The Welfare Costs of Urban Traffic Regulations

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Motivation

- Rise in regulations to reduce road traffic externalities:
  - Traffic congestion
  - Pollution (CO_2, PM, NO_X)
- Two standard policies:
  - Driving restrictions (license-plate digits, car vintage...)
  - Road tolls (uniform, distance based, ...)
- Questions:
  - How large are the costs of urban traffic regulations?
  - What is the best policy instrument?

This paper

- We build and estimate a structural model that represents individual transportation decisions and traffic conditions
- Application: Paris metropolitan area ("Île-de-France")
- Measure welfare costs of hypothetical traffic policies:
  - Simple driving restrictions
  - Fixed and per km tolls
  - (in the paper) Quota of driving licenses allocated through an auction
  - (in the paper) Vintage-based driving restrictions
- (in the paper) Investigate how to mitigate the policy costs

Scope of the model

The model has two components:

- Choice of a transportation mode and departure period (peak/non-peak hour)
  - Trips' origins, destinations and routes are fixed
  - Focus on non-avoidable trips
- Area-specific congestion technology for road traffic
  - Represents how speed changes with road traffic
  - Consider 3 areas: city center/close suburb, ring roads, highways

Car speeds and number of drivers are equilibrium outcomes

Why endogeneize traffic congestion?

- Change in speed modifies the incentives to drive
- Travel time gains mitigate the welfare costs of regulations

Overview of the results

- Peak hour policies are costly for individuals:
  - Substitution to other modes/non-peak hour costly
  - Gains in speed only partly mitigate the costs
- If the tax revenue is fully redistributed, some policies are welfare improving
- Tolls dominate driving restrictions because they generate tax revenue

Related literature

Structural models of transportation decisions:

- Lucinda et. al (2017, JTEP): Welfare effects under fixed congestion
- Basso and Silva (2014, AEJ): Endogenous congestion over a representative road

Reduced-form models of congestion:

- Couture et al. (2018, ReStat): Determinants of speed
- Li et al. (2020, AEJ), Anderson (2014, AER): Exogenous shocks to identify congestion technology

Structural "bottleneck" models of congestion:

- Arnott et al. (1990 JUE, 1993 AER): Theory framework
- Hall (2019, JEEA): Distributional effects of road pricing
- Kreindler (2020, WP): Effects of congestion charges using experimental data
- De Palma et al. (1997): METROPOLIS traffic model

Outline

1. Transportation mode choice model

2. Congestion technology

3. Analyzing different toll levels

4. Comparing across policies

Model

- Discrete choice nested logit model
- Sequential decision
  1. Choice of a mode $\in$ {car, public transport, motorbike, bicycle, walk}
  2. For car and public transport: choice between peak and non-peak hours
- We estimate parameters of the utility function:

$$U_{njt} = \beta_{njt} + \gamma_n \log(\text{duration}_{njt}) + \alpha \times \text{cost}_{nj} + \zeta_{nj} + \sigma\epsilon_{njt}$$

  - Indexes: individual n, mode j and period t
  - $\zeta_{nj} + \sigma\epsilon_{njt}$ iid and extreme value distributed
  - σ: degree of independence between peak & non-peak hour
- Individuals choose the mode that maximizes utility within their choice set
- We can express the probability to choose a transportation mode for each individual
- Estimate the model parameters to maximum the likelihood of the sample

Data on transportation decisions

Survey data from 2010-2011: “Enquête Globale de Transport”

Restrict to study and work-related trips (non-avoidable trips), first trip of the day, trips $\geq$ 700 meters

$\Rightarrow$ 12,973 choices, representing 4 million individuals (1/3 population)

Departure periods defined as:

- Peak hour = 7:00-8:59 a.m
- Non-peak hour = before and after, in the morning

Expected car durations obtained from TomTom API

Expected public transport duration and itinerary from Google Maps

More about queries

Overcrowding in public transport

- Average occupancy rate in a metro line:

$$\text{overcrowding}_{l,t} = \frac{\text{No. passengers/hr}_{l,t}}{\text{Metro capacity}_l \times \text{No. metro/hr}_{l,t}}$$

