Congestion pricing on a road network: A study using the dynamic equilibrium simulator METROPOLIS

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Outline of presentation

1. Introduction and motivation
2. Structure of METROPOLIS
3. Laboratory network
4. Results
5. Conclusions

1. Introduction and motivation

Introduction and Motivation…

Topology of tolling schemes

Link tolls	Bridges, tunnels, Highways
Cordon tolls	Norwegian cities
Area schemes	Singapore, London

Comprehensive:

- Kilometre-based charges for Heavy Goods Vehicles (Switzerland, Germany, Austria, New Zealand)
- Nationwide car tolls envisaged for UK in 10+ years

Introduction and Motivation…

Time structure of tolls

Flat	Majority of toll roads
Single step	Singapore 1975-98, London, French motorways
Multi-step	Singapore 2005, SR 91 (California)
Dynamic	Interstate 15 (California)

Introduction and Motivation

Basic modeling requirements

Detailed road network representation
(tolls induce re-routing)

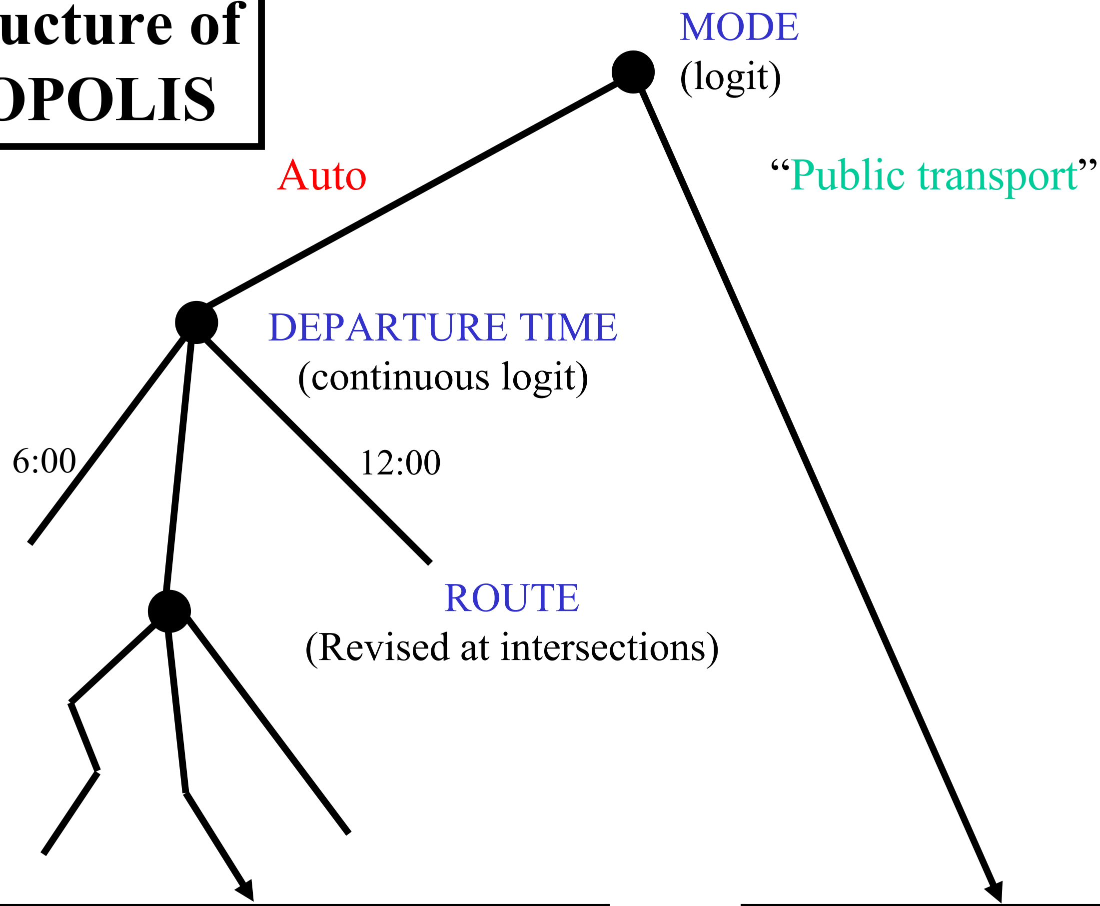
Endogenous trip-timing decisions
(tolls induce retiming of trips)

Elastic automobile travel demand
(tolls induce modal switching)

Consistent welfare analysis

2. The METROPOLIS simulator

Basic structure of METROPOLIS



Auto cost	
Travel time	Free-flow + congested
Schedule delay	Early, late
Toll	Link & time dependent

