Challenges of Implementing Incentive Mechanisms for Reducing Infrastructure Congestion

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Congestion is Here to Stay

Example 1: Mobile Data

<table>
<thead>
<tr>
<th>Year</th>
<th>Traffic (Exabytes)</th>
<th>CAPEX (Billions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>1</td>
<td>$48</td>
</tr>
<tr>
<td>2012</td>
<td>2</td>
<td>$41</td>
</tr>
<tr>
<td>2013</td>
<td>3</td>
<td>$34</td>
</tr>
<tr>
<td>2014</td>
<td>4</td>
<td>$31</td>
</tr>
<tr>
<td>2015</td>
<td>5</td>
<td>$28</td>
</tr>
</tbody>
</table>

Source: Ericsson
Source: IHS
Source: Markit

Congestion is Here to Stay

Example 2: Highways

<table>
<thead>
<tr>
<th>Year</th>
<th>VMT (Trillions)</th>
<th>Public Road Mileage (Lane Miles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980</td>
<td>1.5</td>
<td>3.0</td>
</tr>
<tr>
<td>1990</td>
<td>2.0</td>
<td>4.0</td>
</tr>
<tr>
<td>2000</td>
<td>2.5</td>
<td>5.0</td>
</tr>
<tr>
<td>2010</td>
<td>3.0</td>
<td>6.0</td>
</tr>
</tbody>
</table>

Source: Federal Highway Administration

Congestion is Here to Stay

Example 2: Electricity Generation, Transmission and Distribution

Circuit Miles

<table>
<thead>
<tr>
<th>Year</th>
<th>Circuit Miles</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>10,000</td>
</tr>
<tr>
<td>2015</td>
<td>12,000</td>
</tr>
</tbody>
</table>

Congestion Externalities

Externality: An actor’s choice affects other’s utility
E.g. My decision to drive during rush hour increases the delay of other drivers on my route

Congestion Externality: The more actors choose an action (route) the worse it gets

Figure 1: SUV driver imposing an externality on a pedestrian
**Congestion Externalities**

*Example: Braess’s Paradox*

- Population Normalized to 1
- Fixed Delays (units = tens of minutes)
- Equilibrium Delay: 1.5 (15 minutes)

**Congestion Externalities**

*Example: Braess’s Paradox*

- Population Normalized to 1
- Equilibrium Delay: 2 (20 minutes)

Drivers impose an externality on each other at traffic light and crosswalk queues:
- Total crosswalk delay: \( x_2 \) (Delay times population suffering it)
- Marginal cost to whole population for increasing crosswalk traffic: \( 2x_2 \)
- But each driver only sees cost of \( x_1 \). Make them pay!

**Pigovian Tax**

- Make people pay for their externality
- Aligns individual and social optimization problems to make optimum achieved
- Lots of challenges for practical implementation
- E.g. Monetary value of time different for different people, measurement difficulties, disincentive for revealing willingness to pay, etc...

**Incentives in Transit**

*Incentives for Singapore’s Commuters*

- Travel off-peak and increase your chance of winning.

**More Incentives**

*Unlimited Data!*

- Bits
- *Three Part Tariff*
- *Overage* rate
- *Cap* Monthly charge
- *Incentives in Transit*
Externalities and Public Goods

Public Good
- Cannot easily exclude others from enjoying
- Consumption by one doesn’t impair others from consuming

Problem
- One cannot capture full value from investing in
- A non-contributor can still enjoy
- Depending on voluntary donations will lead to severe underinvestment in public goods
- Most common fix: government + taxes

Lotteries and Externalities

Money for public good increases vs. voluntary contributions! (Morgan 2000)
- Even though prize is “skimmed” from the proceeds

Intuition
- Voluntarily contributing to public creates positive externality
  - One underinvests since individual can’t capture full benefit
- Lottery creates negative externality
  - Contributing decreases others’ expected winnings
  - Partially offsets the positive externality, hence
  - Better alignment of individual and social objectives

Lotteries for Congestion

Incentive Scheme:
- Earn ticket for shifting demand to off-peak
- Reward given randomly

Incentive Mechanisms for Internet Congestion Management:
Fixed-Budget Rebate versus Time-of-Day Pricing
Panfil Lukowicz, Gabriel Athavale, Ali Mesgarzadeh, Sayed Amin, and M. Snehal Surya
(IEEE Transactions on Networking 2014)

Feedback Loop 1:
- $\theta$ – Parameter characterizing cost of shifting demand
- Congestion worsens, creates pressure to shift, pushes threshold right

Feedback Loop 2:
- $\theta$ – Parameter characterizing cost of shifting demand
- As more people shift...
  - Expected reward drops ...
  - Incentive to shift weakens
- If very few people shift...
  - Expected raffle reward high...
  - Incentive for more people to shift
Incentive Mechanisms for Internet Congestion Management: Fixed-Budget Rebate versus Time-of-Day Pricing

- Parameter characterizing cost of shifting demand

\[ \theta \]

- Threshold

Advantageous to shift

Not Advantageous to shift

Alternative: Time of Day Pricing

- Challenge: Setting Prices
  - Too little discount → no one shifts
  - Too big of a discount → too many (or everyone!) shifts

Key Finding:

- Raffle Scheme more robust to parameter uncertainty than fixed time of day prices

Challenges for Incentive Schemes

Raffle Based Schemes

- How do you identify a shift in demand from a fake demand?
  - E.g. Download bogus movies at night to get rewarded for downloading in advance
  - A usage based pricing component could be disincentive enough, but what about plans that are free up to a cap?
  - Maybe one should be forced to watch it to qualify for bonuses?

Challenges for Incentive Schemes

All schemes

- How to communicate/educate user of effect of decisions:
  - How much is streaming this movie going to cost me?
  - How much is running turn by turn directions on Google Maps going to cost me in a foreign country?
  - How much is shifting the clothes dryer run to night going to save me?
- Can bonuses be made more personalized to reduce cost?

Challenges for Incentive Schemes

Tampering and Theft

- Pricing dependent on more observables → more opportunities to gain from hacking, tampering, etc.

Challenges for Incentive Schemes

Data Tampering and Theft

- Need better schemes to identify using multiple data sources
  - E.g. Inferring sensor tampering from other measurements of electrical distribution system
Challenges for Incentive Schemes

Privacy
- Collection of more behavioral data can be used in unintended ways

Closing Thoughts
- Ability to cost-effectively collect data from millions of users, and offer them behavior-dependent incentives is relatively new opportunity
- Challenges abound
  - Scheme design, user education and willingness to accept, security, privacy, etc.
  - Infrastructure congestion necessitates moving forward with new incentive schemes