The Co-Evolution of Land Use and Road Networks

Guest Lecture, CE8214

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“**Paul Krugman has formulated a new theory...** Economies of scale combined with reduced transport costs ... help to explain why an increasingly larger share of the world population lives in cities and why similar economic activities are concentrated in the same locations...”

---The Royal Swedish Academy of Sciences
Increasing returns
Transportation cost
Movement of productive factors
(Fujita, Krugman and Venables, 1999)
Transportation and Land Use are Interdependent Shapers of Urban Form
Organization of Talk

- Literature
- SIGNAL - A Simulation Model of Co-evolution
- Conclusions
von Thunen Model

FIGURE 6-4: Hypothetical Rent Gradients and Land-Use Zones
Central Place Theory
• Core and Periphery Model

• Integrated Transportation and Land Use Model
  - Lowry
  - ITLUP
  - MEPLAN
  - URBANSIM
Lowry Model

- Generalized Cost Matrix
- Friction Factor
- Ratio of Population to Workers
activity location

price

supply of land and/or floorspace

spatial interaction

accessibility

disutility

supply of transport

transport demand

land market

transport market

lag in time
• Relocation (Multinomial Logit Model)
• Price (Hedonic Regression)
• External Travel Demand Model
Signal

- Simulator of Integrated Growth of Network and Land use
  - Simulate the co-evolution of land use and road networks.
  - Implement a bottom-up process that incorporates independent route choices of travelers, location decisions of businesses (jobs) and residents (workers), as well as investment decisions of autonomous roads.
  - Kept as simple as possible that captures salient components, while enabling us to display and analyze the emergent patterns of land use and network on a large scale.
**Model Framework**

- **User-defined Land uses**
- **User-defined Network**
- **Travel Demand Models**
- **Road Investment Models**
- **Access and Land use Models**

**Interface**

- **Trip Generation**
- **Trip Distribution**
- **Traffic Assignment**
- **Revenue Model**
- **Cost Model**
- **Investment Model**
- **Accessibility**
- **Employment Location**
- **Population Location**
Travel Demand Models

1. Trip Generation

\[ O_i = \xi_1 E_i + \xi_2 P_i \]
\[ D_i = \psi_1 E_i + \psi_2 P_i \]

where
\( O_i \) = the number of trips that originate in Zone \( i \)
\( D_i \) = the number of trips that are destined to Zone \( i \)
\( E_i \) = the employment (jobs) in a zone.
\( P_i \) = the population (resident workers) in this zone.

2. Trip Distribution

\[ T_{ij} = K_i K_j O_i D_j e^{\varepsilon_{ij}} \]

where
\( T_{ij} \) = number of trips from zone \( i \) to zone \( j \)
\( K_i, K_j \) = balancing coefficients;

\[ t_{ij} = \begin{cases} \sum_a (\delta_{i,j}^a t_a) + t_{m,j} + t_{m,i} & i \neq j \\ t_{m,i} & i = j \end{cases} \]

where
\( t_{m,i} \) represent the generalized intra-zonal travel time.

\[ t_{m,i} = t_m^0 \left[ 1 + \left( \frac{G_i}{G} \right)^2 \right] \]

where
\( t_m^0 \) = specified base intra-zonal travel cost,
\( G_i = E_i + P_i \), the number of activities in zone \( i \)

3. Mode Choice

Single mode is assumed

4. Traffic Assignment

Calibrated Stochastic User Equilibrium (SUE)
Road Investment Models

1. Revenue Model

\[ R_{a+b} = \tau l_a \left( f_a + f_b \right) \]

Where
- \( R_{a+b} \) = Revenue collected from links a and b
- \( \tau \) = the regulated toll rate
- \( l_b = l_a \), link length

2. Cost Model

\[ S_{a+b} = l_a C_a^{\sigma_2} \left( f_a^{\sigma_1} + f_b^{\sigma_1} \right) \]

Where
- \( S_{a+b} \) = Cost spent links a and b
- \( \sigma_1, \sigma_2 \) = specified flow and capacity powers.

3. Investment Model

\[ C_{a}^{k+1} = C_a^k \left( \frac{R_{a+b}^k}{S_{a+b}^k} \right)^\rho \]

Where
- \( C_a = C_b \) is the capacity of link a and b
- \( \rho \) = specified coefficient that affects the speed of convergence
Access and Land Use Models
Assumptions

Residence and employment are the only types of activities, and their totals are kept equal and constant.

Accessibility to population and to employment are the only factors that affect location decisions.