Public transport cost	
Travel time	Exogenous
Schedule delay	—
Penalty	Exogenous

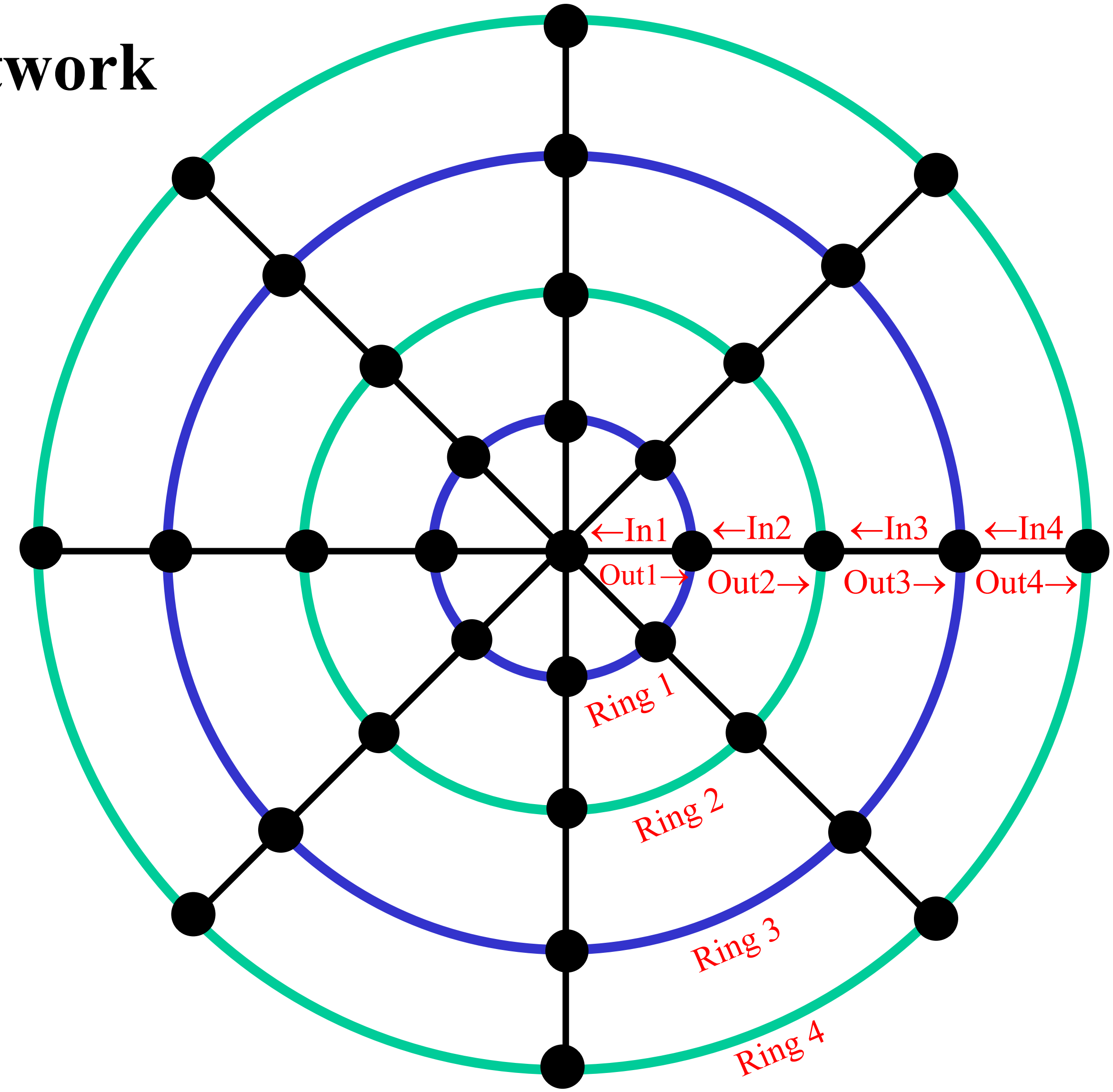
Systematic cost for auto trip

$$C_A(t) = \begin{cases} \underbrace{\alpha_A \mathrm{T}_A(t)}_{Travel\ time\ \cos t} \\ +\underbrace{\beta Max\left[0, t^* - \Delta - t - \mathrm{T}_A(t)\right]}_{Early\ arrival\ \cos t} \\ +\underbrace{\gamma\ Max\left[0, t + \mathrm{T}_A(t) - t^* - \Delta\right]}_{Late\ arrival\ \cos t} \\ +\underbrace{\tau}_{Toll} \end{cases}$$

