The Evolution of Transportation Networks

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David Levinson
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Questions

• Why do networks expand and contract?
• Do networks self-organize into hierarchies?
• Are roads an emergent property?
• Can investment rules predict location of network expansions and contractions?
• How can this improved knowledge help in planning transportation networks?
If They Come, Will You Build It?
Flowchart of the simulation model

Scope
- Exogenous:
  - economic growth
  - land use dynamics
- Endogenous:
  - travel behavior/demand
  - link maintenance and expansion costs
  - network revenue (pricing)
  - investment
  - induced supply
  - induced demand

TIME

- Exogenous land use, demographic, economic changes
- Year t-1
- Network t
- Trip Generation
  - Zone production and attraction totals
- Trip Distribution
  - OD demand; k = 0
- UE Traffic Assignment
  - Link flow k
  - k = k + 1
  - Link toll k
  - Yes
  - Flow, toll, travel time, OD cost
  - No
  - flow k = flow k–1 ?
  - Yes
  - Flow, toll, travel time, OD cost
- Revenue Model
  - Revenue
- Cost Model
  - Maintenance cost
  - Construction cost
  - New capacity and free-flow speed
- Investment Model
  - Flow, toll, travel time, OD cost
- OD cost table t
- OD cost table t + 1
Network

- Grid network
  - Finite Planar Grid
  - Cylindrical network
  - Torus network
- Modified (Interrupted) Grid
- Realistic Networks (Twin Cities)
- Initial speed distribution
  - Every link with same initial speed
  - Uniformly distributed speeds
  - Actual network speeds

Ideal Chinese Plan
Land Use & Demography

- Small land blocks
- Population, business activity, and geographical features are attributes
- Uniformly and bell-shaped distributed land use are modeled
- Actual Twin Cities land use is also tested
- Land use is assumed exogenous (future research aimed at testing endogenous land use)
Trip Generation

- Using land use model trips produced and attracted are calculated for each cell.
- Cells are assigned to network nodes using voronoi diagram.
- Trips produced and attracted are calculated for a network node using voronoi diagram.

Figure 3: An example representation of voronoi diagram.
Calculates trips between network nodes

- Gravity model
- Working on agent-based trip distribution

\[ T_{rs} \propto \frac{p_r q_s}{e^{w d_{rs}}} \]

Where:

- \( T_{rs} \) is trips from origin node \( r \) to destination node \( s \)
- \( p_r \) is trips produced from node \( r \)
- \( q_s \) is trips attracted to node \( s \)
- \( d_{rs} \) is cost of travel between nodes \( r \) and \( s \) along shortest path
- \( w \) is “friction factor”
Route Choice

- Wardrop’s User Equilibrium Principle, travelers choose path with least generalized cost of traveling (s.t. all other travelers also choosing the least cost path)
- Cases
  - No Congestion
    - Dijkstra’s Algorithm
  - With Congestion
    - Origin Based Assignment (Boyce & Bar-Gera)
    - Stochastic User Equilibrium (Dial)
    - Agent-based Assignment (Zhang and Levinson, Zhu and Levinson)

Flow on a link is

\[ f_a = \sum_{rs} T_{rs} \cdot \delta_{a,rs} \]

Where

\[ \delta_{ars} = \begin{cases} 1 & \text{if } a \in K_{rs} \\ 0 & \text{otherwise} \end{cases} \]

\( K_{rs} \) is a set of links along the shortest path from node \( r \) to node \( s \).
Link Performance Function

- Generalized link travel cost function

\[ t_a = \lambda \cdot \frac{l_a}{v_a} \left[ 1 + \theta_1 \left( \frac{f_a}{F_a} \right)^{\theta_2} \right] + \tau_a \]

- \( l_a \) is length of link
- \( v_a \) is speed of link \( a \)
- \( \lambda \) is value of time
- \( \tau_a \) is "toll"
- \( \theta_1, \theta_2 \) are coefficients

In No Congestion Case, \( \theta_1 = 0 \)
Revenue And Cost Models

- Toll is the only source of revenue
- Annual revenue generated by a link is total toll paid by the travelers
  \[ \tau_a = \rho_0 l_a^{\rho_1} v_a^{\rho_2} \]
  \[ R_a = \tau_a (365 \cdot f_a) \]
- Initially assume only one type of cost, function of length, flow, link speed
  \[ C_a = \mu \cdot l_a^{\alpha_1} \cdot f_a^{\alpha_2} \cdot v_a^{\alpha_3} \]
Network Investment Model (1)

- A link based model
- Speed of a link improves if revenue is more than cost of maintenance, drops otherwise

\[ v_{a}^{t+1} = v_{a}^{t} \left( \frac{R_{a}}{C_{a}} \right)^{\beta} \]

