Impact of Transport Supply and Demand Management Strategies on Land Value

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### Profitability of Operators

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<tbody>
<tr>
<td>Operating margin before tax</td>
<td>6.0%</td>
<td>14%</td>
</tr>
<tr>
<td>Operating return on net fixed asset</td>
<td>0.7%</td>
<td>14%</td>
</tr>
<tr>
<td>Total return (including property profit) on net fixed asset</td>
<td>5.1%</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Objectives

- To analyze public policies, e.g. railway development strategies, cross-subsidization between housing market and transportation infrastructure projects, public housing provision
- To investigate the distribution of costs and returns among different stakeholders.
- To develop an analytical framework for an integrated land use and transport system.
- To study the impact of transport management strategies on residential location choices and the resultant land value.
An integrated land use and transport system...

Yellow box

Residents

Utility maximization

Location choices

Developers

Bid-rent process

Housing price / Land value

Profit maximization

Housing supply

Pink box

Accessibility

Green box

Transport modal choices

Travel time & fare, revenue

Benefit & risk tradeoff

Transport infrastructure provision

Comprehensive land use & transport plans

Stakeholder groups
...modeled by an analytical framework

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<th>To be decided…</th>
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<td>TS-DM strategies: Network expansion and/or Road pricing, etc. ( (y^{(r)}, p^{(r)}) )</td>
<td>Government/Planners (Planning perspective)</td>
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<td>A general equilibrium</td>
<td>Housing provision ( S^{r(\tau)} )</td>
<td>Developers’ decision</td>
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<td>Residential location ( r )</td>
<td>Residents’ location and travel choices</td>
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<td>Workplaces ( s )</td>
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<td>Travel modes ( m )</td>
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<td></td>
<td>Travel routes ( p )</td>
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</tbody>
</table>
A general equilibrium formulation

- Resident location choice problem
  - Bid-rent at different locations
  - Transportation cost/accessibility
  - Housing supply
  - Utility maximization

- Developer housing supply problem
  - Bid-rent at different locations
  - Cost of housing supply
  - Profit maximization
General equilibrium formulation over time

- A quasi dynamic structure
  - Different time adaptabilities of sub-systems
    - Residents’ travel behavior
    - Residents’ location choice
    - Housing investment
    - Transport infrastructure investment
  - Implying that given a time period $\tau$, residents’ location and travel choices are made under a fixed land use and transport system

<table>
<thead>
<tr>
<th>Time 0</th>
<th>Time 1</th>
<th>Time 2</th>
<th>Time T</th>
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<tbody>
<tr>
<td>Government/Other providers</td>
<td>Transport infra. investment</td>
<td>Transport infra. investment</td>
<td>Transport infra. investment</td>
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<tr>
<td>Residents</td>
<td>Location and travel choice</td>
<td>Location and travel choice</td>
<td>Location and travel choice</td>
</tr>
<tr>
<td>Developers</td>
<td>Housing provision</td>
<td>Housing provision</td>
<td>Housing provision</td>
</tr>
</tbody>
</table>
Resident location choice problem

- Bid-rent process for residential location choice
- Household “with multi-members”

**Diagram:**

- **Group decision making → Households**
  - \( Zon_{i}/s_{1} \)
  - ...
  - \( Zon_{r}/s_{s} \)

- **Bid-rent process → Location choice**

- **Individual decision making → Members**
  - **Modal choice →**
    - Auto
    - Metro
  - **Route choice →**
    - \( Path_{1} \)
    - ...
    - \( Path_{p} \)