3. Laboratory network

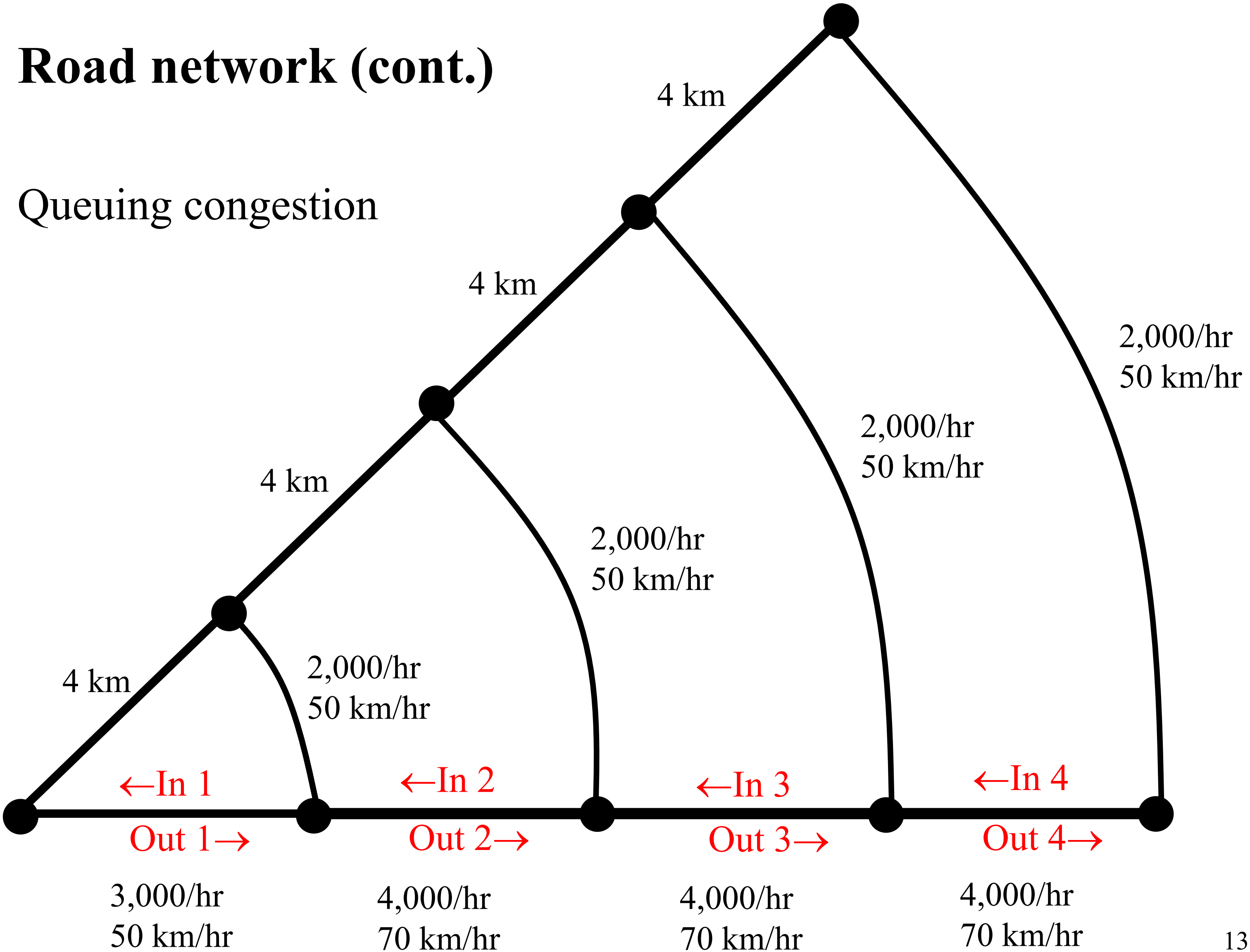
Road network

Radius 16 km.



Road network (cont.)

Queuing congestion



“Public transport” network

Travel time = Shortest path distance
by road @ 40 km/h

Trip demand

- Morning commuting trips
- Static O-D matrix
- Mean 8,000 trips per zone $\Rightarrow$ 264,000 trips
- O-D demand exponential function of (free-flow) travel time. Trips per O-D pair: 123-660

