Congestion pricing

Theory and applications

Michel Bierlaire

Introduction to transportation systems

EPFL

Motivation

Objective

Solve a complex social problem: congestion

Philosophy

- Create incentives.
- Don't plan details.
- People will figure out what to do.

Source: [Eliasson, 2012]

Congestion pricing

Definition

Pricing mechanisms to charge the users of public goods for the negative externalities generated by the peak demand in excess of available supply.

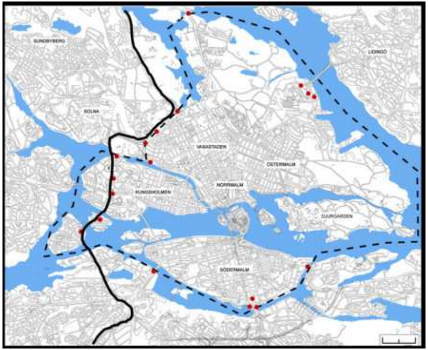
Source: Wikipedia (Photo: Kalleboo)

Congestion pricing

Implementations

- 1975: Singapore
- 2001: Rome
- 2003: London
- 2006: Stockholm
- 2008: Milan
- 2013: Gothenburg
- and others...

Stockholm example

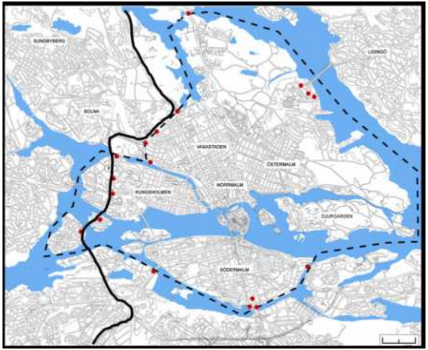


History

- January 3–July 31, 2006: trial period.
- August 2006: referendum imposed by opponents.
- Results:
  - City of Stockholm: yes.
  - Outside Stockholm: no.
- August 2007: congestion charges reintroduced.

Source: [Börjesson et al., 2012]

Stockholm example

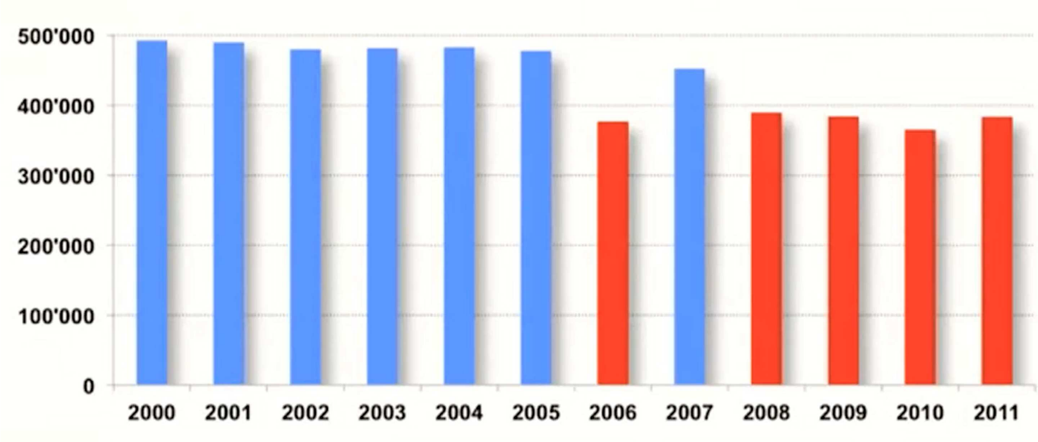


Format

- Toll cordon around the inner city.
- Peak hours (7:30–8:30, 16:00–17:30): 2 €
- 30 minutes before/after peak hours: 1.5 €
- Rest of the day: 1 €
- From 18:30 to 6:30: free.
- Maximum charge per day: 6 €.
- Until end of 2008, alternative fuel cars exempted.

Stockholm example

Immediate impact: 20% less cars [Eliasson, 2012]



