Differentiated Congestion Pricing of Urban Transportation Networks with Vehicle Tracking Technologies

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Traditionally tolls are anonymous

Travelers have different sets of available paths

With respect to system travel time, the best choice for one user can be the worst choice for another user!

Vehicle tracking technologies enable us to differentiate users

Anonymous scheme enhanced with tracking data → Differentiated scheme
Price Differentiation

Economic concept
- Defined by Dupuit (1894)
- Identical products sold at different prices

Examples in transportation pricing
- One two-way ticket is cheaper than two one-way tickets
- Senior citizens pay lower bus fare
- Trucks pay more toll than cars
- Nonlinear congestion pricing

We investigate another type of differentiated pricing scheme that differentiates travelers with respect to their travel characteristics.
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We investigate another type of differentiated pricing scheme that differentiates travelers with respect to their *travel characteristics*. 
How does the differentiated pricing scheme work?
Definitions

Anonymous scheme: Everyone pays the same amount of toll.
Differentiated scheme: Toll depends on travel characteristics.

Level of differentiation:
- L0: None → anonymous scheme
- L1: Origin → origin-specific scheme
- L2: Origin and destination → OD-specific scheme
- L3: Path → path-based scheme
Anonymous scheme: Everyone pays the same amount of toll.
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## Level of Differentiation

<table>
<thead>
<tr>
<th>Path</th>
<th>L0</th>
<th>L1</th>
<th>L2</th>
<th>L3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\pi_9$</td>
<td>$\pi_9^2$</td>
<td>$\pi_9^{2,3}$</td>
<td>$\pi_{4,8,9,11}$</td>
</tr>
<tr>
<td>2</td>
<td>$\pi_9$</td>
<td>$\pi_9^1$</td>
<td>$\pi_9^{1,3}$</td>
<td>$\pi_{2,8,9,11}$</td>
</tr>
<tr>
<td>3</td>
<td>$\pi_9$</td>
<td>$\pi_9^1$</td>
<td>$\pi_9^{1,4}$</td>
<td>$\pi_{2,8,9,12}$</td>
</tr>
<tr>
<td>4</td>
<td>$\pi_9$</td>
<td>$\pi_9^1$</td>
<td>$\pi_9^{1,4}$</td>
<td>$\pi_{1,6,9,12}$</td>
</tr>
</tbody>
</table>
Scenario 1:
- All the links are available for tolling (first-best)
- The objective is to minimize the toll revenue while keeping the total travel time at the lowest level

Scenario 2:
- Some of the links cannot be charged a toll (second-best)
- The objective is to minimize total travel time
Sioux Falls Network

- 24 nodes
- 76 links
- 528 OD pairs
- 14 tollable links for second-best pricing
### Implementation on Sioux Falls Network

**Table:** Results of differentiated pricing for Sioux Falls network

<table>
<thead>
<tr>
<th>Tolling Scheme</th>
<th>First-best</th>
<th>Second-best</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min. Revenue</td>
<td>Reduction</td>
</tr>
<tr>
<td>Anonymous</td>
<td>23.441</td>
<td>0.00%</td>
</tr>
<tr>
<td>Origin-specific</td>
<td>0.750</td>
<td>96.80%</td>
</tr>
<tr>
<td>OD-specific</td>
<td>0.616</td>
<td>97.37%</td>
</tr>
<tr>
<td>Path-based</td>
<td>0.182</td>
<td>99.23%</td>
</tr>
<tr>
<td>User Equilibrium</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>System Optimum</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

- Differentiated schemes perform significantly better than anonymous schemes.
- For both the first-best and second-best conditions, higher levels of differentiation lead to more favorable results.
Great potential, but at a price!!!
Privacy

- Location privacy: the ability to prevent other parties from learning one’s current or past location
- Arises when providing a service requires location data
- Differentiated pricing requires the knowledge of travelers’ travel characteristics such as the origin and destination of each trip for an OD-specific scheme
- The OD data may imply home/work locations. Even if they are anonymous, they can be used to identify individuals (Krumm, 2009).
- The sole fact of being tracked by the tolling system can also cause inconvenience or discomfort.
Value of Privacy

