - No traffic congestion
  - Single transportation mode + residential location choice
    - Considering static traffic congestion
      - Solow (1972), Kanemoto (1980), Anas & Xu (1999), Li et al. (2013)
  - Single transportation mode + residential location choice
    - Considering dynamic traffic congestion
**Literature review** - introduction to urban model

- **Multi transportation modes + residential location choice**

  **No traffic congestion**


- **Multi transportation modes + residential location choice**

  **No dynamic traffic congestion**

  ✓ Haring et al. (1976), Buyukeren & Hiramatsu (2016)

- **Multi transportation modes + residential location choice + dynamic congestion-induced departure time choice**

  ✓ This paper
Motivation

Q1: What are the impacts of transit improvement on the performance of urban system when considering dynamic congestion and mode split effect?

Q2: How land-use and transport policies can be designed to maintain sustainable urban developments?
Model framework

◆ The interactions in a city

- Government’s decision
- Land use regulation
- Urban spatial structure
- Residents’ residential location
- Commuting cost
- Spatial distribution
- Residents’ travel choice equilibrium (mode choice, departure time)

Railway Policies

◆ Equilibria of the urban system

(i) Transportation equilibrium with mode and departure time choices;
(ii) Urban spatial equilibrium with residential location choice.
Assumptions

$n_i$, number of residents in area $i$; $R_i$, Land rent in area $i$; $H_i$, Land supply in area $i$.

- A closed, two-zone, monocentric city;
- The intra-zonal travel costs are ignored;
- Two congestible transportation modes;
- Homogeneous and rational residents;
- Fixed land size at the core, fixed land price at the suburb.
Equilibrium of mode and departure time choices

◆ Highway travel cost (bottleneck model, bottleneck capacity is $w$)

$$C_h(t) = \alpha[T_h + T_w(t)] + \beta[t^* - T_h + T_w(t)]_+ + \gamma[T_h + T_w(t) - t^*]_+ + F_h$$

- Travel time cost
- Schedule delay cost
- Monetary cost

➢ Highway equilibrium cost

$$C_h = \alpha T_h + \frac{\beta \gamma}{\beta + \gamma} \frac{n_{2h}}{w} + F_h$$

◆ Railway travel cost

$$C_r(t) = \alpha T_r + \beta(t^* - T_r - t)_+ + \gamma(t - t^* + T_r)_+ + \psi^2 T_r r_r(t) + (F_r - \phi)$$

- Travel time cost
- Schedule delay cost
- Crowding cost
- Fare

➢ Railway equilibrium cost

$$C_r = \alpha T_r + \sqrt{2\beta \gamma \psi \xi T_r n_{2r} / (\beta + \gamma)} + (F_r - \phi)$$
Equilibrium of mode and departure time choices

◆ Mode-choice equilibrium: all residents who travel from the suburb to the core should have the same and minimal trip cost, regardless of their transport modes.

\[ C_h = C_r \]

To ensure both modes are used, the mode-choice equilibrium requires the following two conditions:

\[ C_h (n_2) > C_r (0) \]
\[ C_h (0) > C_r (n_2) \]

If all suburb residents choose to travel by only one mode, their travel cost would be higher than the cost of unused mode.
General urban spatial equilibrium

◆ Residents’ consumption and location choice behaviors

- Residents earn $Y$ each year and the income will be spent on transportation, housing and other non-housing composite good. The objective of the residents is to maximize their respective utilities within their budget constraint.

$$\max U(z_i, q_i)$$  Utility function

$$s.t. \quad z_i + R_i q_i = Y - TC_i$$  Average annual travel cost

- Average unit annual rental price at area $i$
- Average consumption of housing at area $i$
- Composite goods consumed at area $i$
General urban spatial equilibrium

- Urban spatial equilibrium conditions
  (a) Migration equilibrium
  \[ V(R_1, Y - TC_1) = V(R_2, Y - TC_2) = u \rightarrow \text{Equilibrium utility} \]
  
  (b) Land-market equilibrium
  \[ n_1q_1(R_1,u) = H_1 \quad n_2q_2(R_2,u) = H_2 \]

  (c) Budget constraints
  \[ E(R_1,u) - Y = E(R_2,u) + TC_h - Y = E(R_2,u) + TC_r - Y = 0 \]

  (d) Population conservation
  \[ n_1 + n_2 = N \]

  Where \( E(R_i,u) = z(R_i,u) + R_iq(R_i,u) \) represents the minimum expenditure.
Effects of reducing transit dispatching headway ($\xi$) and increasing transit subsidy ($\phi$)

<table>
<thead>
<tr>
<th></th>
<th>Proposition 1: Reduce $\xi$</th>
<th>Proposition 2: Increase $\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equilibrium utility $u$</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Core</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Population $n_1$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Land rent $R_1$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Suburb</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Highway users $n_{2h}$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Land area $H_2$</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Highway peak-period $D_h$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Railway peak-period $D_r$</td>
<td>-</td>
<td>+</td>
</tr>
</tbody>
</table>

Considering the modal substitution and dynamic congestion, transit improvement methods cause: increase of utility level, decrease of the core population, increase of the suburb area.
Effects of reduce railway dispatching headway ($\xi$) and increasing railway subsidy ($\phi$) on departure rate