**OD demand** → **Generalized travel cost (Accessibility)**
Residential location choice

- For each residential location, the rent is derived based on residents’ willingness-to-pay for that location

\[
WP_{k/r(\tau)} = I_k^{(\tau)} - f(U_{k/r(\tau)}^k) + \sum_i \alpha_i^k \cdot X_i^{r(\tau)} + l_{rk(\tau)}^r - \mu_{rk(\tau)} + wp
\]

\[
WP_{k/r(\tau)} = b_k^{(\tau)} + \sum_i \alpha_i^k \cdot X_i^{r(\tau)} + l_{rk(\tau)}^r - \mu_{rk(\tau)}
\]

where,

- \(b_k^{(\tau)}\) — Utility index by setting \(b_k^{(\tau)} = I_k^{(\tau)} - f(U_{k/r(\tau)}^k) + wp\)
- \(I_k^{(\tau)}\) — Household income
- \(X_i^{r(\tau)}\) — Intrinsic housing attributes, e.g. lot size, building age, etc.
- \(l_{rk(\tau)}^r\) — Location externalities influenced by location and travel choices
- \(\mu_{rk(\tau)}\) — Generalized travel cost / Accessibility
Residential location choice

- The two choice processes is mathematically proven to produce identical residential location choices; hence they are consistent.
Residential location choice

According to the bid-rent process, the location \( r \) to be occupied by residents of income group \( k \) is expressed the following probability

\[
Pr^{k/r(\tau)} = \frac{\exp\left(\beta_{r}^{(\tau)} \cdot WP^{k/r(\tau)}\right)}{\sum_{k'} \exp\left(\beta_{r}^{(\tau)} \cdot WP^{k'/r(\tau)}\right)}
\]

From the perspective of landowners:
Different income groups are potential choices for the landowner to rent to
Groups offering higher WP would have a higher probability to be chosen by the landowner

\[
O^{r(\tau)} = S^{r(\tau)} \cdot Pr^{k/r(\tau)}
\]

The resultant housing rent/price in location \( r \) is expressed by the log-sum term, adjusted by the housing supply at that location:

\[
\varphi^{r(\tau)} = \frac{1}{\beta_{r}^{(\tau)}} \ln\left(\sum_{k' \in K} \exp\left(\beta_{r}^{(\tau)} \cdot WP^{k'/r(\tau)}\right)\right) - \frac{1}{\beta_{r}^{(\tau)}} \cdot \ln(S^{r(\tau)})
\]
Residential location choice

From the perspective of residents, they will choose a residence that maximize their utility, expressed as a consumer surplus term defined as:

\[ CS^{rk(\tau)} = WP^{k/r(\tau)} - \phi^{r(\tau)} \]

\[ Pr^{rk(\tau)} = \frac{\exp \left( \beta^{r(\tau)} \cdot CS^{rk(\tau)} \right)}{\sum_{r'} \exp \left( \beta^{r(\tau)} \cdot CS^{r'k(\tau)} \right)} \]

\[ O^{rk(\tau)} = H^{k(\tau)} \cdot Pr^{rk(\tau)} \]

From the perspective of residents:
Different locations are choices for resident to choose from
The location that offers a higher consumer surplus for income group k would have a probability of being chosen by them

(Household’s) consumer surplus
Residential location choice

- **OD demand**
  - In the planning process, with some aggregation assumptions, classifying households into $k$ income groups
  - Assuming there are exogenous job choice models, i.e.
    - the proportions to each work destination $s$ for each income group $k$ are fixed, i.e.
      \[
      \sum_s \Pr^{sk(\tau)} = 1
      \]
    - the average number of workers per household in each income group $k$ are also given, i.e.
      \[
      n^{k(\tau)}
      \]
  - Then the resultant OD demand is obtained by

\[
q^{rsk(\tau)} = O^{rk(\tau)} \cdot \Pr^{sk(\tau)} \cdot n^{k(\tau)}
\]
Travel choice

- Household member’s travel choice

\[
V_{m}^{rsk(\tau)} = \beta_{m}^{k(\tau)} \cdot c_{m}^{rsk(\tau)} + \gamma_{m}^{k(\tau)}
\]

\[
V_{p|m}^{rsk(\tau)} = -c_{p|m}^{rsk(\tau)}
\]

\[
Pr_{p,m}^{rsk(\tau)} = \frac{\exp(\beta_{m}^{(\tau)} \cdot V_{m}^{rsk(\tau)})}{\sum_{m' \in M^{rs}} \exp(\beta_{m}^{(\tau)} \cdot V_{m'}^{rsk(\tau)})} \cdot \frac{\exp(\beta_{p}^{(\tau)} \cdot V_{p|m}^{rsk(\tau)})}{\sum_{p' \in P_m^{ps}} \exp(\beta_{p}^{(\tau)} \cdot V_{p'|m}^{rsk(\tau)})}
\]

