Economics of Road Network Ownership

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Road Network Ownership

Local/Municipal Government

Decentralization

Competitive Market

Nationalization

Privatization

Centralization

Centralized Government

Private Monopoly

U.S. 2006

2006
Questions about Network Ownership

For a specific road network...

What is the optimal ownership structure given certain demand characteristics and cost functions?

Whether/How should ownership changes take place?

Practical Implications

Private toll roads

Public private partnership/competition

Regulation on price, investment, and ownership
Research Objectives

Welfare consequences of …

- Centralized public ownership
- Decentralized private ownership (market-oriented)

Implications of alternative ownership on

- Prices (tax, toll)
- Network capacity
- Regulatory needs and policies

Methodological focus

- Quantitative modeling
- Equilibrium (point) and evolutionary (process) analyses
Method

Optimization and Simulation

EXOGENOUS VARIABLES
Land use, Demographics, Socio-Economic Changes

NETWORK MODEL

Year t-1

Flows

Technology:
Maintenance Cost
Construction Cost

Policy:
Pricing Policy
Revenue
Investment Policy
Ownership

Year t

Toll/Tax

Year t+1

Network t

Flow

Behavior: Travel Demand Estimation
Zone-based, Gravity distribution, Single Mode, User equilibrium traffic assignment

Network t+1
Centralized Ownership

Pricing Policy

Fuel taxes, Registration fees, Distance-based tolls
= Average cost pricing

Investment Strategy

Construction budget = Revenue – Maintenance Cost
Priority: Links with the highest benefit/cost ratios

Solve $\max_{\Delta \text{Capacity}} \text{BCRatio}(\Delta \text{Capacity})$
for each link

At the end of each fiscal year: Budget = Expenditure
Decentralized Ownership: Pricing

A Dynamic Pricing Game among All Roads

-Uncertainty and incomplete information

Profit-Maximizing Pricing through Adaptive Learning

1. Estimate a demand curve based on (price, flow) data in previous years for each link;

2. Solve Maximize Profit(price);

3. Case A: $P_{Low} < \text{Price}^* < P_{High}$
   
   New Price = Price*

   Case B: $\text{Price}^* < P_{Low}$ or $> P_{High}$

   New Price = $P_{Low}(1 - j)$
   
   or = $P_{High}(1 + j)$
Decentralized: Investment

Rate of Return

\[(\text{Lifecycle Revenue} - \text{Lifecycle Cost})/\text{Capital Cost}\]

- Links can borrow or earn interest through a “Bank” agent
- If Rate of return > interest rate \(\rightarrow\) Borrow & Build capacity
  Otherwise \(\rightarrow\) Pay off loan or Save

Profit Estimation for Capacity Expansion

- Consider two sources of additional profit after expansion
  1. Ability to charge higher tolls
  2. Ability to attract more users
Fixed Demand: Equilibrium Analysis

Equilibrium Capacity on a 10by10 Grid Network

Capacity (veh/hr)
- Blue: 0 ~ 1000
- Green: 1000 ~ 2000
- Yellow: 2000 ~ 4000
- Orange: 4000 ~ 8000
- Red: > 8000

Socially Optimal

Centralized Ownership

Decentralized Ownership
Fixed Demand: Equilibrium Analysis 2

Equilibrium Toll

<table>
<thead>
<tr>
<th>Toll ($)</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 ~ 0.5</td>
<td>Blue</td>
</tr>
<tr>
<td>0.5 ~ 1</td>
<td>Green</td>
</tr>
<tr>
<td>1 ~ 4</td>
<td>Yellow</td>
</tr>
<tr>
<td>4 ~ 8</td>
<td>Orange</td>
</tr>
<tr>
<td>&gt; 8</td>
<td>Red</td>
</tr>
</tbody>
</table>

Socially Optimal

Centralized Ownership

Decentralized Ownership
Decentralized Ownership with Regulation

Determination of the Optimal Ceiling Price

Million $
Fixed Demand: Evolutionary Analysis

Net Social Benefit (M$)

- Socially Optimal
- Decentralized: Profit-Maximizing
- Centralized: Average Cost Pricing
- Decentralized: Price Ceiling
Fixed Demand: Evolutionary Analysis 2

Average Toll ($)
Fixed Demand: Evolutionary Analysis 3

Cumulative Number of Capacity Expansion Projects

- Socially Optimal
- Decentralized: Profit-Maximizing
- Centralized: Average Cost Pricing
- Decentralized: Price Ceiling
Variable Demand: Evolutionary Analysis

Net Social Benefit (M$)

- Socially Optimal
- Decentralized: Profit-Maximizing
- Centralized: Average cost pricing
Variable Demand: Evolutionary Analysis 2

Average Toll ($)

- Socially Optimal
- Decentralized: Profit-Maximizing
- Centralized: Average cost pricing

