Welfare and Financial Implications of Unleashing Private Sector Investment Resources on Transportation Networks

Lei Zhang
Assistant Professor
Department of Civil and Environmental Engineering
University of Maryland
lei@umd.edu
Road Network Ownership Regimes

- Local/Municipal Government
- Nationalization
- Centralized Government
- Privatization
- Competitive Market
- Centralization
- Private Monopoly
Private Sector Investment

Types of Investment

- Long-term lease to operate existing facilities
  e.g. Chicago Skyway, Virginia Pocahontas Parkway, Indiana Toll Road System

- Capacity expansion and operation of existing facilities
  e.g. Texas’s I-635

- Construction and operation of new facilities
  e.g. Dulles Greenway, California SR 125, Texas Hwy 130
Research Questions

- To what extent can private sector investment resources help mitigate/solve existing transportation problems?
- What are the societal benefits and costs of private-sector involvement in transportation financing?
- How should we introduce and regulate private toll roads to maximize public welfare?
Two Stylized Small Networks

a. Parallel Network
One OD pair and two roads

b. Serial Network
Three OD pairs and two roads

Users choose trip frequency, departure time, and route.
A Game Theoretical Model

Public roads maximize welfare

\[
\text{Maximize} \sum_{\tau, F} \left( \int_0^q P(q) dq \right) - \sum_a C(f^a, F^a) \cdot f^a + \sum_a \tau^a f^a - \sum_a S \cdot \Delta F^a
\]

Private roads maximize profit

\[
\text{Maximize} \sum_{\tau, F} \tau^a f^a - \sum_a S^a F^a
\]

Subject to…

\(\checkmark\) Supply demand equilibrium conditions
\(\checkmark\) Cost functions
## Numerical Result – Parallel Network

<table>
<thead>
<tr>
<th>Ownership Route A-Route B</th>
<th>Status quo</th>
<th>Socially Optimal</th>
<th>Private-Private</th>
<th>Free-Private</th>
<th>Public-Private</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toll A ($/veh)</td>
<td>0</td>
<td>4.47</td>
<td>6.98</td>
<td>0</td>
<td>5.40</td>
</tr>
<tr>
<td>Toll B ($/veh)</td>
<td>0</td>
<td>4.47</td>
<td>6.98</td>
<td>5.475</td>
<td>5.62</td>
</tr>
<tr>
<td>Capacity A (veh/hr)</td>
<td>2624</td>
<td>2708</td>
<td>1316</td>
<td>1480</td>
<td>2320</td>
</tr>
<tr>
<td>Capacity B (veh/hr)</td>
<td>2624</td>
<td>2708</td>
<td>1316</td>
<td>1228</td>
<td>2175</td>
</tr>
<tr>
<td>VC Ratio A (no unit)</td>
<td>1.62</td>
<td>1.12</td>
<td>1.21</td>
<td>2.49</td>
<td>1.14</td>
</tr>
<tr>
<td>VC Ratio B (no unit)</td>
<td>1.62</td>
<td>1.12</td>
<td>1.21</td>
<td>1.12</td>
<td>1.09</td>
</tr>
<tr>
<td>Rate of return A</td>
<td>–</td>
<td>–</td>
<td>69%</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Rate of return B</td>
<td>–</td>
<td>–</td>
<td>69%</td>
<td>22%</td>
<td>22%</td>
</tr>
<tr>
<td>Welfare Change ($)</td>
<td>0</td>
<td>8351</td>
<td>4131</td>
<td>-3244</td>
<td>7801</td>
</tr>
<tr>
<td>Efficiency</td>
<td>0</td>
<td>1</td>
<td>0.49</td>
<td>-0.39</td>
<td>0.93</td>
</tr>
</tbody>
</table>
## Numerical Result – Serial Network

<table>
<thead>
<tr>
<th>Ownership Route A-Route B</th>
<th>Status quo</th>
<th>Socially Optimal</th>
<th>Private-Private</th>
<th>Free-Private</th>
<th>Public-Private</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toll A ($/veh)</td>
<td>0</td>
<td>4.47</td>
<td>8.41</td>
<td>0</td>
<td>2.67</td>
</tr>
<tr>
<td>Toll B ($/veh)</td>
<td>0</td>
<td>4.47</td>
<td>8.41</td>
<td>11.42</td>
<td>10.34</td>
</tr>
<tr>
<td>Capacity A (veh/hr)</td>
<td>19740</td>
<td>16250</td>
<td>7405</td>
<td>16220</td>
<td>14490</td>
</tr>
<tr>
<td>Capacity B (veh/hr)</td>
<td>19740</td>
<td>16250</td>
<td>7405</td>
<td>9349</td>
<td>8450</td>
</tr>
<tr>
<td>VC Ratio A (no unit)</td>
<td>1.42</td>
<td>1.12</td>
<td>1.02</td>
<td>1.22</td>
<td>1.12</td>
</tr>
<tr>
<td>VC Ratio B (no unit)</td>
<td>1.42</td>
<td>1.12</td>
<td>1.02</td>
<td>1.00</td>
<td>1.04</td>
</tr>
<tr>
<td>Rate of return A</td>
<td>–</td>
<td>–</td>
<td>71%</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Rate of return B</td>
<td>–</td>
<td>–</td>
<td>71%</td>
<td>127%</td>
<td>116%</td>
</tr>
<tr>
<td>Welfare Change ($)</td>
<td>0</td>
<td>46310</td>
<td>8130</td>
<td>13110</td>
<td>21890</td>
</tr>
<tr>
<td>Efficiency</td>
<td>0</td>
<td>1</td>
<td><strong>0.18</strong></td>
<td><strong>0.28</strong></td>
<td><strong>0.47</strong></td>
</tr>
</tbody>
</table>
Toll Road Dynamics in the Real World