Where:
- \( v_{a}^{t} \) is speed of link \( a \) at time step \( t \)
- \( \beta \) is speed reduction coefficient

No revenue sharing between links: Revenue from a link is used in its own investment.
Initial Assumptions

- **Base case**
  - Network - speed \(\sim U(1, 1)\)
  - Land use \(\sim U(10, 10)\)
  - Friction factor \(w=0.01\)
  - Travel cost, Revenue \(d_a \{\lambda =1.0, \rho_o =1.0, \rho_1 =1.0, \rho_2 =0.0\}\)
  - Infrastructure Cost \(\{\mu =365, \alpha_1 =1.0, \alpha_2 =0.75, \alpha_3 =0.75\}\)
  - Investment model \(\{\beta =1.0\}\)
  - Speeds on links running in opposite direction between same nodes are averaged
Case 1: Base 15x15

Figure 5 Equilibrium speed distribution for the base case on a 15x15 grid network
Case 2: Same as base case but initial speeds $\sim U(1, 5)$

Initial network

<table>
<thead>
<tr>
<th>Slow</th>
<th>Fast</th>
</tr>
</thead>
</table>

Equilibrium network state after 8 iterations

Figure 7  Equilibrium speed distribution for case 2 on a 15x15 grid network
Case 3: Base case with a downtown

Initial network

Equilibrium network state after 7 iterations
Slow Fast

Figure 9  Equilibrium speed distribution for case 3 on a 15x15 grid network
Case 5: 50x50 Network
Case 6: A River Runs Through It
Case 7: Self-Fulfilling Investments

- Invest in what is normally (base case) lowest volume links.
- Results in that being highest volume link.
- Decisions do matter: Can use investment to direct outcome.
Case A - Results

Probability Distribution of Flows

Rank

10X10
15X15
20X20
30X30
Twin Cities 1998
# Four Twin Cities Experiments

<table>
<thead>
<tr>
<th>Initial condition</th>
<th>Allow for link contraction?</th>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>1978 Twin Cities network with real 1978 capacity</td>
<td>Experiment 1</td>
<td></td>
<td>Experiment 2</td>
</tr>
<tr>
<td>1978 network with uniform capacity (400veh/h)</td>
<td>Experiment 3</td>
<td></td>
<td>Experiment 4</td>
</tr>
</tbody>
</table>

- Value of time = $10/hr - MnDOT Value
- Link performance function $\theta_1 = 0.15; \theta_2 = 4$ - BPR Function
- Friction factor $\omega = 0.1$ - Empirical
- Revenue Model $\{\rho_1 = 1.0, \rho_2 = 1.0, \rho_3 = 0.75\}$
- Infrastructure Cost $\{\mu = 365, \alpha_1 = 20, \alpha_2 = 1, \alpha_3 = 1.25\}$ - CRS in link length, DRS in speed
- Coefficient in speed-capacity regression model ($\mu_1 = -30.6, \mu_2 = 9.8$) - Empirical
- Improvement model $\{\beta = 0.75\}$ DRS in link expansion
- CRS, DRS, IRS = Constant, Decreasing, Increasing Returns to Scale
Results

Experiment 1: predicted 1998 network

Experiment 2: predicted 1998 network

Experiment 3: predicted 1998 network

Experiment 4: predicted 1998 network
Conclusions

• Succeeded in growing transportation networks (Proof of concept)
• Sufficiency of simple link based revenue and investment rules in mimicking a hierarchical network structure
• Hierarchical structure of transportation networks is a property of boundaries & asymmetries not entirely a design
• Investment policy can drive shape of hierarchy
• Model scales to metropolitan area (Application of concept)
• Levinson, David and Bhanu Yerra (2005) Self Organization of Surface Transportation Networks. Transportation Science (in press)
• Zhang, Lei and David Levinson. (2004a) An Agent-Based Approach to Travel Demand Modeling: An Exploratory Analysis. Transportation Research Record: Journal of the Transportation Research Board #1898 pp. 28-38
• Levinson, D, and Wei Chen (2004) Area Based Models of New Highway Route Growth presented at 2004 World Conference on Transport Research, Istanbul
• Xie, Feng and David Levinson (2005) The Decline of Over-invested Transportation Networks
• Xie, Feng and David Levinson (2005) Measuring the Topology of Road Networks
• Xie, Feng and David Levinson (2005) The Topological Evolution of Road Networks
• Levinson, David and Bhanu Yerra (2005) How Land Use Shapes the Evolution of Road Networks
• Zhang, Lei and David Levinson (2005) The Economics of Transportation Network Growth
¿Questions?

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