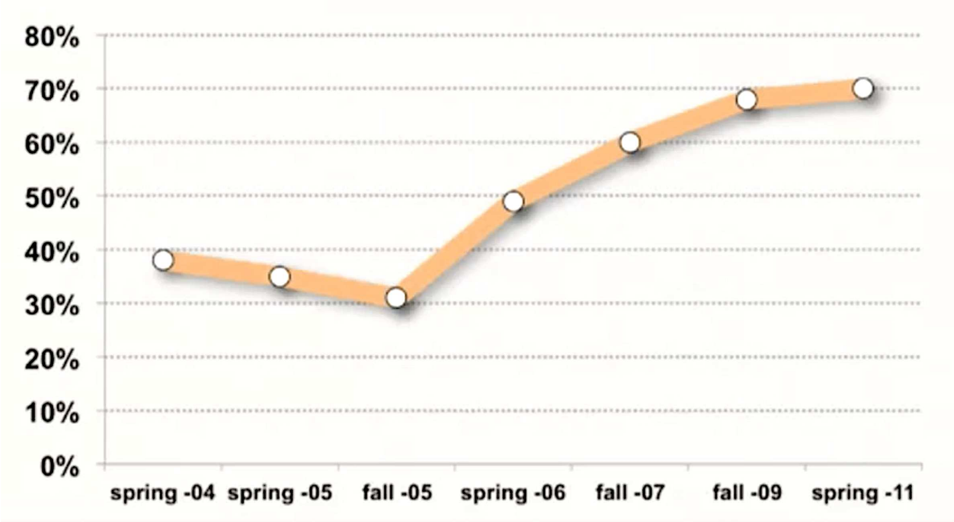
Stockholm example

Where did the cars go?

- travelers cancel trips
- travelers change destination
- travelers change mode
- travelers change departure time

Stockholm example

Public support: from 30-70 to 70-30 [Eliasson, 2012]



Stockholm example

What are the arguments against?

- yet another tax.
- inequity: poors are excluded.
- doubts about the effectiveness.
- what will be done with the revenues?
- congestion is sent somewhere else.

Stockholm example

Long-term effects

- traffic reduction caused by the charges has increased slightly over time,
- increased sales of “clean” vehicles

TED Talk

Jonas Eliasson (2012) “How to solve traffic jams?”.
www.ted.com/talks/jonas_eliasson_how_to_solve_traffic_jams
Recorded at EPFL.

Congestion pricing

What can engineers and scientists do?

- Implementation: data collection, toll collection, enforcement, etc.
- Calculate the right price.

Calculating the right price

What is the “right” price?

- If Pat Trafficson travels, she “pays” a cost, which is a combination of the time she spends, and the money she pays.
- This is what she tries to minimize when she makes travel choices.
- But her choices have an effect on others.
- Her presence increases the level of congestion.
- She deteriorates the general level of service.
- She has to pay for that.
- But how much?
- The right price = the value of the deterioration that she generates.
- “Polluter pays” principle.

Traffic assignment

User equilibrium

$$y^* = \mathrm{argmin}_y \sum_\ell \int_0^{x_\ell} t_\ell(z)dz$$

subject to

$$\sum_p y_p^q = f_q, \qquad \forall q,$$

$$y_p^q \geq 0, \quad \forall p, q.$$

System optimum

$$\tilde{y}^* = \mathrm{argmin}_y \sum_\ell x_\ell t_\ell(x_\ell)$$

subject to

$$\sum_p y_p^q = f_q, \qquad \forall q,$$

$$y_p^q \geq 0, \quad \forall p, q.$$

$\sum_\ell x_\ell^* t_\ell(x_\ell^*) - \sum_\ell \tilde{x}_\ell^* t_\ell(\tilde{x}_\ell^*) \geq 0$: price of anarchy

Optimality conditions: derivative of the objective function

User equilibrium

$$\frac{\partial}{\partial y_p^q}\left[\sum_{\ell'}\int_0^{x_{\ell'}} t_{\ell'}(z)dz\right] =$$

$$\sum_{\ell}\frac{\partial x_\ell}{\partial y_{pq}}\frac{\partial}{\partial x_\ell}\left[\sum_{\ell'}\int_0^{x_{\ell'}} t_{\ell'}(z)dz\right] =$$

$$\sum_{\ell} P_{\ell p} t_\ell(x_\ell) =$$

$$c_p^q.$$

see previous lecture

System optimum

$$\frac{\partial}{\partial y_p^q}\left[\sum_{\ell'} x_{\ell'} t_{\ell'}(x_{\ell'})\right] =$$

$$\sum_{\ell}\frac{\partial x_\ell}{\partial y_{pq}}\frac{\partial}{\partial x_\ell}\left[\sum_{\ell'} x_{\ell'} t_{\ell'}(x_{\ell'})\right] =$$

$$\sum_{\ell} P_{\ell p}\left(t_\ell(x_\ell) + x_\ell\frac{\partial t_\ell(x_\ell)}{\partial x_\ell}\right)$$

$$\tilde{t}_\ell(x_\ell) = t_\ell(x_\ell) + x_\ell\frac{\partial t_\ell(x_\ell)}{\partial x_\ell}$$

Marginal costs

Observations

- If the users are experimenting the following cost function

$$\tilde{t}_\ell(x_\ell) = t_\ell(x_\ell) + x_\ell \frac{\partial t_\ell(x_\ell)}{\partial x_\ell}$$

  the user equilibrium is equivalent to the system optimum.
- Therefore, the extra cost that should be charged is