Land Use and Economic Growths in All Zones

Year t

USERS
1. Trip frequency,
2. Destination
3. Route choices

PUBLIC ROADS
1. Pricing choice
2. Capacity choice

PRIVATE ROADS
1. Pricing Choice
2. Capacity Choice
3. Learning

REGULATOR
Regulation on price, capacity, and market entry

Network t

PRIVATE ROADS Costs

PRIVATE ROADS Revenue

CONSTRUCTOIN MAINTENANCE COSTS

Network t+1

PRIVATE ROADS Regulation on price, capacity, and market entry

PRIVATE ROADS Market entry Choice

Private Sector Investment Resources

Flow

Revenue Costs

Toll/Tax

Toll/Tax

Tax/Toll

Toll

TIME

Year t-1

Year t

Year t+1

TIME
A Simulation-Based Approach

Demand Side
☞ Four-step travel demand model

Supply Side
☞ Empirically estimated road construction and maintenance cost functions

Public Roads
☞ Welfare-maximizing pricing and capacity choices
☞ Budget-balancing choices

Private Roads
☞ Profit-maximizing decision on market entry, pricing, and capacity

Regulator
☞ Minimum regulation on private roads
Test Network
Twin Cities, Minnesota

- 7776 nodes, 20486 Links, ~ 6 million trips daily

Assumptions for the Test Network

- Private roads estimate demand elasticities adaptively
- Once a private road is built, the parallel public road will not be tolled, and will not be expanded for 10 years
- Capacity expansion is discrete (1-lane, 2-lane, etc.)
- When driving on public roads, drivers pay $0.056/km
- Multiple non-cooperative private-sector investors
- 25-year life-cycle for roads with a 10% discount rate
New Private Toll Roads 2006~2020
Toll Road Growth and Toll Rate Dynamics

Total private sector investment: $19.5 Billion
Profitability of Private Sector Investment

Percentage of Private Roads Making Profits

Average Annual Rate of Investment Return: 18.2%
Welfare Impact of Private Investment

Net Social Benefit ($Million)

- Socially Optimal
- No Private Investment
- Free Entry of Private Roads

Total Welfare Increase: $6.7 Billion
User Benefit: $1.1 Billion
Private Profit: $5.6 Billion

Year
Conclusions

- Analytical methods for evaluating the welfare and financial impact of private toll roads are available and can be applied to real-world scenarios.
- Don’t expect private sector investment resources to eliminate congestion.
- Private toll road projects profitable in the long run do not necessarily guarantee near-term profits.
- If network effects are ignored, private investors tend to charge overly high tolls that work against profit maximization goals.
- Private investment improves social welfare, even when it is minimally regulated.
- Proper regulation distributes more benefits to users.
Future Research Directions

Multiple user classes and the distributional effects

Demand uncertainty and risk considerations

Optimal regulation
Thank you!
Research Design

Evaluating a Mixed-Ownership Policy

- Free entrance of private toll roads on a public road network

Comparing Pricing, Welfare, and Financial Consequences between Mixed-Ownership and

- Status quo (Gas tax, general taxes, public ownership only)
- Completely market-oriented approach
- Socially optimal

Methodological focus

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

Pure Strategy Nash Equilibrium

- FOC + Equilibrium Constraints
- System of 24 non-linear equations for the parallel-serial network
- Solve for all stationary points
- Evaluate objectives at all stationary points
- Not applicable to large networks