- Individuals value their privacy differently
- They can be grouped into categories of privacy unconcerned, privacy pragmatists, and privacy fundamentalists
- Mathematically, we can use a distribution to represent different individual valuations of privacy across the population
- Given the distribution, we can find the percentage of travelers who benefit from differentiated schemes
Example: Nine-node Network

Figure: Nine-node Network

OD demands: $[1, 3] = 10$  
$[1, 4] = 20$  
$[2, 3] = 30$  
$[2, 4] = 40$
## Example: Nine-node Network

**Table:** The percentage of travelers who benefit from origin-specific scheme

<table>
<thead>
<tr>
<th>Network Condition</th>
<th>First-best</th>
<th></th>
<th>Second-best</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>OD pair</td>
<td>[1,3]</td>
<td>[1,4]</td>
<td>[2,3]</td>
<td>[2,4]</td>
</tr>
<tr>
<td>Travel Cost Saving</td>
<td>7.2</td>
<td>-0.1</td>
<td>7.2</td>
<td>7.2</td>
</tr>
<tr>
<td>$\beta \sim U(0, 4)$</td>
<td>100.00</td>
<td>0.00</td>
<td>100.00</td>
<td>100.00</td>
</tr>
<tr>
<td>$\beta \sim U(0, 16)$</td>
<td>45.00</td>
<td>0.00</td>
<td>45.00</td>
<td>45.00</td>
</tr>
<tr>
<td>$\beta \sim EXP(0.500)$</td>
<td>97.27</td>
<td>0.00</td>
<td>97.27</td>
<td>97.27</td>
</tr>
<tr>
<td>$\beta \sim EXP(0.125)$</td>
<td>59.34</td>
<td>0.00</td>
<td>59.34</td>
<td>59.34</td>
</tr>
</tbody>
</table>

- Not everyone would like the differentiated pricing
- The savings of time and toll that some travelers enjoy from differentiated schemes are offset by the loss of their privacy
- When average value of privacy is high, there are still some travelers who benefit from origin-specific scheme
What is the solution to privacy issue?
We propose an incentive program that allows each traveler to opt in to differentiated schemes

- Self-selection mechanism: travelers who choose to reveal their private information will pay differentiated tolls while those who remain anonymous will pay uniform tolls
- Anonymous scheme preserves location privacy
- Differentiated scheme offers incentives
- In the simplest setting, the travel cost difference between differentiated and anonymous schemes can be viewed as incentive
Implementation on Nine-node Network

Table: Incentive program under first-best conditions

<table>
<thead>
<tr>
<th>Pricing Scheme</th>
<th>Distribution of $\beta$</th>
<th>$E(\beta)$</th>
<th>Toll Rev.</th>
<th>Privacy Cost</th>
<th>Total User Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anonymous</td>
<td>-</td>
<td>-</td>
<td>887.60</td>
<td>0.00</td>
<td>887.60</td>
</tr>
<tr>
<td>Origin-specific</td>
<td>-</td>
<td>2</td>
<td>311.60</td>
<td>200.00</td>
<td>511.60</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>4</td>
<td>311.60</td>
<td>400.00</td>
<td>711.60</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>8</td>
<td>311.60</td>
<td>800.00</td>
<td>1111.60</td>
</tr>
<tr>
<td>Hybrid</td>
<td>$U(0, 4)$</td>
<td>2</td>
<td>247.82</td>
<td>28.46</td>
<td>276.28</td>
</tr>
<tr>
<td></td>
<td>$U(0, 8)$</td>
<td>4</td>
<td>235.25</td>
<td>58.47</td>
<td>293.72</td>
</tr>
<tr>
<td></td>
<td>$U(0, 16)$</td>
<td>8</td>
<td>220.76</td>
<td>116.96</td>
<td>337.72</td>
</tr>
<tr>
<td></td>
<td>$EXP(0.500)$</td>
<td>2</td>
<td>249.84</td>
<td>17.49</td>
<td>267.33</td>
</tr>
<tr>
<td></td>
<td>$EXP(0.250)$</td>
<td>4</td>
<td>237.43</td>
<td>35.52</td>
<td>272.95</td>
</tr>
<tr>
<td></td>
<td>$EXP(0.125)$</td>
<td>8</td>
<td>213.08</td>
<td>71.02</td>
<td>284.10</td>
</tr>
</tbody>
</table>