- Then the resultant path flow for each transport mode \( m \) is

\[
f_{p,m}^{rsk(\tau)} = q_{p,m}^{rsk(\tau)} \cdot Pr_{p,m}^{rsk(\tau)}
\]
Travel cost

* Link with household’s residential location choice

\[ \mu^{\text{rsk}(n)} = \frac{1}{\beta_m^{(\tau)}} \cdot \ln \sum_{m' \in M^r} \exp(\beta_m^{(\tau)} \cdot V^{\text{rsk}(n)}_{m'}) \quad \text{Individual’s perceived travel cost} \]

\[ \mu^{\text{rk}(\tau)} = f(\mu^{\text{rsk}(n)} \mid n = 1, \ldots, N) \quad \text{Household’s perceived accessibility} \]

(Group decision mechanisms)
Household group decision

- Group decision mechanisms to measure locational accessibility
  - (Zhang and Timmermans, 2004, 2005; Zhang et al., 2009)
  - Combine the travel costs incurred to different members

\[ \mu_{rk} = f(\mu_{rsk}^{(n)} | n = 1, \ldots, N) \]

Alternative specifications:

- Members’ total travel cost
  \[ \mu_{rk} = \mu_{rsk(1)} + \mu_{rsk(2)} + \ldots + \mu_{rsk(N)} \]

- Overall travel cost considering members’ relative influences
  \[ \mu_{rk} = \sum_{n} (w_{k}^{(n)} \cdot \mu_{rsk}^{(n)}) \]

*where* \( w_{k}^{(n)} = \exp \left( \sum_{j} \chi_{j} A_{j}^{k(n)} \right) / \sum_{n} \exp \left( \sum_{j} \chi_{j} A_{j}^{k(n)} \right) \)

- To represent the preference of the member with the lowest travel cost
  \[ \mu_{rk} = \min(\mu_{rsk}^{(n)} | n = 1, \ldots, N) \]
Developers’ decision on housing provision $S^{r(\tau)}$

Under the principle of profit maximization

$$
\Pr^{r(\tau)} = \frac{\exp(\lambda^{(\tau-n_2)} \cdot \pi^{r(\tau-n_2)})}{\sum_{r' \in R} \exp(\lambda^{(\tau-n_2)} \cdot \pi^{r'(\tau-n_2)})}, \quad \forall \tau \geq 0, n_2 \geq 1
$$

$$
\pi^{r(\tau-n_2)} = \phi^{r(\tau-n_2)} - b_H^{r(\tau-n_2)}
$$

Following a quasi dynamic structure

$$
S^{r(\tau)} = \begin{cases} 
S^{r(0)}, & 0 \leq \tau < n_2 \\
S^{(\tau)} \cdot \Pr^{r(\tau)}, & \tau \geq n_2 
\end{cases}
$$
General equilibrium formulation over time

- The problem is formulated as an equivalent Nonlinear Complementarity Problem (NCP)
  - i.e. to find $\mathbf{Z}^* \geq 0$ such that $\mathbf{F}(\mathbf{Z}^*) \geq \mathbf{0}$ and $\mathbf{Z}^T \cdot \mathbf{F}(\mathbf{Z}^*) = 0$
  - where,

$$
\mathbf{Z} = \begin{cases}
  f_{p,m}^{rsk(\tau)}, \forall r, s, m, p, k, \tau \\
  S^{r(\tau)}, \forall r, \tau \geq n_2 \\
  b^k(\tau), \forall k, \tau
\end{cases}
$$

$$
\mathbf{F}(\mathbf{Z}) = \begin{cases}
  f_{p,m}^{rsk(\tau)} - q^{rsk(\tau)} \cdot \mathbf{P}_{p,m}^{rsk(\tau)}, \forall r, s, m, p, k, \tau \\
  S^{r(\tau)} - S^{(\tau)} \cdot \mathbf{P}^{r(\tau)}, \forall r, \tau \geq n_2 \\
  \sum_r S^{r(\tau)} \cdot \mathbf{P}^{k/r(\tau)} - H^k(\tau), \forall k, \tau
\end{cases}
$$
General equilibrium formulation over time