People want to live near jobs, but far from other people to maximize available space and to avoid potential competitors for jobs, while employment wants to be accessible both to other employment and to people (who are their suppliers of labor and customers).
**Accessibility**

\[
A_{i,E} = \sum_{j=1}^{J} E_j e^{-\theta t_{ij}}
\]

\[
A_{i,P} = \sum_{j=1}^{J} P_j e^{-\theta t_{ij}}
\]

where

- \(A_{i,E}\) = accessibility to employment (jobs) from zone \(i\).
- \(A_{i,P}\) = accessibility to population (workers) from zone \(i\).
- \(\theta = \epsilon\) in trip distribution, the impedance factor in travel.
Potential

\[ U_{i,E} = A_{i,E}^{\beta_1} A_{i,P}^{\beta_2} \]
\[ U_{i,P} = A_{i,E}^{\beta_3} A_{i,P}^{\beta_4} \]

- \( U_{i,E} \) = Potential of zone \( i \) to attract employment.
- \( U_{i,P} \) = Potential of zone \( i \) to attract population.
- \( \beta_1, \beta_2, \beta_3 > 0 \), centripetal forces
- \( \beta_4 < 0 \), centrifugal force
Redistribution

\[ E_{i}^{k+1} = \sum_{j} \left\{ E_{j}^{k} \frac{(U_{i,E}^{k})^{\psi}}{\sum_{s}(U_{s,E}^{k})^{\psi}} \right\} \]

\[ P_{i}^{k+1} = \sum_{j} \left\{ P_{j}^{k} \frac{(U_{i,P}^{k})^{\psi}}{\sum_{s}(U_{s,P}^{k})^{\psi}} \right\} \]

i = moving destination zone number at iteration k+1
j = moving origin zone number

\[ \psi = \begin{cases} 
1, & \text{if } j = i \\
0, & \text{if } j \neq i
\end{cases} \]

reluctance to move
Measures

Gini

Equivalent radius \((r)\)

\[
E = \sum_{j=1}^{n} E_j d_j^2
\]

Where

\(E_j\) = employment of zone \(j\)

\(d_j\) = distance of zone \(j\) to the center of a region
**Numerical Example**

A hypothetical metropolitan area where:

Both the population and employment are distributed over a two-dimensional grid, stretching 10 km in both dimensions, divided into a 20X20 grid lattice of land use cells (400 zones).

A total of 400,000 people are living in the city, which is equivalent to an average of 1,000 residents in each zone. Total employment equals 400,000 as well (and each resident holds a job).

Two-way roads connect the centroids of each pair of adjacent zones, thus forming a 20X20 grid of road network as well, comprising 400 nodes and 1520 links.
Experiments and Hypotheses

Experiments

<table>
<thead>
<tr>
<th>No.</th>
<th>Link capacity</th>
<th>Employment</th>
<th>Population</th>
<th>Dynamics</th>
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<tr>
<td>1</td>
<td>Uniform</td>
<td>Uniform</td>
<td>Uniform</td>
<td>Roads: Fixed, Land uses: Evolving</td>
</tr>
<tr>
<td>2</td>
<td>Uniform</td>
<td>Uniform</td>
<td>Uniform</td>
<td>Roads: Evolving, Land uses: Evolving</td>
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<tr>
<td>3</td>
<td>Uniform</td>
<td>Concentrated</td>
<td>Uniform</td>
<td>Roads: Fixed, Land uses: Evolving</td>
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<tr>
<td>4</td>
<td>Uniform</td>
<td>Concentrated</td>
<td>Uniform</td>
<td>Roads: Evolving, Land uses: Evolving</td>
</tr>
</tbody>
</table>

Hypotheses

- Initially flat land uses become more concentrated, and initially concentrated become less so.
- The degree to which land uses are concentrated is reinforced when road networks are allowed to vary rather than remain constant.

\[
0 < \Delta Gini(Ex.1) < \Delta Gini(Ex.2) \\
\Delta r(Ex.2) < \Delta r(Ex.1) < 0 \\
\Delta Gini(Ex.3) < \Delta Gini(Ex.4) < 0 \\
0 < \Delta r(Ex.4) < \Delta r(Ex.2)
\]
Network Evolution without versus with land use dynamics every 10 iterations
Road capacity without land use dynamics

