Markets for Transport
Eliminating Congestion through Scheduling, Routing, and Real-time Pricing

Peter Cramton
University of Cologne and University of Maryland
Rick Geddes
Cornell University
Axel Ockenfels
University of Cologne

7 June 2018 [latest slides, paper, two-pager]
Urbanization and other developments create congestion
Global congestion costs $1 trillion/year, and growing
Today, average U.S. driver incurs 42 hours/year in road delays
Averages in Germany are 30 hours/year and in Los Angeles, 104 hours/year
<table>
<thead>
<tr>
<th>RANK</th>
<th>WORLD RANK</th>
<th>CITY</th>
<th>COUNTRY</th>
<th>CONGESTION LEVEL</th>
<th>MORNING PEAK</th>
<th>EVENING PEAK</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>Stuttgart</td>
<td>Germany</td>
<td>34% ↑1%</td>
<td>49%</td>
<td>64%</td>
</tr>
<tr>
<td>2</td>
<td>56</td>
<td>Cologne</td>
<td>Germany</td>
<td>34% ↑4%</td>
<td>52%</td>
<td>61%</td>
</tr>
<tr>
<td>3</td>
<td>61</td>
<td>Hamburg</td>
<td>Germany</td>
<td>33% ↑3%</td>
<td>48%</td>
<td>53%</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>Nuremberg</td>
<td>Germany</td>
<td>30% ↑2%</td>
<td>45%</td>
<td>53%</td>
</tr>
<tr>
<td>5</td>
<td>76</td>
<td>Munich</td>
<td>Germany</td>
<td>30% ↑1%</td>
<td>51%</td>
<td>53%</td>
</tr>
<tr>
<td>6</td>
<td>84</td>
<td>Berlin</td>
<td>Germany</td>
<td>29% ↑1%</td>
<td>43%</td>
<td>50%</td>
</tr>
</tbody>
</table>
“The Fundamental Law of Road Congestion”
Duranton and Turner (AER 2011)

Supply side policies typically not effective
  – If unpriced capacity is added, the road will often become as congested as it was before
  – Scarcity of urban land
  – Financial constraints

Ride-hailing services or self-driving cars unlikely to cure congestion
  – Uber supports road pricing as “the most effective way to manage vehicles on the road”
  – Lyft suggests that “congestion pricing . . . has not caught on in a big enough way”
A key externality, and how (not) to address it
The users of road and other transportation networks not only experience congestion, they create it. In deciding how and when to travel, most travelers take into account the congestion they expect to experience; few consider the costs their trips impose on others by adding to congestion. (Mohring 2001)
“The number of vehicles that get through per hour can drop by as much as 50 percent when severe congestion sets in. At high-traffic levels, the freeway is kept in this condition of ‘collapse’ for several hours after the rush of commuters has stopped.”

*US Federal Highway Administration*
Time- and location-

independent charges ineffective

Constant charges (such as in the new German Maut system) often do not reduce congestion

(Martin and Thornton 2017 provide empirical evidence)
Step 1: Vehicle measurement of road use

- Real time kinematic
  - 2 cm accuracy
  - Retail cost $1000, but will drop dramatically to $50 with scale
Solution: Congestion pricing

- addresses congestion externality (Vickrey 1963)
- addresses environmental externality
- encourages drivers to explore travel alternatives during peak times
- simplifies consumer decision-making
- improves safety
- allows joint optimization of all transport (roads and transit)
- provides essential information to direct scarce investment resources
- generates the funds that underlie that investment with non-distortionary taxes
- adopts basic fairness principles
- allows scarce road space to be allocated to those who value it most highly
- incentivizes technological innovations that reduce demand on scarce capacities
Case studies
Singapore

Pioneered congestion pricing in 1975

Toll gantries form a cordon around urban center, and on expressways

While counterfactual situation is not quantifiable, regular revisions on charges affect congestion

E.g., when charges were levied per trip rather per day, traffic levels decreased by 15% (Menon 2000)
Since 2013

Today, vehicles are charged £11.50 per day if they drive in charging zone (exemptions and discounts)