- Nonlinear complementarity conditions

\[
\begin{align*}
& f_{p,m}^{rsk(\tau)} (f_{p,m}^{rsk(\tau)} - q^{rsk(\tau)} \cdot Pr_{p,m}^{rsk(\tau)}) = 0, \quad \forall r, s, m, p, k, \tau \\
& f_{p,m}^{rsk(\tau)} - q^{rsk(\tau)} \cdot Pr_{p,m}^{rsk(\tau)} \geq 0, \quad \forall r, s, m, p, k, \tau \\
& S^r(\tau) (S^r(\tau) - S^{(\tau)} \cdot Pr^r(\tau)) = 0, \quad \forall r, \tau \geq n_2 \\
& S^r(\tau) - S^{(\tau)} \cdot Pr^r(\tau) \geq 0, \quad \forall r, \tau \geq n_2 \\
& b^k(\tau) \left( \sum_r S^r(\tau) \cdot Pr^{k/r}(\tau) - H^k(\tau) \right) = 0, \quad \forall k, \tau \\
& \sum_r S^r(\tau) \cdot Pr^{k/r}(\tau) - H^k(\tau) \geq 0, \quad \forall k, \tau \\
& f_{p,m}^{rsk(\tau)} \geq 0, \quad \forall r, s, m, p, k, \tau \\
& S^r(\tau) \geq 0, \quad \forall r, \tau \geq n_2 \\
& b^k(\tau) \geq 0, \quad \forall k, \tau
\end{align*}
\]
General equilibrium formulation over time

- Solved by reformulating as a smooth and unconstrained optimization problem by minimizing the gap function to zero

\[
\min G(Z) = \sum_{\tau} \sum_{rsmkp} \mathcal{G}\left( f_{p,m}^{rsk(\tau)}, f_{p,m}^{rsk(\tau)} - q_{p,m}^{rsk(\tau)} \cdot Pr_{p,m}^{rsk(\tau)} \right)
+ \sum_{\tau} \sum_{r} \mathcal{G}\left( S^{r(\tau)}, S^{r(\tau)} - S^{(\tau)} \cdot Pr^{r(\tau)} \right)
+ \sum_{\tau} \sum_{k} \mathcal{G}\left( b^{k(\tau)}, \sum_{r} S^{r(\tau)} \cdot Pr^{k/r(\tau)} - H^{k(\tau)} \right)
\]

\[
\mathcal{G}(c, d) = \frac{1}{2} \phi^{2}(c, d)
\]

\[
\phi(c, d) = \sqrt{c^{2} + d^{2}} - (c + d) \quad \text{Fischer function}
\]
Convex equilibrium formulation over time

- The existence and uniqueness of the equilibrium solutions
  - Proved by formulating as two equivalent convex optimization problems:

  - Residential choice problem

  \[
  \min_{b^{k(\tau)}, \phi^{r(\tau)}, x_a^{(\tau)}} Z_1 = \sum_a x_a^{(\tau)} \cdot t_a^{(\tau)} - \sum_a \int_0^{x_a^{(\tau)}} t_a^{(\tau)}(\omega) d\omega - \sum_k H^{k(\tau)} \cdot b^{k(\tau)} \\
  + \sum_r S^{r(\tau)} \cdot \phi^{r(\tau)} + \frac{1}{\beta^{(\tau)}} \sum_{k,r} \exp(\beta^{(\tau)} \cdot (W P^{k/r(\tau)} - \phi^{r(\tau)}))
  \]