Road capacity with land use dynamics

Round 00

<table>
<thead>
<tr>
<th>Color</th>
<th>Capacity (veh/hr)</th>
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<tbody>
<tr>
<td>Blue</td>
<td>0-1000</td>
</tr>
<tr>
<td>Green</td>
<td>1000-2000</td>
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<tr>
<td>Yellow</td>
<td>2000-3000</td>
</tr>
<tr>
<td>Orange</td>
<td>3000-4000</td>
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<tr>
<td>Red</td>
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Road capacity without land use dynamics

Road capacity with land use dynamics

Round 10
Road capacity without land use dynamics

Road capacity with land use dynamics

Round 20
Road capacity without land use dynamics

Road capacity with land use dynamics

<table>
<thead>
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<th>Color</th>
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<tr>
<td>0-1000</td>
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<tr>
<td>1000-2000</td>
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</tr>
<tr>
<td>2000-3000</td>
<td></td>
</tr>
<tr>
<td>3000-4000</td>
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<tr>
<td>4000+</td>
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</tr>
</tbody>
</table>

Round 30
Road capacity without land use dynamics

Road capacity with land use dynamics

Round 40
Road capacity without land use dynamics

Road capacity with land use dynamics

Round 50
Road capacity without land use dynamics

Road capacity with land use dynamics

Round 60
Road capacity without land use dynamics

Road capacity with land use dynamics

Round 70
Road capacity without land use dynamics

Road capacity with land use dynamics

Round 80
Road capacity without land use dynamics

Road capacity with land use dynamics

Round 90

<table>
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<tr>
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<tr>
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<td>1000 - 2000</td>
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<tr>
<td>Yellow</td>
<td>2000 - 3000</td>
</tr>
<tr>
<td>Orange</td>
<td>3000 - 4000</td>
</tr>
<tr>
<td>Red</td>
<td>4000+</td>
</tr>
</tbody>
</table>
Road capacity without land use dynamics

Road capacity with land use dynamics

Round 100
Results: Gini

1 less equitable

0 more equitable
**Results: Equivalent Radius**

![Graph showing Iteration vs. Radius of employment (km) for different experiments: Expt.1: Uniform/Dynamic land use-Fixed road, Expt.2: Uniform/Dynamic land use-Dynamic road, Expt.3: Concentrate/Dynamic land use-Fixed road, Expt.4: Concentrate/Dynamic land use-Dynamic road.](image-url)
Activity evolution without versus with network dynamics
Employment density without network dynamics

Employment density with network dynamics

Round 00
Employment density without network dynamics

Employment density with network dynamics

Round 02
Employment density without network dynamics

Employment density with network dynamics

Round 04
Employment density without network dynamics

Employment density with network dynamics

Round 06
Employment density without network dynamics

Employment density with network dynamics

Round 08
Employment density without network dynamics

Employment density with network dynamics

Round 10
Employment density without network dynamics

Employment density with network dynamics

Round 12
Employment density without network dynamics

Employment density with network dynamics

Round 14
Employment density without network dynamics

Employment density with network dynamics

Round 16
Employment density
without network dynamics

Employment density
with network dynamics

Round 18
Employment density without network dynamics

Employment density with network dynamics

Round 20
Results: Gini

1 less equitable

0 more equitable
RESULTS: EQUIVALENT RADIUS
This paper developed a simple co-evolution model of transportation and land use which incorporates independent route choices of travelers, location decisions of businesses (jobs) and residents (workers), as well as investment decisions of autonomous roads.
Experimental results show that the degree of both employment and population concentration is reinforced when road networks are allowed to vary rather than remain constant. This corroborates experience with Rail and Underground in London prior to rise of automobile.
Similarly, network hierarchy is reinforced when land use is allowed to vary rather than remain constant.
Contemporary integrated transportation and land use models that neglect road dynamics could underestimate the concentration of land uses.
Empirical Study

- Twin Cities Network
- Estimation & Calibration of Models (Markov Chain, Logistic Regression Model, MCCA)
- 75x75 m² grid (610,000 cells)
- 10 land use categories