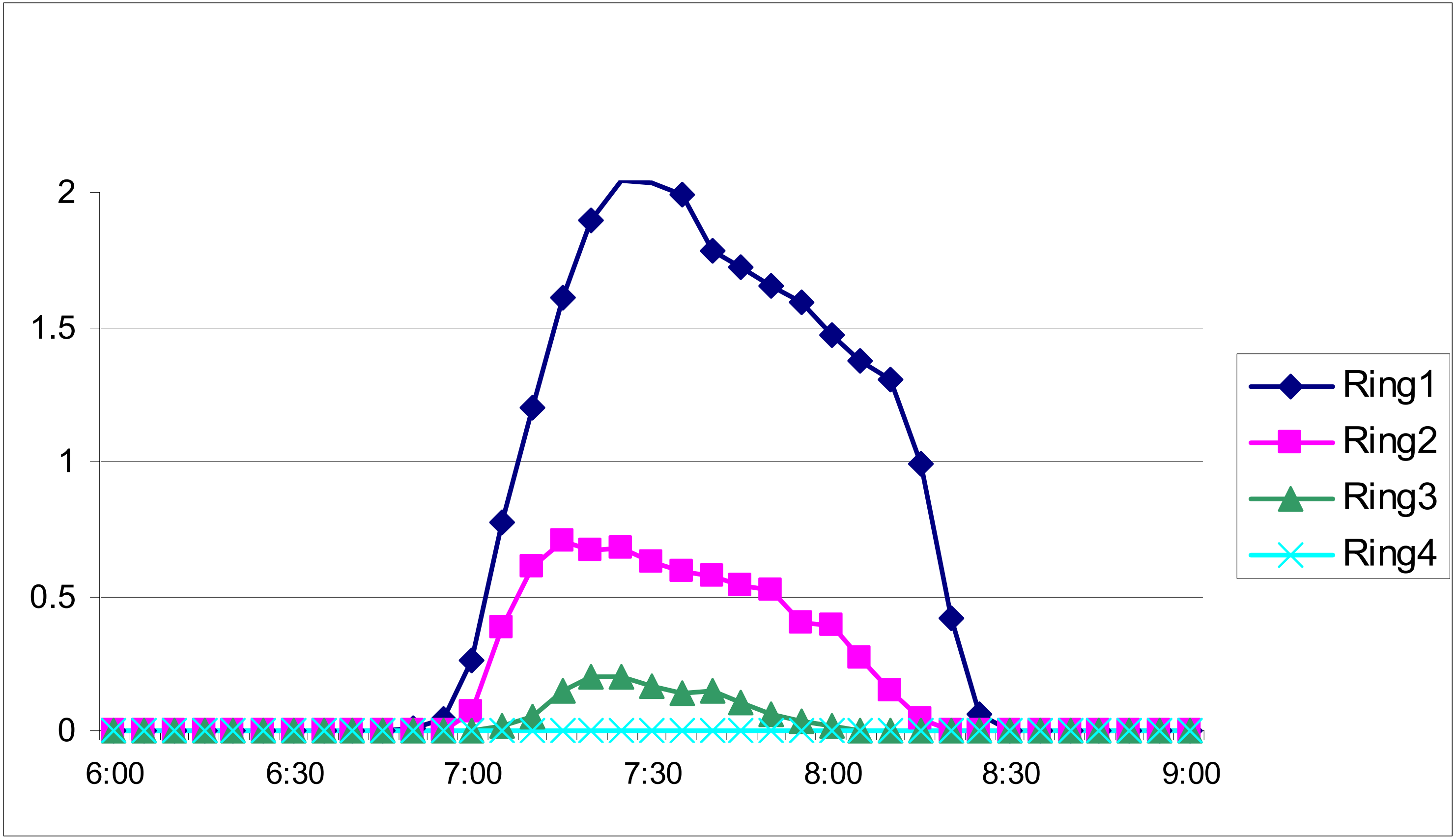
Demand parameters	
Mode choice	
Logit scale parameter	$5
Auto	
Logit departure time choice	$2
Desired arrival time	8:00 (st. dev. 0:20)
On-time window (full)	10 mins
Early cost	$6/hr
Late cost	$25/hr
Travel time cost	$10/hr
Public transport	
Travel time cost	$15/hr
Fixed penalty	$10

4. Results

No-toll equilibrium

Auto share	70.6%
Distance	15.0 km
Travel time	22.1 mins
Speed	40.7 km/h
Congestion index	38.5%

Congestion indexes: Ring roads



Tolling regimes considered

Comprehensive

- Five-minute step tolls (approx. system optimum)
- Flat tolls

Cordon toll on Ring 2

- Flat
- Half-hour time steps

Area within Ring 2

- Flat
- Half-hour time steps

Comprehensive 5-minute step tolls

Externalities: Road link congestion only.

Public transport: Neither economies nor diseconomies.