- Anonymous scheme yields highest toll revenue; origin-specific leads to highest privacy cost while hybrid scheme results in smallest user cost
- Higher average value of privacy leads to higher total user cost
Implementation on Nine-node Network

Table: Incentive program under second-best conditions

<table>
<thead>
<tr>
<th>Pricing Scheme</th>
<th>Distribution of $\beta$</th>
<th>$E(\beta)$</th>
<th>Travel Time</th>
<th>Privacy Cost</th>
<th>Total System Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anonymous</td>
<td>-</td>
<td>-</td>
<td>2361.16</td>
<td>0.00</td>
<td>2361.16</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>2</td>
<td>2306.10</td>
<td>200.00</td>
<td>2506.10</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>4</td>
<td>2306.10</td>
<td>400.00</td>
<td>2706.10</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>8</td>
<td>2306.10</td>
<td>800.00</td>
<td>3106.10</td>
</tr>
<tr>
<td>Origin-specific</td>
<td>$U(0, 4)$</td>
<td>2</td>
<td>2291.79</td>
<td>9.13</td>
<td>2300.92</td>
</tr>
<tr>
<td></td>
<td>$U(0, 8)$</td>
<td>4</td>
<td>2296.76</td>
<td>13.08</td>
<td>2309.84</td>
</tr>
<tr>
<td></td>
<td>$U(0, 16)$</td>
<td>8</td>
<td>2304.63</td>
<td>17.57</td>
<td>2322.20</td>
</tr>
<tr>
<td>Hybrid</td>
<td>$EXP(0.500)$</td>
<td>2</td>
<td>2291.45</td>
<td>5.82</td>
<td>2297.27</td>
</tr>
<tr>
<td></td>
<td>$EXP(0.250)$</td>
<td>4</td>
<td>2293.47</td>
<td>9.56</td>
<td>2303.04</td>
</tr>
<tr>
<td></td>
<td>$EXP(0.125)$</td>
<td>8</td>
<td>2299.10</td>
<td>13.30</td>
<td>2312.40</td>
</tr>
</tbody>
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<tr>
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<th>Privacy Cost</th>
<th>Total System Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anonymous</td>
<td>-</td>
<td>-</td>
<td>74.043</td>
<td>0.000</td>
<td>74.043</td>
</tr>
<tr>
<td>Origin-specific</td>
<td>-</td>
<td>0.02</td>
<td>73.060</td>
<td>7.212</td>
<td>80.272</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>0.04</td>
<td>73.060</td>
<td>14.424</td>
<td>87.474</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>0.08</td>
<td>73.060</td>
<td>28.848</td>
<td>101.908</td>
</tr>
<tr>
<td>Hybrid</td>
<td>U(0, 0.04)</td>
<td>0.02</td>
<td>73.294</td>
<td>0.118</td>
<td>73.412</td>
</tr>
<tr>
<td></td>
<td>U(0, 0.08)</td>
<td>0.04</td>
<td>73.421</td>
<td>0.138</td>
<td>73.421</td>
</tr>
<tr>
<td></td>
<td>U(0, 0.16)</td>
<td>0.08</td>
<td>73.591</td>
<td>0.163</td>
<td>73.753</td>
</tr>
<tr>
<td></td>
<td>EXP(50.0)</td>
<td>0.02</td>
<td>73.272</td>
<td>0.086</td>
<td>73.357</td>
</tr>
<tr>
<td></td>
<td>EXP(25.0)</td>
<td>0.04</td>
<td>73.355</td>
<td>0.106</td>
<td>73.461</td>
</tr>
<tr>
<td></td>
<td>EXP(12.5)</td>
<td>0.08</td>
<td>73.455</td>
<td>0.163</td>
<td>73.618</td>
</tr>
</tbody>
</table>

- The model works for a more realistic network
- Similar observations can be made
Summary

Contributions:

- Explored a new class of tolling schemes that charge different amount of toll for users with different origins, destinations, or paths.
- Developed a modeling approach for travelers location privacy
- Proposed an incentive program that allows the tolling agency to take advantage of the potentials of differentiated pricing without doing harm to travelers privacy rights.

Conclusion:

- Differentiated pricing may not be appealing for everyone
- Distribution of value of privacy has a significant effect on the acceptability of differentiated schemes
- Incentive program can create a win-win situation for all travelers
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Questions? mzangui@ufl.edu