*Transport for London* concluded in 2014 that the charges were:

“continuing to deliver congestion relief that [is] broadly in line with the 30 percent reduction achieved in the first year of operation”
Milan

Since 2008, environmental charge (Ecopass), cordon around the city

Charge differentiated according to emissions, from 0 to 10€/weekday

In the first year, number of charged vehicles decreased 56%, traffic was reduced 21%, and emissions 14-23%

In 2011, 80% voted for extending the system
Since 2006, cordon around the city, 2€ in peak and 1€ off-peak times

Traffic volumes reduced by 20%, leading to reductions of queuing times of 30-50% (Eliasson, Hultkrantz, Nerhagen & Rosqvist 2009)

Public support increased from around 30% in 2005 to almost 70% in 2007, and increasing
The effect of a 2€ charge in Stockholm

Monday, 2 Jan 2006
(last day without charges)
Stockholm before and after the 2€ charge

Monday, 2 Jan 2006
(last day without charges)

Tuesday, 3 Jan 2006
(first day with charges)

Source: Eliasson (2015)
Express lanes in the United States
New initiatives around the world

Germany (Maut, driving bans?)
California (per mile fee?)
NYC (cordon?)
Phoenix (?)
Singapore (?)
...

A market for transport that eliminates all congestion
The time is right

Congestion becomes unbearable
– Many cities and countries open to congestion pricing
– Yet, most proposals (like per-mile-fee and Maut) not efficient

Advances in mobile communications enable
– Precise (to 1 cubic meter) location of vehicles
– Easy communication of preferences, prices, schedules

Advances in computers and markets enable
– efficient scheduling/routing and pricing of transport
– based on best practice from existing time and locational markets
Key market principle: open access

Transport network is open to all
Nondiscriminatory terms
Network capacity cannot be withheld
=> Efficient congestion pricing

Basis for restructured electricity markets in US, Europe, ...
Simple congestion pricing

Independent system operator (ISO) maximizes the value of roads (free-flow)
Product: Slot on congested road segment at particular time (10 minute time interval)
ISO establishes prices for each slot
User price depends on the vehicle-specific demand for road capacity and pollution
Apps guide consumers in making transport choices consistent with their preferences
Open access transport network
(Independent System Operator)

Users/vehicles

Integrated wholesale and retail market

Simple market model
A wholesale market

Forward trading mitigates risks
Service providers compete for road use in forward markets as well as in real time
Service providers develop user apps that allow easy expression of demand
Service providers guide users, both in scheduling future demand as well as routing during real time
Open access transport network (Independent System Operator)

Wholesale market

Service providers

SP_1

SP_2

SP_3

Users/vehicles

A B C D E F G

Retail market

Wholesale market model as electricity successfully operating for two decades
ERCO Load with Real Time and Day Ahead Prices

- Real Time Price Average
- Day Ahead Price Average
- ERCOT Load ('0000 MWh)
• 52 inches of rainfall in southeast Texas
• Harvey made landfall multiple times
  • Category 4 near Port Aransas, Texas
  • Tropical storm in Cameron, Louisiana
• More than 42,000 lightning strikes
• Record number of tornado warnings in southeast Texas

Transmission Damage
Multiple opportunities to trade
- Reduces risk of service provider
- Facilitates planning of service provider
- Provides price transparency
- Mitigates market power
All markets use single-price auction

Wholesale preferences expressed as piecewise-linear strictly-decreasing demand curves
Consistent with underlying preferences
Unique clearing prices and quantities
Cross Bronx Expressway from Exit 6A to Exit 2, on a workday at 8:20am