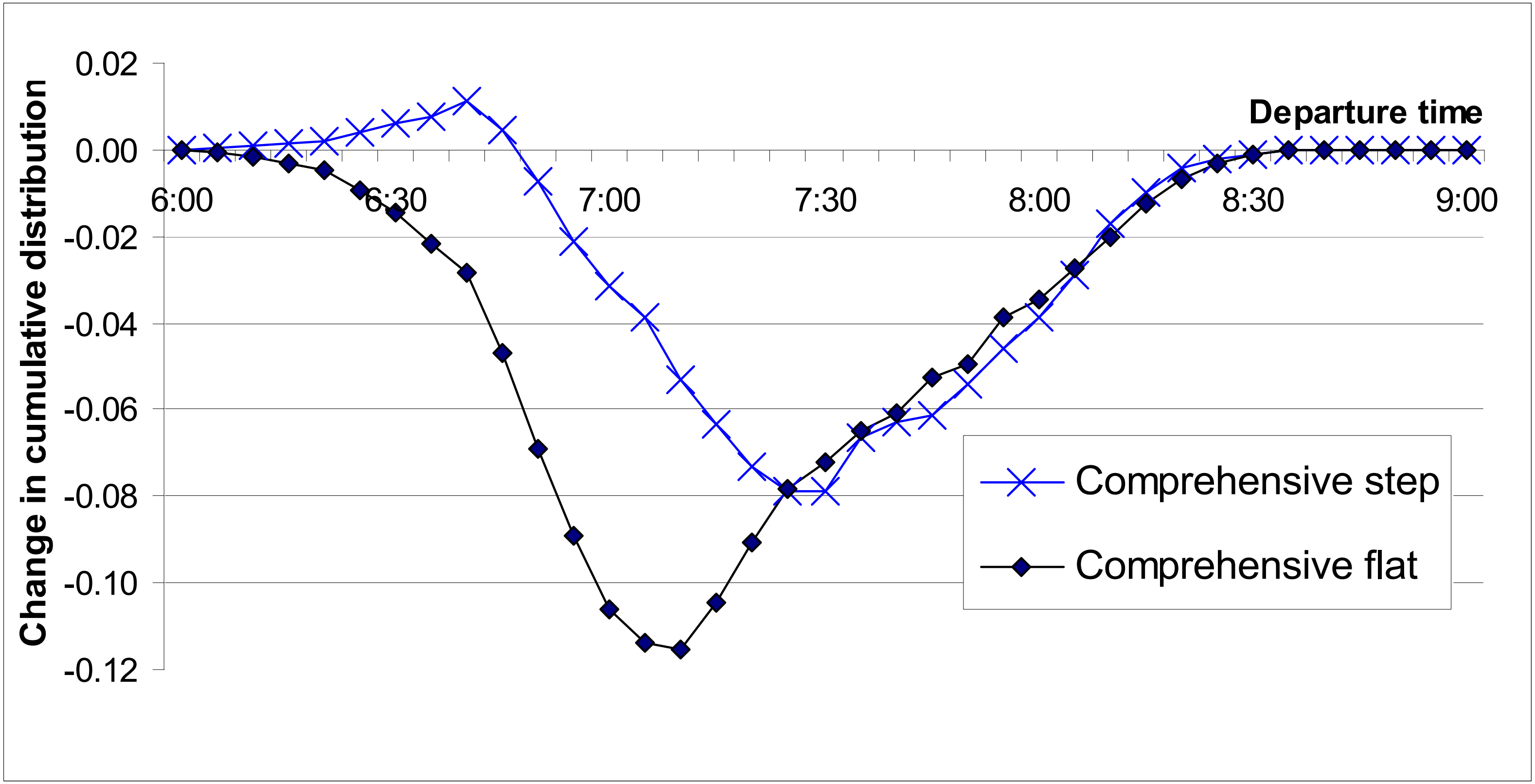
⇒ Time-dependent anonymous link tolls suffice to support system optimum.

But computationally demanding.

Heuristic solution via “no-queue” tolling.

Non-zero tolls on all links except those without queuing {In4, Out4, Ring4}

Impact of comprehensive tolls on departure times



Welfare impacts of comprehensive tolls

Regime:	No-toll	Comprehensive	
		Five-minute step	Flat
Optimal toll level(s)		5 min. step tolls on all links except In4, Out4, Ring 4	**In**: $0.73, $2.15, $2.00, $0.00 **Out**: $1.37, $1.06, $0.76, $0.00 **Ring**: $0.42, $0.51, $0.27, $0.00
AutoShare	71%	69%	64%
Congestion	38.5%	4.8%	11.0%
VehKm [10^3]	279.6	280.0	255.4
Travel cost	$5.16	$5.56	$6.33
Welfare gain/capita		$204.84	$94.14
Toll revenue/capita		$215.08	$333.81
Welfare gain/revenue		0.952	0.282
Relative welfare gain		100%	46%
Gainers no rebate		29%	11%
Gainers100% rebate		83%	67%
Rebate: 50% gain		33%	78%
St. dev. of CS change		1.123	1.191