  - l = metro line
  - t = period: peak or non-peak hour

- Individual trip overcrowding level:

$$\overline{\text{overcrowding}}_{n,t} = \sum_{l=1}^{L} w_{nl} \times \text{overcrowding}_{l,t}$$

  - w_{nl} = % of individual's trip duration in the metro line l

▸ Data and estimates

Descriptive statistics

- Average trip distance = 12.9 km
- Average trip duration = 34.8 minutes
- 82% of individuals hold a car, 35.2% choose to drive
- Peak hour chosen by: 65% of drivers, 67.6% of pub. transit users
- Driving at peak hour is on average 30% slower
- Pub. transit overcrowding: non-peak hour = 107%,
  peak hour : 167%
- Average cost = €0.9, average driving cost = €1.17,
  average pub. transit cost = €1.25

Estimation results: mean coefficients

Variable	Est.	Std. err.
Log(duration)	-1.87**	0.06
Cost	-0.35**	0.019
Bicycle	-3.4**	0.087
Public transport, peak	-1.13**	0.101
Public transport, non-peak	-1.83**	0.266
Motorized 2-wheel	-3.77**	0.157
Car peak - mean	-2.67**	0.155
Car non peak	-3.76**	0.175
No. layovers in public transport	-0.42**	0.036
Railway only	-0.011	0.057
Public transport overcrowding	-0.108**	0.026
σ	0.895**	0.075

*Significance level: **1%. Duration in minutes, cost in €. Standard errors computed using the delta-method.*

Heterogeneity parameters: ▸ Additional estimates

Estimation results: Summary

- Value of travel time (€/hr):

Min	Q1%	Mean	Median	Q99%	Max
1.03	2.43	14.3	9.61	78	388

Note: weighted using the survey weights.

▸ VOT by income

- Elasticities: Probability of driving with respect to trip duration:

	Peak	Non-peak
Duration peak	-1.43	0.76
Duration non-peak	0.4	-1.73

Note: weighted using the survey weights.

▸ Distributions

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Congestion technology

- How the speed changes with traffic density:

$$\text{speed}_t^a = f^a(\text{occupancy}_t^a)$$

  - speed_t^a at time t in area a (in km/hr)
  - occupancy is the measure of car density = fraction of the time (in %) during which the street is occupied by a vehicle
  - f^a technology in area a to be estimated

- f^a approximated by Bernstein polynomials of degree L:

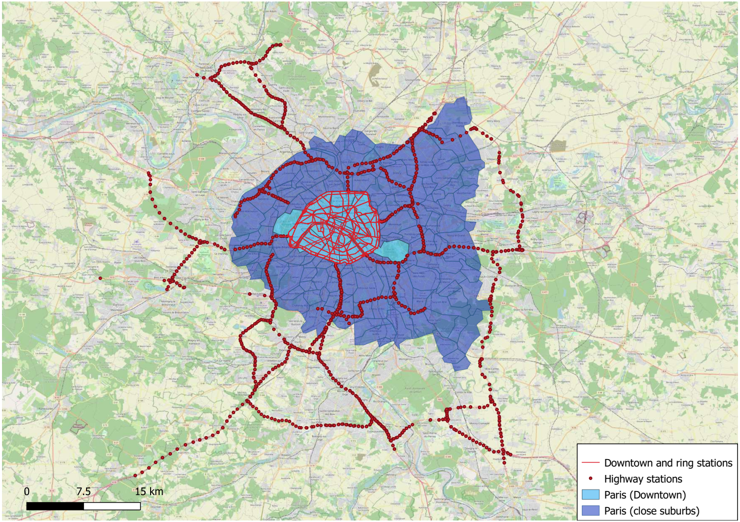
$$f^a(\text{occupancy}_t^a) = \sum_{l=0}^{L} B^l(\text{occupancy}_t^a).\theta_l^a$$