(Iacono and Levinson, 2008)
Logistic Regression Models

\[ P(L_t) = f(R_{t-1}, C_{t-1}, I_{t-1}, V_{t-1}, R_{\text{neighbor}, t-1},
C_{\text{neighbor}, t-1}, I_{\text{neighbor}, t-1}, V_{\text{neighbor}, t-1}, Z_{t-1}, Z_{\text{neighbor}, t-1}) \]
<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>S.E.</th>
<th>t</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Residential</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residential&lt;sub&gt;_t−1&lt;/sub&gt;</td>
<td>1.98</td>
<td>0.04</td>
<td>50.49</td>
</tr>
<tr>
<td>Commercial&lt;sub&gt;_t−1&lt;/sub&gt;</td>
<td>2.00</td>
<td>0.13</td>
<td>15.75</td>
</tr>
<tr>
<td>Industrial&lt;sub&gt;_t−1&lt;/sub&gt;</td>
<td>2.55</td>
<td>0.11</td>
<td>24.18</td>
</tr>
<tr>
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<td>0.04</td>
<td>54.05</td>
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<tr>
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<td>1.73</td>
<td>0.01</td>
<td>162.13</td>
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<tr>
<td>Commercial&lt;sub&gt;_neighbor,t−1&lt;/sub&gt;</td>
<td>0.81</td>
<td>0.02</td>
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<tr>
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<tr>
<td>Vacant&lt;sub&gt;_neighbor,t−1&lt;/sub&gt;</td>
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<td>-29.57</td>
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<td>-151.87</td>
</tr>
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<td></td>
<td></td>
</tr>
<tr>
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<td>0.13</td>
<td>19.76</td>
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<tr>
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<td>0.16</td>
<td>13.51</td>
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<tr>
<td>Industrial&lt;sub&gt;_t−1&lt;/sub&gt;</td>
<td>3.07</td>
<td>0.19</td>
<td>16.03</td>
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<tr>
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<td>0.13</td>
<td>20.96</td>
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<tr>
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<td>39.61</td>
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<tr>
<td>Constant</td>
<td>-10.91</td>
<td>0.17</td>
<td>-63.59</td>
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## 1990-2000

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<th>Coefficient</th>
<th>S.E</th>
<th>t</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Residential</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Residential$_{t-1}$</td>
<td>4.64</td>
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<td>Industrial$_{t-1}$</td>
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<td>Vacant$_{t-1}$</td>
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<td>14.95</td>
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<tr>
<td>Industrial$_{neighbor,t-1}$</td>
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<td>0.01</td>
<td>8.64</td>
</tr>
<tr>
<td>Vacant$_{neighbor,t-1}$</td>
<td>0.30</td>
<td>0.00</td>
<td>64.28</td>
</tr>
<tr>
<td>Road$_{t-1}$</td>
<td>-0.98</td>
<td>0.05</td>
<td>-20.61</td>
</tr>
<tr>
<td>Road neighbor$_{neighbor,t-1}$</td>
<td>-0.11</td>
<td>0.01</td>
<td>-11.32</td>
</tr>
<tr>
<td>Accessibility ($10^4$)$_{t-1}$</td>
<td>0.01</td>
<td>0.00</td>
<td>2.80</td>
</tr>
<tr>
<td><strong>Commercial</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residential$_{t-1}$</td>
<td>2.88</td>
<td>0.06</td>
<td>48.04</td>
</tr>
<tr>
<td>Commercial$_{t-1}$</td>
<td>4.55</td>
<td>0.06</td>
<td>74.27</td>
</tr>
<tr>
<td>Industrial$_{t-1}$</td>
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<tr>
<td>Vacant</td>
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<td>0.06</td>
<td>43.63</td>
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<td>23.33</td>
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<td>24.70</td>
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<td>Road$_{neighbor,t-1}$</td>
<td>0.22</td>
<td>0.01</td>
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## Prediction

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<tr>
<th>Prediction Year</th>
<th>Percent Correct</th>
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<tbody>
<tr>
<td>1968</td>
<td>95.4%</td>
</tr>
<tr>
<td>1978</td>
<td>80.8%</td>
</tr>
<tr>
<td>1990</td>
<td>78.8%</td>
</tr>
<tr>
<td>2000</td>
<td>83.3%</td>
</tr>
</tbody>
</table>
MCCA

\[ P = \begin{bmatrix}
    p_{11} & \ldots & p_{1n} \\
    \vdots & \ddots & \vdots \\
    p_{n1} & \ldots & p_{nn}
\end{bmatrix} \]