<table>
<thead>
<tr>
<th></th>
<th>Price</th>
<th>Quantity</th>
<th>Quantity Change</th>
<th>Commitment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Future Rounds</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$36.00/trip</td>
<td>-1,000 trips/day</td>
<td>-2,200 trips/day</td>
<td>-$554,400</td>
<td></td>
</tr>
<tr>
<td>$28.00/trip</td>
<td>-200 trips/day</td>
<td>-1,400 trips/day</td>
<td>-$274,400</td>
<td></td>
</tr>
<tr>
<td>$24.00/trip</td>
<td>500 trips/day</td>
<td>-700 trips/day</td>
<td>-$117,600</td>
<td></td>
</tr>
<tr>
<td>$20.00/trip</td>
<td>2,000 trips/day</td>
<td>800 trips/day</td>
<td>$112,000</td>
<td></td>
</tr>
<tr>
<td>Current Round</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$8.40/trip</td>
<td>2,644 trips/day</td>
<td>1,444 trips/day</td>
<td>$84,907</td>
<td></td>
</tr>
<tr>
<td>$8.00/trip</td>
<td>2,666 trips/day</td>
<td>1,466 trips/day</td>
<td>$82,096</td>
<td></td>
</tr>
<tr>
<td>Past Rounds</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$6.00/trip</td>
<td>2,833 trips/day</td>
<td>1,633 trips/day</td>
<td>$68,586</td>
<td></td>
</tr>
<tr>
<td>$4.00/trip</td>
<td>3,000 trips/day</td>
<td>1,800 trips/day</td>
<td>$50,400</td>
<td></td>
</tr>
<tr>
<td>Price Floor</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$1.50/trip</td>
<td>4,000 trips/day</td>
<td>2,800 trips/day</td>
<td>$29,400</td>
<td></td>
</tr>
</tbody>
</table>

Forward Position: 1,200 trips/day
Auction Supply: 7,000 trips/day
Maximum Commitment: $115,049
<table>
<thead>
<tr>
<th>Type</th>
<th>Mon</th>
<th>Tue</th>
<th>Wed</th>
<th>Thu</th>
<th>Fri</th>
<th>Sat</th>
<th>Sun</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily trip</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type</th>
<th>Mon</th>
<th>Tue</th>
<th>Wed</th>
<th>Thu</th>
<th>Fri</th>
<th>Sat</th>
<th>Sun</th>
</tr>
</thead>
<tbody>
<tr>
<td>Round trip</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>One way</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multi-stop</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Begin</th>
<th>Wed, 1 Nov 2017</th>
<th>Thu, 30 Nov 2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>End</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Depart</th>
<th>Arrive</th>
<th>Home to Work</th>
<th>Work to Home</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8:00am</td>
<td>8:28am</td>
<td>+10 min</td>
</tr>
<tr>
<td></td>
<td>5:00pm</td>
<td>5:28pm</td>
<td>+50 min</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Alternatives and Price Change</th>
<th>Later</th>
<th>Earlier</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+10 min</td>
<td>$ 0.45</td>
<td>-10 min</td>
</tr>
<tr>
<td>+20 min</td>
<td>$ (0.20)</td>
<td>-20 min</td>
</tr>
<tr>
<td>+30 min</td>
<td>$ (0.46)</td>
<td>-30 min</td>
</tr>
<tr>
<td>+40 min</td>
<td>$ (1.11)</td>
<td>-40 min</td>
</tr>
<tr>
<td>+50 min</td>
<td>$ (1.21)</td>
<td>-50 min</td>
</tr>
<tr>
<td>+60 min</td>
<td>$ (1.40)</td>
<td>-60 min</td>
</tr>
<tr>
<td>+70 min</td>
<td>$ (1.56)</td>
<td>-70 min</td>
</tr>
<tr>
<td>+80 min</td>
<td>$ (1.82)</td>
<td>-80 min</td>
</tr>
<tr>
<td>+90 min</td>
<td>$ (2.01)</td>
<td>-90 min</td>
</tr>
</tbody>
</table>

Cost per trip: $ 3.76

Add to Cart
How today’s apps would change
Research questions
Excellent topic for behavioral research

Complex trade-offs across time, roads and money
Drivers’ responses to market unknown
Players’ perception of policy most relevant
Lab and field experiments useful
(Martin and Thornton 2017)
Vehicle: MD 012 ABC

via I-495 W 28 min
Fastest route, the usual traffic
Leave around 8:30 AM
$3.42↑

via I-66 W 38 min
22.4 miles
27.8 miles
$3.78↑

4:21 AM–6:32 AM 2 h 11 min
Today’s transport is mostly free, but comes at the cost of uncertain congestion delays.