Year
Variable Demand: Evolutionary Analysis 3

Cumulative Number of Capacity Expansion Projects

- **Socially Optimal**
- **Decentralized: Profit-Maximizing**
- **Centralized: Average cost pricing**

![Graph showing cumulative number of capacity expansion projects over years](image)
Conclusions

Nothing is perfect

<table>
<thead>
<tr>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centralized</td>
<td></td>
</tr>
<tr>
<td>Status quo</td>
<td>Low tolls, Ineffective</td>
</tr>
<tr>
<td>Cost recovery</td>
<td>Sub-optimal capacity</td>
</tr>
<tr>
<td>Decentralized</td>
<td></td>
</tr>
<tr>
<td>Responsiveness</td>
<td>High tolls</td>
</tr>
<tr>
<td>Market-oriented</td>
<td>Risk of over-investment</td>
</tr>
</tbody>
</table>

When appropriate regulation is imposed (e.g. $P_{\text{max}}$) and/or travel demand is steadily increasing (e.g. 3%) Results are in favor of decentralized market-oriented approach
Future Studies

Analysis on real-world networks (Portland, OR, Twin Cities, MN)

Consideration of hybrid ownership and ownership dynamics

Assessment of more sophisticated regulatory policies
Thank you!
Detailed Flowchart

Exogenous land use, demographic, economic changes

Year t-1
Network t

Trip Generation
Zone production and attraction totals

Trip Distribution
OD demand; k = 0

OD cost table t

UE Traffic Assignment
Link flow k
flow k = flow k - 1?
No
Pricing Model
k = k + 1
Link toll k
Yes

Flow, toll, travel time, OD cost

Revenue Model
Revenue

Cost Model
Maintenance cost
Construction cost

Investment Model
New capacity and free-flow speed

Network t + 1

OD cost table t + 1

Year t

Year t+1

Network t + 1

Measures of Network Effectiveness: VHT, VKT, CS, Revenue, etc.
Travel Demand

Notes:

- Supply and demand do not have to be solved simultaneously;
- An agent-based travel forecasting system is desirable;
- Incremental/Adaptive changes in travel behavior are important.

Trip generation and distribution

- Zone-based structure
- Doubly-constraint gravity model

\[ q_{rs}^i = m_r O_r n_s D_s \cdot d(t_{rs}^{i-1}) \]

Traffic assignment

- Origin-based User Equilibrium Assignment (Bar-Gera and Boyce 2003)
- Generalized link travel cost function

\[ VOT \cdot BPR \text{ travel time} + \text{Toll} \]

\[ t_a^i = \lambda \frac{l_a}{v_a^i} \left[ 1 + \theta_1 \left( \frac{f_a^i}{F_a^i} \right)^{\theta_2} \right] + \tau_a^i \]
Revenue and cost functions

Revenue

- A notion of link revenue is convenient in describing various policies
  \[ R^i = τ_a \cdot (ψ \cdot f^i) \]

Cost

- Only a portion of maintenance cost is volume-dependent (Paterson and Archondo-Callo 1991)
- Link maintenance cost \((M)\) function for all links:
  \[ M^i = \mu \cdot (l_a)^{α_1} \cdot (F_a^i)^{α_2} \cdot (f_a^i)^{α_3} \]
- Empirical studies suggest (Karamalaputi and Levinson 2003) link expansion cost depends on link length, capacity and capacity change
- Link expansion cost \((K)\) function:
  \[ K^i = φ \cdot (l_a)^{σ_1} \cdot (F_a^i)^{σ_2} \cdot (F_a^{i+1} - F_a^i)^{σ_3} \]
## Model Parameters

A complete set of parameters derived for the Twin Cities

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
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<tbody>
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<td>$\lambda$</td>
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<td>$\alpha_3$</td>
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<td>$\rho_2$</td>
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<td>$\Phi$</td>
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<tr>
<td>$\rho_3$</td>
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<td>$\sigma_1$</td>
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</tr>
<tr>
<td>$\mu$</td>
<td>20</td>
<td>$\sigma_2$</td>
<td>1.25</td>
</tr>
<tr>
<td>$\alpha_1$</td>
<td>1</td>
<td>$\sigma_3$</td>
<td>1</td>
</tr>
</tbody>
</table>
Model Capabilities

The agent-based simulation model of network growth seems to be a promising new approach to analyze pricing, investment strategies, and ownership structures because:

☞ It considers both short- and long-run network dynamics;

☞ It can evaluate alternative sub-optimal policies;

☞ It can be easily applied to large-scale real-world networks without loss of details or computational hurdles;

☞ It can incorporate results from studies of organizational behavior and ownership arrangements without additional modeling efforts;
Test Network

Initial conditions

❖ Uniform land use with one million total trips

❖ All links are one-lane with capacity 735 veh/hr

❖ A very congested network (average speed 10 km/h)

❖ Homogenous users