  - Housing supply problem

  \[
  \min_{S^{r(\tau)}} Z_2 = \frac{1}{\lambda^{(\tau-n_2)}} \sum_r (S_r^{r(\tau)} \cdot \ln S_r^{r(\tau)} - S_r^{r(\tau)}) - \sum_r S_r^{r(\tau)} \cdot \pi^{r(\tau-n_2)}
  \]

  s.t. \quad S_r^{r(\tau)} = S_r^{r(0)}, \quad \forall 0 \leq \tau < n_2

  \quad S_r^{r(\tau)} \geq 0, \quad \forall \tau \geq n_2
Convex equilibrium formulation over time

- First order conditions with respect to $b^{k(\tau)}$

\[
\frac{\partial Z_1}{\partial b^{k(\tau)}} = b^{k(\tau)} \left[ -H^{k(\tau)} + \sum_{r'} \exp\left(\beta^{(\tau)} \cdot (WP^{k/r'(\tau)} - \varphi^{r'(\tau)})\right) \right] = 0
\]

\[
H^{k(\tau)} = \sum_{r'} \exp\left(\beta^{(\tau)} \cdot (WP^{k/r'(\tau)} - \varphi^{r'(\tau)})\right)
\]

\[
H^{k(\tau)} = \sum_{r'} O^{r'k(\tau)}
\]

\[
Pr^{rk(\tau)} = \frac{O^{rk(\tau)}}{H^{k(\tau)}} = \frac{\exp\left(\beta^{(\tau)} \cdot (WP^{k/r'(\tau)} - \varphi^{r'(\tau)})\right)}{\sum_{r'} \exp\left(\beta^{(\tau)} \cdot (WP^{k/r'(\tau)} - \varphi^{r'(\tau)})\right)}
\]

Equivalent to the residential choice probability
Convex equilibrium formulation over time

- First order conditions with respect to rent:

\[
\frac{\partial Z_1}{\partial \phi^{r(\tau)}} = S^{r(\tau)} - \sum_k \exp\left(\beta^{(\tau)} \cdot (WP^{k/r(\tau)} - \phi^{r(\tau)})\right) = 0
\]

\[S^{r(\tau)} = \sum_k O^{rk(\tau)}\]

\[
Pr^{k/r(\tau)} = \frac{O^{rk(\tau)}}{S^{r(\tau)}} = \frac{\exp\left(\beta^{(\tau)} \cdot (WP^{k/r(\tau)} - \phi^{r(\tau)})\right)}{\sum_{k'} \exp\left(\beta^{(\tau)} \cdot (WP^{k'/r(\tau)} - \phi^{r(\tau)})\right)} = \frac{\exp\left(\beta^{(\tau)} \cdot WP^{k/r(\tau)}\right)}{\sum_{k'} \exp\left(\beta^{(\tau)} \cdot WP^{k'/r(\tau)}\right)}
\]

Equivalent to the bid-rent occupancy probability

- The housing rent can be obtained by making it the subject of the condition

\[
\phi^{r(\tau)} = \frac{1}{\beta^{(\tau)}} \ln \left(\sum_{k'} \exp\left(\beta^{(\tau)} \cdot WP^{k'/r(\tau)}\right)\right) - \frac{1}{\beta^{(\tau)}} \cdot \ln(S^{r(\tau)})
\]

Equivalent to the bid-rent
Convex equilibrium formulation over time

- First order conditions with respect to link flow:

\[
\frac{\partial Z_1}{\partial x_a^{(\tau)}} = \left( x_a^{(\tau)} - \sum_k \sum_r \exp \left( \beta^{(\tau)} \cdot (W \cdot P^{k/r(\tau)} - \phi^{r(\tau)}) \right) \cdot \Pr_{p,m}^{rsk(\tau)} \cdot \delta^{rs(\tau)}_{a,p|m} \right) \cdot \frac{\partial t_a^{(\tau)}}{\partial x_a^{(\tau)}} = 0
\]

\[
\left( x_a^{(\tau)} - \sum_{sk} \sum_r q^{rsk(\tau)} \cdot \Pr_{p,m}^{rsk(\tau)} \cdot \delta^{rs(\tau)}_{a,p|m} \right) \cdot \frac{\partial t_a^{(\tau)}}{\partial x_a^{(\tau)}} = 0
\]