Distributional impacts of comprehensive tolls

Destin.	Origin											
	Ring 0		Ring 1		Ring 2		Ring 3		Ring 4		All origins	
Ring 0	(a)	(c)	25%	99%	26%	0%	20%	0%	17%	0%	22%	28%
	(b)	(d)	$0.20	$0.43	$0.07	-$0.63	-$0.22	-$1.54	-$0.32	-$1.45	-$0.05	-$0.74
Ring 1	39%	78%	29%	83%	33%	0%	30%	0%	31%	0%	31%	22%
	$0.33	$0.06	$0.04	$0.24	$0.02	-$0.94	-$0.23	-$1.87	-$0.25	-$1.77	-$0.09	-$1.05
Ring 2	44%	0%	31%	1%	30%	3%	28%	0%	28%	0%	30%	1%
	$0.17	-$0.93	-$0.12	-$0.79	$0.04	-$0.42	-$0.19	-$1.41	-$0.20	-$1.34	-$0.12	-$1.01
Ring 3	45%	0%	28%	0%	28%	1%	38%	0%	30%	29%	31%	8%
	$0.49	-$1.59	$0.02	-$1.41	-$0.10	-$0.94	$0.23	-$0.31	$0.03	-$0.19	$0.05	-$0.74
Ring 4	50%	0%	27%	0%	23%	0%	28%	0%	32%	31%	28%	6%
	$0.66	-$1.98	-$0.05	-$1.80	-$0.05	-$1.38	-$0.02	-$0.69	-$0.01	-$0.17	-$0.01	-$1.05
All destins.	44%	27%	29%	29%	29%	1%	30%	0%	29%	12%	30%	11%
	$0.37	-$0.90	-$0.02	-$0.74	-$0.01	-$0.89	-$0.09	-$1.21	-$0.13	-$1.00	-$0.05	-$0.96