\[ P_{ij} = f(L_{t-1}, N1_{t-1}, N2_{t-1}) \]
### 1990-2000 MCCA

<table>
<thead>
<tr>
<th>Land Use</th>
<th>Predicted 2000</th>
<th>Actual 2000</th>
<th>Difference</th>
<th>Percent</th>
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<td>4,616</td>
<td>5,400</td>
<td>117.0%</td>
</tr>
<tr>
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<td>18,779</td>
<td>4,352</td>
<td>23.2%</td>
</tr>
<tr>
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<td>14,849</td>
<td>16,275</td>
<td>109.6%</td>
</tr>
<tr>
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<td>24,102</td>
<td>23,777</td>
<td>325</td>
<td>1.4%</td>
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<tr>
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<td>123,222</td>
<td>68,565</td>
<td>54,657</td>
<td>79.7%</td>
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<tr>
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<td>6,923</td>
<td>37.8%</td>
</tr>
<tr>
<td>Railway</td>
<td>2,636</td>
<td>1,523</td>
<td>1,113</td>
<td>73.1%</td>
</tr>
<tr>
<td>Residential</td>
<td>177,809</td>
<td>186,347</td>
<td>-8,538</td>
<td>-4.6%</td>
</tr>
<tr>
<td>Vacant</td>
<td>136,899</td>
<td>217,387</td>
<td>-80,488</td>
<td>-37.0%</td>
</tr>
<tr>
<td>Water</td>
<td>52,752</td>
<td>52,771</td>
<td>-19</td>
<td>0.0%</td>
</tr>
</tbody>
</table>
Conclusion

Evidences from both the simulation study and the empirical study reveal network growth reinforces the concentration of land use.
Land use also enhances hierarchical structure of network, forming a positive feedback loop.
This self-reinforcement process could reach a saturation stage.
Thank You

- More available at: http://nexus.umn.edu
- Email: dlevinson@umn.edu
- zhuxx120@umn.edu
## Sensitivity

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Citation</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\xi_1, \xi_2$</td>
<td>Coefficients in trip generation and attraction</td>
<td>Eq.(1)</td>
<td>0.5, 1.0, 1.0, 0.5</td>
<td>Specified</td>
</tr>
<tr>
<td>$\psi_1, \psi_2$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$t_m^0$</td>
<td>Base intra-zonal travel time</td>
<td>Eq.(5)</td>
<td>10 min</td>
<td>Empirical estimate</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Value of time</td>
<td>Eq.(7)</td>
<td>$10/\text{h}$</td>
<td>Empirical estimate</td>
</tr>
<tr>
<td>$\tau$</td>
<td>Toll rate</td>
<td>Eq.(8)</td>
<td>$1/\text{veh.km}$</td>
<td>Empirical estimate</td>
</tr>
<tr>
<td>$\sigma_1, \sigma_2$</td>
<td>Coefficients in cost model</td>
<td>Eq.(9)</td>
<td>0, 1.0</td>
<td>Specified</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Capacity reduction factor</td>
<td>Eq.(10)</td>
<td>0.1</td>
<td>Specified*</td>
</tr>
<tr>
<td>$\omega_1, \omega_2$</td>
<td>Coefficients in the capacity-freeflow speed loglinear function</td>
<td>Eq.(11)</td>
<td>-30.6, 9.8</td>
<td>Empirical calibration</td>
</tr>
<tr>
<td>$\alpha, \beta$</td>
<td>Coefficients in BPR function</td>
<td>Eq.(12)</td>
<td>0.15, 4.0</td>
<td>Empirical calibration</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Trip distribution coefficient; Reduction factor in accessibility model</td>
<td>Eq.(3), Eq.(13), Eq.(14)</td>
<td>0.048/\text{min}</td>
<td>Empirical calibration*</td>
</tr>
<tr>
<td>$\lambda_1, \lambda_2, \lambda_3, \lambda_4$</td>
<td>Coefficients in zonal desirability model</td>
<td>Eq.(15), Eq.(16)</td>
<td>1.0, 1.0, 0.9, -0.9</td>
<td>Specified*</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Reluctance to move</td>
<td>Eq.(17), Eq.(18)</td>
<td>0.80</td>
<td>Specified*</td>
</tr>
</tbody>
</table>
Sensitivity

(i) Sensitivity Analysis of rho: Gini

(ii) Sensitivity Analysis of theta: Gini

(iii) Sensitivity Analysis of lambda 3: Gini

(iv) Sensitivity Analysis of mu: Gini
Land Use Evolution With and Without Road Dynamics
**Movie**

- Underground + Surface Rail in London
The Sequence of Development?