A Numerical Example…
**Solution Method - Toll**

**According to first-order necessary optimality conditions**

<table>
<thead>
<tr>
<th>Ownership</th>
<th>Parallel Network</th>
<th>Serial Network</th>
</tr>
</thead>
<tbody>
<tr>
<td>Private-Private</td>
<td>$$\frac{U_f^B c^1}{U_f^B + c^1} f^A$$</td>
<td>$$\frac{(c^2 + c^3) f^A U_f^B + c^6 f^A}{(c^3 + c^4) + c^5 U_f^B}$$</td>
</tr>
<tr>
<td>Private-Free</td>
<td>$$\tau_A = f^A U_{f_A} + \ldots$$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$$\frac{U_f^B c^1}{U_f^B + c^1} f^A$$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$$\tau_A = f^A U_{f_A} + \ldots$$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$$\tau_B = 0$$</td>
<td></td>
</tr>
<tr>
<td>Public-Private</td>
<td>$$\frac{c^1}{U_f^B + c^1} \left( \tau^B - f^B U_{f_B} \right)$$</td>
<td>$$\left[ \frac{c^3}{(c^3 + c^4) + c^5 U_f^B} \right] \left( f^B U_f^B - \tau^B \right)$$</td>
</tr>
<tr>
<td>A-B</td>
<td>$$\tau_A = f^A U_{f_A} + \ldots$$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$$\frac{U_f^B c^1}{U_f^B + c^1} f^B$$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$$\tau_B = f^B U_{f_B} + \ldots$$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$$c^1 \equiv |P_f|; \quad c^2 \equiv |P_{q^{12}} P_{q^{13}}|; \quad c^3 \equiv |P_{q^{12}} P_{q^{23}}|; \quad c^4 \equiv |P_{q^{13}} P_{q^{23}}|; \quad c^5 \equiv \sum_{b} P_{q}^{b}; \quad c^6 \equiv \prod_{b} P_{q}^{b}.$$  

**Parallel network has been studied by:**

de Palma and Lindsey 2000, Verhoef 2002 among others
# Numerical Result - Parallel-Serial Network

<table>
<thead>
<tr>
<th>Ownership</th>
<th>Status Quo</th>
<th>Socially Optimal</th>
<th>Competition Scenario 1</th>
<th>Competition Scenario 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toll A ($/veh/link)</td>
<td>0</td>
<td>4.47</td>
<td>5.70</td>
<td>5.79</td>
</tr>
<tr>
<td>Toll B ($/veh/link)</td>
<td>0</td>
<td>4.47</td>
<td>5.70</td>
<td>5.47</td>
</tr>
<tr>
<td>Toll C ($/veh/link)</td>
<td>0</td>
<td>4.47</td>
<td>8.40</td>
<td>8.36</td>
</tr>
<tr>
<td>Capacity A (veh/hr)</td>
<td>9870</td>
<td>8125</td>
<td>6753</td>
<td>(Fix.)8125</td>
</tr>
<tr>
<td>Capacity B (veh/hr)</td>
<td>9870</td>
<td>8125</td>
<td>3784</td>
<td>3372</td>
</tr>
<tr>
<td>Capacity C (veh/hr)</td>
<td>19740</td>
<td>16250</td>
<td>8125</td>
<td>(Fix.)8125</td>
</tr>
<tr>
<td>Rate of return 1</td>
<td>–</td>
<td>–</td>
<td>60%</td>
<td>55%</td>
</tr>
<tr>
<td>Rate of return 2</td>
<td>–</td>
<td>–</td>
<td>28%</td>
<td>22%</td>
</tr>
<tr>
<td>? Welfare ($)</td>
<td>0</td>
<td>46310</td>
<td>24560</td>
<td>26080</td>
</tr>
<tr>
<td>Efficiency</td>
<td>0</td>
<td>1</td>
<td>0.53</td>
<td>0.56</td>
</tr>
</tbody>
</table>
Revenue and cost functions

Revenue

鬶 A notion of link revenue is convenient in describing various policies

Revenue  Toll  •  Flow

\[ E^i_a = \tau^i_a \cdot (\psi \cdot f^i_a) \]

Cost

 Bowen  A portion of maintenance cost is volume-dependent (Paterson and Archondo-Callo 1991)

 Bowen  link maintenance cost \((M)\) function for all links:

\[ M^i_a = \mu \cdot (l^i_a)^{\alpha_1} \cdot (F^i_a)^{\alpha_2} \cdot (f^i_a)^{\alpha_3} \]

 Bowen  Empirical studies suggest (Karamalaputi and Levinson 2003) link expansion cost depends on link length, capacity and capacity change

 Bowen  Link expansion cost \((K)\) function:

\[ K^i_a = \phi \cdot (l^i_a)^{\sigma_1} \cdot (F^i_a)^{\sigma_2} \cdot (F^i_{a+1} - F^i_a)^{\sigma_3} \]
### Model Parameters

A complete set of parameters derived for the Twin Cities

<table>
<thead>
<tr>
<th>Parameter ( \lambda )</th>
<th>Value ( 10 )</th>
<th>Parameter ( \alpha_2 )</th>
<th>Value ( 1.25 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \theta_1, \theta_2 )</td>
<td>0.15, 4</td>
<td>( \omega_1, \omega_2 )</td>
<td>-30.6, 9.8</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>0.1</td>
<td>( \eta_0, \eta_1, \eta_2 )</td>
<td>341, 273, 162</td>
</tr>
<tr>
<td>( \rho_1 \cdot \psi )</td>
<td>1</td>
<td>( \Phi )</td>
<td>1</td>
</tr>
<tr>
<td>( \rho_2 )</td>
<td>1</td>
<td>( \sigma_1 )</td>
<td>1</td>
</tr>
<tr>
<td>( \rho_3 )</td>
<td>0</td>
<td>( \sigma_2 )</td>
<td>1.25</td>
</tr>
<tr>
<td>( \mu )</td>
<td>20</td>
<td>( \sigma_3 )</td>
<td>1</td>
</tr>
<tr>
<td>( \alpha_1 )</td>
<td>1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>