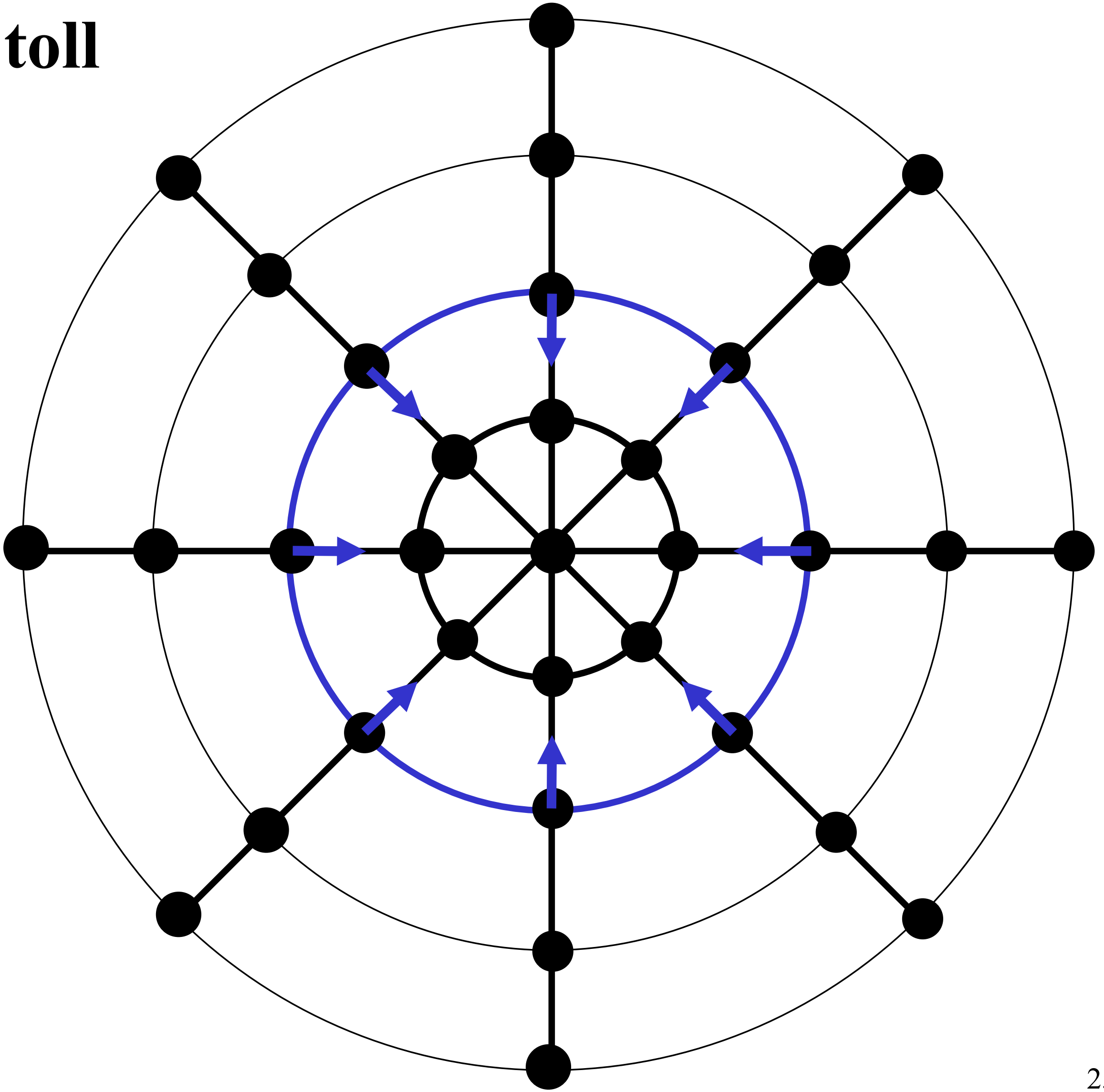
(a) % travelers gaining from step toll

(b) Mean change in consumer's surplus/trip from step tolls

(c) % travelers gaining from flat toll

(d) Mean change in consumer's surplus/trip from flat tolls

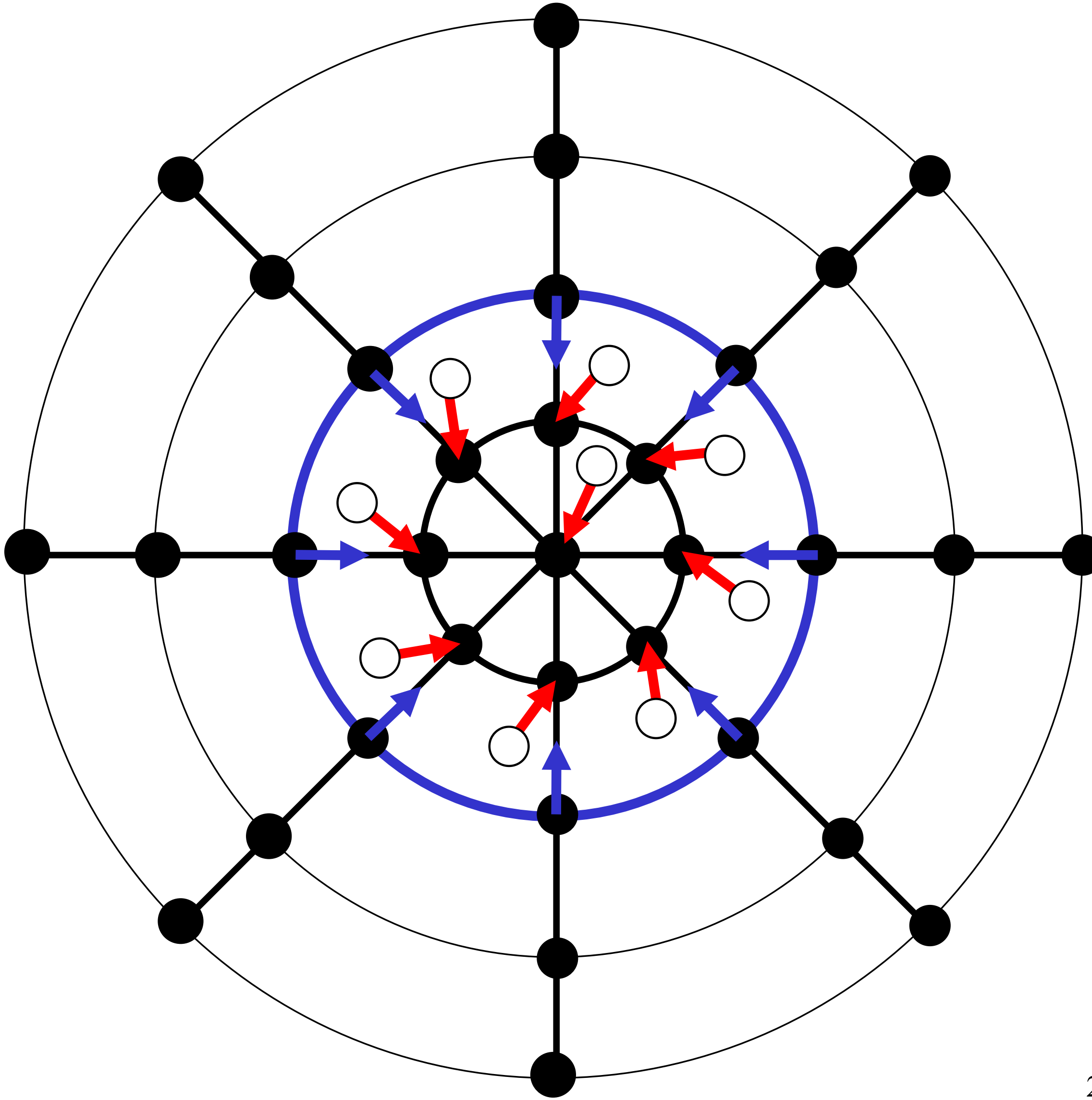
Cordon toll



Welfare impacts of cordon tolls

Regime:	No-toll	Comprehensive		Cordon	
		Five-minute step	Flat	Flat	Half-hour step
Optimal toll level(s)		5 min. step tolls on all links except In4, Out4, Ring 4	**In**: $0.73, $2.15, $2.00, $0.00 **Out**: $1.37, $1.06, $0.76, $0.00 **Ring**: $0.42, $0.51, $0.27, $0.00	$4.97	<6:30: $0.00 6:30-7:00: $0.90 7:00-7:30: $5.78 7:30-8:00: $4.39 8:00-8:30: $2.29 >8:30: $0.00
AutoShare	71%	69%	64%	66%	69%
Congestion	38.5%	4.8%	11.0%	21.2%	16.1%
VehKm [10^3]	279.6	280.0	255.4	264.5	276.4
Travel cost	$5.16	$5.56	$6.33	$5.65	$5.35
Welfare gain/capita		$204.84	$94.14	$47.22	$89.80
Toll revenue/capita		$215.08	$333.81	$168.01	$121.10
Welfare gain/revenue		0.952	0.282	0.281	0.742
Relative welfare gain		100%	46%	23%	44%
Gainers no rebate		29%	11%	37%	41%
Gainers100% rebate		83%	67%	71%	75%
Rebate: 50% gain		33%	78%	16%	10%
St. dev. of CS change		1.123	1.191	1.127	0.76

Area toll



Welfare impacts of area tolls

Regime:	No-toll	Comprehensive		Cordon		Area	
		Five-minute step	Flat	Flat	Half-hour step	Flat	Half-hour step