Equivalent to SUE traffic assignment

\[
q^{rsk(\tau)} = O^{rk(\tau)} \cdot \Pr_{sk(\tau)}^{sk(\tau)} \cdot n^{k(\tau)}
\]
Convex equilibrium formulation over time

- First order conditions with respect to housing supply:

\[
\frac{\partial Z_2}{\partial S^{r(\tau)}} = \frac{1}{\lambda^{(\tau-n_2)}} \cdot \ln S^{r(\tau)} - \pi^{r(\tau-n_2)} = 0
\]

\[
S^{r(\tau)} = \begin{cases} 
S^{r(0)}, & \forall 0 \leq \tau < n_2 \\
\exp(\lambda^{(\tau-n_2)} \cdot \pi^{r(\tau-n_2)}), & \forall \tau \geq n_2 
\end{cases}
\]

\[
Pr^{r(\tau)} = \frac{S^{r(\tau)}}{S^{(\tau)}} = \frac{\exp(\lambda^{(\tau-n_2)} \cdot \pi^{r(\tau-n_2)})}{\sum_r \exp(\lambda^{(\tau-n_2)} \cdot \pi^{r(\tau-n_2)})}
\]

Equivalent to the housing supply probability
Convex equilibrium formulation over time

- Solution uniqueness conditions

\[
\frac{\partial^2 Z_1}{\partial b_{k_1(\tau)} \cdot \partial b_{k_2(\tau)}} = \beta^{(\tau)} \cdot \sum_r \exp\left(\beta^{(\tau)} \cdot (WP^{k_1/\tau(r)} - \varphi^{r(\tau)})\right) = \beta^{(\tau)} \cdot H^{k_1(\tau)} > 0
\]

\[
\frac{\partial^2 Z_1}{\partial b_{k_1(\tau)} \cdot \partial b_{k_2(\tau)}} = 0, \forall k_1 \neq k_2
\]

\[
\frac{\partial^2 Z_1}{\partial \varphi^{\eta(\tau)} \cdot \partial \varphi^{\eta(\tau)}} = \beta^{(\tau)} \cdot \sum_k \exp\left(\beta^{(\tau)} \cdot (WP^{k/\eta(\tau)} - \varphi^{\eta(\tau)})\right) = \beta^{(\tau)} \cdot S^{\eta(\tau)} > 0
\]

\[
\frac{\partial^2 Z_1}{\partial \varphi^{\eta(\tau)} \cdot \partial \varphi^{\eta(\tau)}} = 0, \forall r_1 \neq r_2
\]

\[
\frac{\partial^2 Z_2}{\partial S^{\eta(\tau)} \cdot \partial S^{\eta(\tau)}} = \frac{1}{\lambda^{(\tau-n_2)} \cdot S^{\eta(\tau)}} > 0
\]

\[
\frac{\partial^2 Z_2}{\partial S^{\eta(\tau)} \cdot \partial S^{\eta(\tau)}} = 0, \forall r_1 \neq r_2
\]

*The uniqueness condition of equivalent formulation of SUE w.r.t. link flow (Sheffi, 1985)*
General equilibrium formulation over time

- For each time period $\tau$, both residential location choice and housing supply form a general equilibrium.
- Assuming that the total housing demand equals to the total supply:
  \[ S^{(\tau)} = \sum_{k \in K} H^{k(\tau)}, \forall \tau \]
- The decision variables are:
  - Household’s utility index $b^{k(\tau)}$
  - Individual’s travel decision (path flow), which encapsulate automatically the residential location choice and transport modal choices $f^{rsmk(\tau)}_{p}$
  - Housing provision in location $r$ in the next time period $S^{r(\tau)}$
Benefit distribution among stakeholders

- The impact of transport supply and demand management on the benefit of
  - heterogeneous income groups of residents
  - housing supplier
- General conditions
  - Single time period
  - One OD pair
  - Fixed housing supply
Benefit distribution among stakeholders