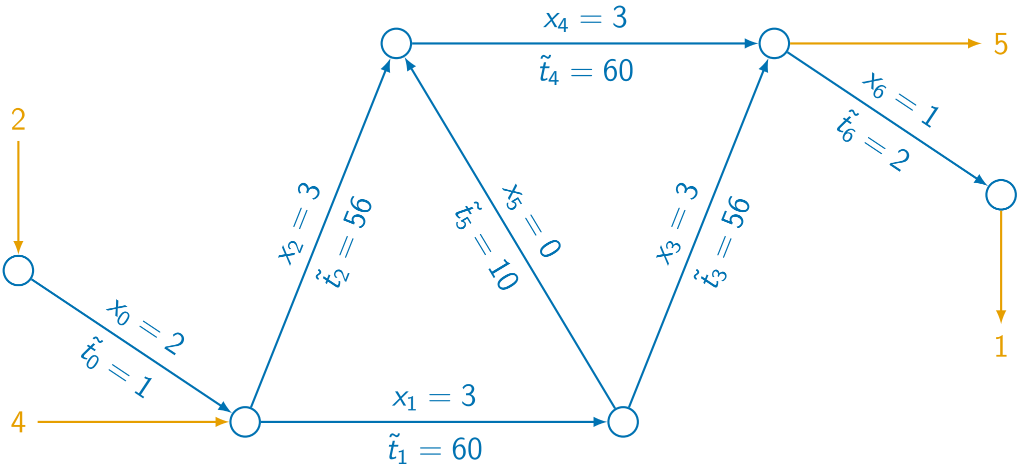
$$x_\ell \frac{\partial t_\ell(x_\ell)}{\partial x_\ell}$$

- This is the total cost paid by all other users of a marginal increase of the flow on a link.

Examples

$$
\begin{aligned}
t_1 &= 10x_1 & \tilde{t}_1 &= 10x_1 + 10x_1 = 20x_1 \\
t_2 &= 50 + x_2 & \tilde{t}_2 &= 50 + x_2 + x_2 = 50 + 2x_2 \\
t_3 &= 50 + x_3 & \tilde{t}_3 &= 50 + x_3 + x_3 = 50 + 2x_3 \\
t_4 &= 10x_4 & \tilde{t}_4 &= 10x_4 + 10x_4 = 20x_4 \\
t_5 &= 10 + x_5 & \tilde{t}_5 &= 10 + x_5 + x_5 = 10 + 2x_5
\end{aligned}
$$

Equilibrium with updated performance functions



$$\tilde{c}^*_{11} = 116,\ \tilde{c}^*_{12} = 118,\ \tilde{c}^*_{21} = 117$$

Equilibrium with updated performance functions

p	flow	x_0	x_1	x_2	x_3	x_4	x_5	x_6	$\tilde{t}_0$	$\tilde{t}_1$	$\tilde{t}_2$	$\tilde{t}_3$	$\tilde{t}_4$	$\tilde{t}_5$	$\tilde{t}_6$	cost
r_1, s_1: $f_{rs} = 3$																
	1		3		3					60		56				116
	2			3		3					56		60			116
	0		3			3	0			60			60	10		130
r_1, s_2: $f_{rs} = 1$																
	1		3		3			1		60		56			2	118
	0			3		3		1			56		60		2	118
	0		3			3	0	1		60			60	10	2	132
r_2, s_1: $f_{rs} = 2$																
	1	2	3		3				1	60		56				117
	1	2		3		3			1		56		60			117
	0	2	3			3	0		1	60			60	10		131

Congestion pricing

Theory

- The extra perceived cost on each link should be

$$x_\ell \frac{\partial t_\ell(x_\ell)}{\partial x_\ell}$$

- It depends on traffic.
- The monetary equivalent should be charged.
- If unit is travel time, use value-of-time to transform into monetary units.

Picture: weris-inc.com

Congestion pricing

Practice

- Difficult to equip all links.
- Information about toll must be received before travelers make decisions. Difficult if toll changes in real-time.
- Value-of-time varies across individuals, trip purposes, trip length, etc. Difficult to charge a different toll to different travelers.

Summary

Theory

- Charge travelers for their contribution to congestion.
- System optimum equivalent to user equilibrium with updated costs.

Practice

- Example of Stockholm.
- Politically sensitive topics.
- Controversies.
- Difficulty of implementation.

Bibliography

Börjesson, M., Eliasson, J., Hugosson, M. B., and Brundell-Freij, K. (2012).
The stockholm congestion charges—5 years on. effects, acceptability and lessons learnt.
Transport Policy, pages 1–12.

Eliasson, J. (2012).
How to solve traffic jams?
TED Talk.