Optimal toll level(s)		5 min. step tolls on all links except In4, Out4, Ring 4	**In**: $0.73, $2.15, $2.00, $0.00 **Out**: $1.37, $1.06, $0.76, $0.00 **Ring**: $0.42, $0.51, $0.27, $0.00	$4.97	<6:30: $0.00 6:30-7:00: $0.90 7:00-7:30: $5.78 7:30-8:00: $4.39 8:00-8:30: $2.29 >8:30: $0.00	$4.30	<6:30: $0.00 6:30-7:00: $0.93 7:00-7:30: $4.41 7:30-8:00: $3.24 8:00-8:30: $1.71 >8:30: $0.00
AutoShare	71%	69%	64%	66%	69%	63%	67%
Congestion	38.5%	4.8%	11.0%	21.2%	16.1%	16.2%	14.9%
VehKm [10^3]	279.6	280.0	255.4	264.5	276.4	253.4	266.9
Travel cost	$5.16	$5.56	$6.33	$5.65	$5.35	$6.59	$6.04
Welfare gain/capita		$204.84	$94.14	$47.22	$89.80	$72.13	$125.36
Toll revenue/capita		$215.08	$333.81	$168.01	$121.10	$337.88	$229.10
Welfare gain/revenue		0.952	0.282	0.281	0.742	0.213	0.547
Relative welfare gain		100%	46%	23%	44%	35%	61%
Gainers no rebate		29%	11%	37%	41%	13%	21%
Gainers100% rebate		83%	67%	71%	75%	56%	67%
Rebate: 50% gain		33%	78%	16%	10%	81%	32%
St. dev. of CS change		1.123	1.191	1.127	0.76	1.01	0.891

5. Conclusions

Conclusions…

Main findings

Superiority of step tolls vs. flat tolls:

- Higher welfare gains ($\cong$ 2x)
- Lower revenues (transfers)

$\Rightarrow$ More favorable to travelers

Conclusions…

Extensions

1. Link tolling
2. Real networks → Paris, Zurich, Brussels, Seoul, Tokyo, …
3. Heterogeneous VOT and schedule delay costs
4. Evening travel
5. Toll discounts to enhance acceptability
6. Use of revenue (acceptability, self-financing, etc.)

Molino model in « REVENUE » (ε charge, competition, revenues, risk & PPT) for a dynamic Engineering/Accounting CBA

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