When transit demand is endogenously determined, the transit improvement policies have a more significant impact on commuters’ travel behaviour. Therefore, it is necessary to analyze the equilibrium of travel behaviours in an urban spatial equilibrium modeling framework.
Land-use and transit policy instruments

(a) **Land-use tax** \(\{s\} \): a tax charged to suburb land use \( R_2 = R_a + s \)

(b) **Cross land use taxation and rail service enhancement** \(\{s, \xi\} \): simultaneous sets \( s > 0 \) and reduce service headway \( \xi \)

(c) **Cross land use taxation and direct railway fare subsidy** \(\{s, \sigma\} \): a proportion (\( \sigma \)) of land-use tax revenue is used to finance transit subsidy \( \phi \): 
\[
\phi = \sigma n_2 q_2 s / 2 \kappa n_{2r}
\]

(d) **Cross optimal road toll and direct railway fare subsidy** \(\{\tau, \sigma\} \): a proportion (\( \sigma \)) of the toll revenue equally among rail users through a transit subsidy \( \phi \):
\[
\phi = \sigma \delta (n_{2h})^2 / (2wn_{2r})
\]
Effects of land-use and transit policy instruments

Effects of land-use and transport policy instruments

<table>
<thead>
<tr>
<th>Policy Instrument</th>
<th>{s}</th>
<th>{s, \xi}</th>
<th>{s, \sigma}</th>
<th>{\tau, \sigma}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highway user $n_{2h}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Equilibrium utility $u$</td>
<td>-</td>
<td>?</td>
<td>?</td>
<td>+</td>
</tr>
<tr>
<td>Suburb land use $H_2$</td>
<td>-</td>
<td>?</td>
<td>?</td>
<td>+</td>
</tr>
</tbody>
</table>

There is a trade-off between the centralizing effect caused by land-use tax and the decentralizing effect caused by improvements of transit services.
Pareto-improving policy designs

◆ **Definition:** A design scheme is said to be **Pareto-improving** if it holds that

\[ u^p \geq u^e \rightarrow \text{Residents’ utility level improves} \]

and

\[ H_2^p \leq H_2^e \rightarrow \text{Urban land does not sprawl} \]

where \( u^p \) and \( H_2^p \), \( u^e \) and \( H_2^e \) are the utility level and size of suburb land area corresponding to Pareto-improving equilibrium and the base equilibrium case.
Joint land use tax and transit headway instrument

For a given land-use tax, as headway decreases, the equilibrium utility increases, the suburb size increases.

Pareto-improving solutions

<table>
<thead>
<tr>
<th>$s$ ($/acre$)</th>
<th>1000</th>
<th>2000</th>
<th>3000</th>
<th>4000</th>
<th>5000</th>
<th>6000</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\xi$ (min)</td>
<td>3.56</td>
<td>2.60</td>
<td>1.90</td>
<td>1.40</td>
<td>1.03</td>
<td>0.75</td>
</tr>
<tr>
<td>$\eta$ (min)</td>
<td>4.05</td>
<td>3.30</td>
<td>2.70</td>
<td>2.20</td>
<td>1.80</td>
<td>1.39</td>
</tr>
</tbody>
</table>
Joint land use tax and transit subsidy instrument

For a given land-use tax, as the transit subsidy ratio increases, the resident’s equilibrium utility level increases, the suburb size increases.

Pareto-improving solutions

<table>
<thead>
<tr>
<th>$s$ ($/acre$)</th>
<th>1000</th>
<th>2000</th>
<th>3000</th>
<th>4000</th>
<th>5000</th>
<th>6000</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma$</td>
<td>40.0%</td>
<td>43.4%</td>
<td>46.0%</td>
<td>49.2%</td>
<td>51.8%</td>
<td>54.8%</td>
</tr>
<tr>
<td>$\bar{\sigma}$</td>
<td>71.7%</td>
<td>80.9%</td>
<td>89.6%</td>
<td>97.8%</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>
Joint land use tax and transit subsidy instrument

- For a given subsidy ratio, the relationships between tax and equilibrium utility are not straight-forward.
- At higher subsidy ratios the utility level - land tax forms a concave curve.
- Setting land use tax ($s = 7400 \$/acre) and using all tax revenue to subsidy transit makes residents’ utility level maximize.
Conclusions

◆ We introduce dynamical departure-time choices into commuters’ travel behaviour in a monocentric city with two alternative transport modes.

➢ The improvement of transit service has a definitive effect on the city structure: it limits the centralization effect, attracts more residents to relocate in the suburb, thus leads to urban sprawl.

➢ If the government improves development of transit at a high level, they must either accept a high level of urban sprawl or implement strict land use regulation to curb urban sprawl.
Further studies

➢ To shift the model from the two-zone city to a more realistic city structure (e.g. a continuous city model or polycentric city structure).

➢ To extend to a city model considering intra-zonal travel behaviours.

➢ To incorporate the influence of environmental externality (e.g., negative effects incurred by residential density and vehicle emissions) so as to create a sustainable urban city system and correct the distortion.
Thank you for listening!
Welcome your comments!