Our market puts a price on transport, but avoids delays (and improves throughput).

Both regimes cause some drivers to leave early, late, or not at all, or to switch roads ...
Behavioral research questions

Do *individuals* pick departure time and roads rationally?

- Simple competitive markets are known to work well (e.g., Smith 1962), but few lab studies look at behavior along different dimensions in competitive markets, such as time and space.
- Economic traffic experiments focus on simple, repeated coordination games without prices (Selten et al. 2007, Chmura/Pitz 2004a,b, Schneider/Weimann 2004, Rapoport et al. 2004), or include a simple toll (Gabuthy et al. 2006, Hartman 2009); almost all experiments induce identical driver preferences, inelastic demand and deterministic supply (but see Lopez 2017).

Which market design effectively promotes participation & acceptance?
Example I: Status quo bias!?

Do voters and politicians underappreciate equilibrium effects (Bó et al. 2017)?

Public support of congestion pricing in Stockholm (source: Eliasson 2015)

"Charges heading for the ditch"
"Bypass threatened by chaos"
"Charging chaos continues"

"Stockholm loves the charges"
"Charges a success"
"Thumbs up for the charges"

Stockholm newspaper front pages, before and three weeks after congestion pricing took effect. Image: Jonas Eliasson
Example II: Fairness!?

Many reject congestion pricing due to fairness
Yet, in fact,
– arguing that congestion charges are unfair is equivalent to arguing that driving in peak times should be subsidized
– most studies show that rich people pay more
– depending on revenue use, poor people benefit most from congestion pricing
Back-of-the-envelope examples

Intuition for simple case: Pricing left lanes of a multi-lane road makes everybody better off
  – Revealed preference for those who pay
  – Less congestion for those who don’t because of improved throughput

All roads priced: Consider a poor worker, who must be at work at 8 am, and no public transit or other substitution is available
  – Free-flow travel time: 30 min
  – Travel time today: up to 90 min
  – Departure time today: 6:30 am, expected arrival at 7:30 am
  – Efficient price for 6:30 am departure time: likely (close to) zero because of improved throughput; plus: expected 30 min travel time saving
Privacy

Google Maps Location

ALLOW LOCATION ACCESS

Never

While Using the App

Always

App explanation: “Choose Always Allow to get navigation, real-time traffic and transit updates, and to see places near you.”
From simple lab to complex natural settings

Simple lab setting
- Induced private values and time costs, simple road network
- Perfectly informed system operator vs optimization based on revealed preferences

Going to the field, step-by-step
- Actual supply and demand conditions, and cost estimates, from Singapore and L.A. to study the effectiveness of market mechanisms under ‘realistic’ conditions
- Real-time experiments to study trade-offs across time and money dimensions: subjects decide when to ‘drive’; working, eating etc. only allowed when not ‘driving’
- Actual driving decisions

Singapore as an ideal test-bed in the field
Incremental implementation

1. Identify issues with current system
2. Introduce measurement; simulate network
3. Introduce initial time-and-location prices (fixed!)
4. Re-estimate prices and introduce refined prices
5. Repeat until learn behavioral response
6. Introduce real-time pricing (e.g. adapts to shocks in supply)
7. Introduce forward purchase (establish sensible default plan)
8. Study long-term impact
Conclusion
An efficient market for transport

Is feasible and fair
Assures transport network is used efficiently
Eliminates congestion
Motivates network investment and provides needed funds
Can effectively address environmental goals
Milton Friedman

There is enormous inertia—a tyranny of the status quo—in private and especially governmental arrangements. Only a crisis—actual or perceived—produces real change. When that crisis occurs, the actions that are taken depend on the ideas that are lying around. That, I believe, is our basic function [as economists]: to develop alternatives to existing policies, to keep them alive and available until the politically impossible becomes politically inevitable.