- **Proposition 1 – supply management**
  - Under conditions
    - \((H_0)\): One OD pair \(r\) and \(s\), households with multiple income groups \(k\)
    - \((H_1)\): One travel route \(p\), travel time reduced by \(\Delta t<0\) with investment cost \(B_T\)
    - \((H_2)\): Homogenous value of time, \(vot^k=vot^>0\)
  - Any travel cost reduction due to transport infrastructure improvement, either in time-based or money-based formulation, will lead to an equivalent increase in land or rental value
  - Consumer surplus (household) ➔
  - Housing supplier surplus ➖
Benefit distribution among stakeholders

• Proposition 2 – supply management
  • Under conditions
    • \((H_0) - (H_1)\)
    • \((H_3)\): Heterogeneous value of time, \(vot^1<vot^2<...<vot^k\)
    • \((H_4)\): Money-based travel cost formulation
  • Residents with higher incomes/higher values of time benefit more from transport improvement as compared with residents with lower incomes/lower values of time
  • Consumer surplus (household) Lowest \(\rightarrow\) \(\rightarrow\) \(\uparrow\) Highest
  • Housing supplier surplus \(\uparrow\)
Benefit distribution among stakeholders

- Proposition 3 – demand management
  - Under conditions
    - $(H_0)$- $(H_1)$
    - $(H_3)$: Heterogeneous value of time, $\text{vot}_1 < \text{vot}_2 < \ldots < \text{vot}_k$
    - $(H_5)$: Time-based travel cost formulation
  - Residents with higher incomes/higher values of time benefit more from demand management, e.g. increasing link toll, as compared with residents with lower incomes/lower values of time
  - Consumer surplus (households’) Lowest $\rightarrow$ Highest
  - Housing supplier’s surplus $\downarrow$
Optimal Transport Supply and Demand Management
System optimization

- Different planning perspectives
  - e.g. Maximize social welfare
- Optimal transport management strategies
  - e.g. Transport Supply and Demand Management, i.e.
  - Highway link expansion $y_a^{(\tau)}$ and link-based congestion pricing $\rho_a^{(\tau)}$
- Under a time-dependent network following a quasi dynamic structure
- With cost recovery conditions

$$NPV = \sum_{\tau} \nu(dr, \tau) \cdot (R_T^{(\tau)} + R_H^{(\tau)}) - \sum_{\tau} \nu(dr, \tau) \cdot (B_T^{(\tau)} + B_H^{(\tau)}) - \sum_{\tau} \nu(dr, \tau) \cdot (M_T^{(\tau)} + M_H^{(\tau)}) \geq 0$$

Producer surplus
System optimization

- Formulated as a mathematical program with equilibrium constraints (MPEC)

\[
\text{Maximize } \quad SW = \sum_{\rho_a^{(r)}, \gamma_a^{(r)}} \nu(dr, \tau) \cdot \sum_{r, s} \sum_k q^{rsk(\tau)} \cdot CS^{rsk(\tau)} + NPV
\]

\[s.t. \quad G(Z) = 0\]

*Constraints defined in the general equilibrium formulation*

\[NPV \geq 0\]

\[y_a^{(r)} \leq \bar{y}_a^{(r)} \leq \underline{y}_a^{(r)}, \forall a, \tau\]

\[\rho_a^{(r)} \leq \bar{\rho}_a^{(r)} \leq \underline{\rho}_a^{(r)}, \forall a, \tau\]
To summarize...

Maximize $SW_{\rho_a^{(\tau)}, y_a^{(\tau)}}$

TS-DM strategies:
Network $\left(v_a^{(\tau)}, \rho_a^{(\tau)}\right)$ and/or Road pricing, etc.