This extension of the railway system by means of feeder lines means that in many ways the early development of the system can be viewed, not in terms of booms and slumps, but in rational steps. By the end of 1833, three of the five English provincial towns with a population of more than 100,000 had railway links with London under construction; by the end of 1836 only Portsmouth remained among English towns of over 50,000 population without a line authorized; and by the end of 1837 most towns of more than 20,000 inhabitants were on or close to the route of an authorized railway. - M.C. Reed
Orderliness Hypothesis:

Places will be connected to the network roughly in order of their population density.
The places that have the highest population per unit area (or population density) will get the network first.
Background

1836 London and Greenwich Railway
1846 Royal Commission on Railway Termini
1854 Metropolitan Railway chartered
1863 Metropolitan Railway opens
1884 “Circle” closed
1890 City and South London Railway (first tube)

Railways not permitted to be developers except Metropolitan Railway --> Metro-Land
Greenbelt
Correlation between Rail Station Density Rank and Population Density Rank
(excluding City of London)  (including City of London)
Correlation Between Underground Station Density Rank & Population Density Rank (excluding City of London) vs (including City of London)
<table>
<thead>
<tr>
<th>Year</th>
<th>Boroughs with Stations (N)</th>
<th>Notable Boroughs (in top N of density) without service at time which eventually get service.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1871</td>
<td>8</td>
<td>Tower Hamlets (2), Southwark (7), Hackney (8)</td>
</tr>
<tr>
<td>1881</td>
<td>14</td>
<td>Tower Hamlets (1), Southwark (6), Hackney (7), Lambeth (9), Lewisham (13), Wandsworth (11)</td>
</tr>
<tr>
<td>1891</td>
<td>23</td>
<td>Hackney (6), Greenwich (15), Waltham Forest (16)</td>
</tr>
<tr>
<td>1901</td>
<td>23</td>
<td>Hackney (6), Greenwich (16), Waltham Forest (15) missing</td>
</tr>
<tr>
<td>1911</td>
<td>23</td>
<td>Hackney (5), Waltham Forest (15), Greenwich (16), Redbridge (22)</td>
</tr>
<tr>
<td>1921</td>
<td>23</td>
<td>Hackney (4), Waltham Forest (15), Greenwich (17), Redbridge (20)</td>
</tr>
<tr>
<td>1931</td>
<td>23</td>
<td>Hackney (4), Waltham Forest (15), Greenwich (17), Redbridge (20)</td>
</tr>
<tr>
<td>1941</td>
<td>25</td>
<td>Greenwich (16), Redbridge (20), Waltham Forest (14)</td>
</tr>
<tr>
<td>1951</td>
<td>27</td>
<td>Greenwich (19)</td>
</tr>
<tr>
<td>1961</td>
<td>27</td>
<td>Greenwich (18)</td>
</tr>
<tr>
<td>1971</td>
<td>27</td>
<td>Greenwich (18)</td>
</tr>
<tr>
<td>1981</td>
<td>27</td>
<td>Greenwich (17)</td>
</tr>
<tr>
<td>1991</td>
<td>27</td>
<td>Greenwich (18)</td>
</tr>
<tr>
<td>2001</td>
<td>28</td>
<td>Greenwich (18)</td>
</tr>
</tbody>
</table>
## Leads and Lags

<table>
<thead>
<tr>
<th></th>
<th>Transport Leads Land Use</th>
<th>Transport Follows Land Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Developed Area</td>
<td>(B) Development densifies in urban area after construction of new transport infrastructure</td>
<td>(A) Constructing new (higher speed) mode in existing urbanized area (e.g. London Transport in early years)</td>
</tr>
<tr>
<td>Undeveloped Area</td>
<td>(C) Constructing new (higher speed) mode in greenfields, to promote development</td>
<td>Still waiting …</td>
</tr>
</tbody>
</table>
Qualitative Model

Rail first inter-city: connects outside -> in
Underground first connects termini, then other points in developed area, and finally connects to new suburbs: inside -> out
Has a decentralizing effect for residences, lowering population density in center, increasing it in suburbs.

Other factors; entrepreneurs, construction costs, South vs. North (income, rail embeddedness, geology, competition, south already more local than north (London in south of England)
London Analysis

Measured more rigorously (*Density and Dispersion: The Co-Development of Land Use and Rail in London*) shows that land development is a positive and statistically significant predictor of future network construction and network construction is a positive and statistically significant predictor of future land development.
SIGNAL: Simulator of Integrated Growth of Network and Land Use

Simulate the co-evolution of land use and road networks. Implement a bottom-up process that incorporates independent route choices of travelers, location decisions of businesses (jobs) and residents (workers), as well as investment decisions of autonomous roads.

Kept as simple as possible to capture salient components, while enabling us to display and analyze the emergent patterns of land use and network on a large scale.