To achieve...
To be decided...
Stakeholders

- Quasi dynamic structure
- Cost recovery constraint

$G(Z) = 0$

A general equilibrium
Equivalent NCP

Developers’ decision

- Stochastic bid-rent process
- Group decision making mechanism
A numerical example
Numerical example

- **Network**
  - Two residential locations 1, 2
  - Two workplaces 5, 6
  - Seven links
- **Demand**
  - Two income groups (high & low)
  - Increasing population for each time interval
  - Workplace choices are exogenously given
- **Three time intervals** $\tau = 0, 1, 2$
- **Three scenarios**
  - Scenario 0: Do-nothing
  - Scenario I: Welfare maximization with TS-DM
  - Scenario II: Welfare maximization with DM alone
Results

- **Housing rents & location choices**
  - Transport strategies influence residents’ location choices. In the long term, the population distribution is more balanced than “do-nothing”
  - Congestion effects (both transport and location externalities) hurt the rent increase, e.g. Zone 2 in Scenario 0
  - TS-DM leads to higher rent increases than DM scheme alone

---

Housing rent over time (Zone 1)

Housing rent over time (Zone 2)
Results

- Transport management strategies increase overall social welfare
- TS-DM is generally better than DM alone
Results

- Housing developer profit increases with TS-DM and decreases with DM alone.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Travel time</th>
<th>Travel cost</th>
<th>Consumers' Surplus</th>
<th>Transport investors' profit*</th>
<th>Housing developers' profit</th>
<th>Producers' surplus</th>
<th>Welfare</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 0</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>0</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
</tr>
<tr>
<td>Scenario I</td>
<td>83.5%</td>
<td>107.1%</td>
<td>97.2%</td>
<td>100%</td>
<td>100.9%</td>
<td>107.8%</td>
<td>104.8%</td>
</tr>
<tr>
<td>Scenario II</td>
<td>97.4%</td>
<td>122.4%</td>
<td>98.4%</td>
<td>89%</td>
<td>96.1%</td>
<td>103.6%</td>
<td>102.2%</td>
</tr>
</tbody>
</table>
Results

- Travel time reduced through both transport strategies
- TS-DM is better than DM alone in congestion relief
- DM alone introduces higher travel costs
- Consumer surplus decreases
Results

- Overall system performance III
  - Congestion pricing brings revenue to transport investor
  - Housing developers may receive extra benefit from optimal TS-DM
  - They may also lose profit due to rent price reduction resulting from increased travel cost
Sensitivity analysis of transport supply

- Conduct the analysis for one period
- Fixed housing supply, workplace choice, and total demand
- Pure transport supply management but varying the levels of transport investment (overall highway capacities)
- Determine the resultant benefits to different stakeholders
Sensitivity analysis of transport supply

- Transport investment and Housing market
  - Developer surplus increases monotonically with transportation supply due to increasing housing rents
  - Consumers may benefit or suffer from transportation supply depending on the tradeoff between travel cost reduction and increased housing rents
  - The possibility of subsidizing transport investment from housing sale depends on the marginal travel cost reduction per unit capacity investment cost and the total housing demand.

![Graph showing the relationship between level of transport improvement and performance](image)
Concluding remarks

- An analytical framework is developed to evaluate the impact of TS-DM strategies on residential location & travel choices, and the resultant housing value in an integrated land use and transport system.
- It also offers a platform to analyze the benefit and cost of different stakeholders.
- A stochastic bid-rent model is incorporated to model household’s residential location choices.
- A quasi-dynamic structure is built to reflect the different time adaptabilities of residents’ behaviors and infrastructure investments.
- The existence and uniqueness of the formulation is established by formulating two equivalent convex mathematical formulations.
- The overall problem is formulated as a MPEC, i.e. time-dependent transport strategies are optimized to achieve planning perspectives, subject to the equilibrium being equality constraints.
Concluding remarks

- Improvements in transportation cost would be transferred to higher willingness-to-pay and hence higher location bid-rents. Developers will always benefit from transportation supply.

- On the other hand, pricing or demand management alone would likely hurt developers, due to reduced willingness-to-pay and hence lower housing rents. But the value of time needs to be carefully calibrated.

- Improvements in the transportation system due to TS-DM strategies may not always benefit consumers, depending on the relative magnitude between the resultant location bid-rent and reduced travel cost.

- A case is made for cross-subsidization between the windfall profit from transportation supply and the cost of this transportation supply (?)
Thank you!