B^l: basis Bernstein polynomials of degree L

θ_l^a: parameters to be estimated

- We rely on hourly traffic data from 1,285 remote sensors over 2016-2017

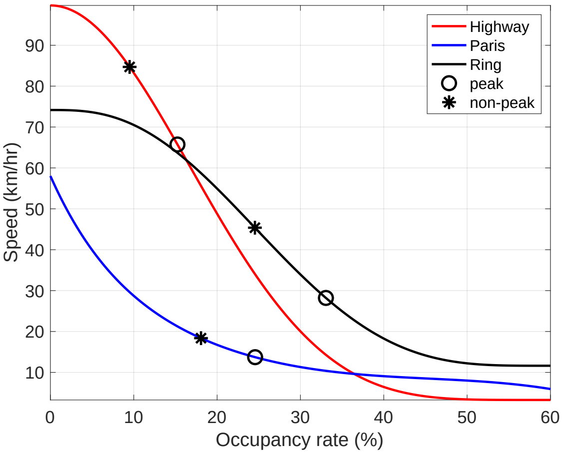
Traffic data



Location of remote sensors in Paris area

Sources: DRIF (highways) and "Mairie de Paris" (city center and ring roads)

Estimated congestion technology



Note: Initial traffic conditions = average speeds from TomTom predicted durations.

From individual decisions to traffic conditions

- We assume the following mapping:

$$\text{occupancy rate}^{\text{peak},a} = \phi^a \times N^{\text{peak},a} + \gamma^a$$
$$\text{occupancy rate}^{\text{non-peak},a} = \phi^a \times N^{\text{non-peak},a} + \gamma^a$$

  - ϕ^a: scale parameter
  - γ^a: irreducible traffic (trucks, delivery cars, buses...)

  - $\frac{\hat{\gamma}^a}{\text{occupancy rate}^{\text{peak, a}}}$ = 0% for highways, ring roads
  - $\frac{\hat{\gamma}^a}{\text{occupancy rate}^{\text{peak, a}}}$ = 15.4% for city center
  - $\frac{\hat{\gamma}^a}{\text{occupancy rate}^{\text{peak, a}}}$ = 37.7% for close suburb

Cost of congestion

What is the deadweight loss from congestion?

Assume (unrealistically) that speed = maximum speed

Total surplus improves by **€5.68 million** per trip and day

It corresponds to €1.76 per potential driver

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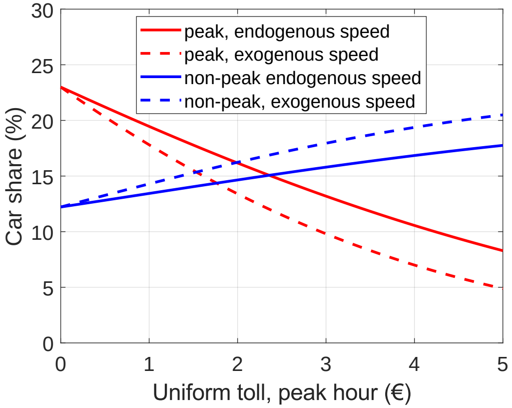
Car shares

Policy: uniform toll at peak-hour

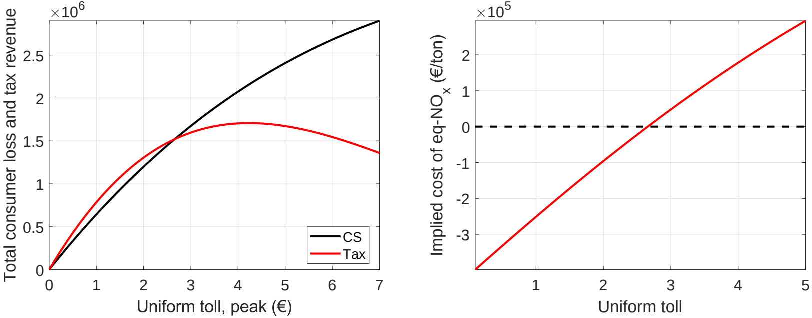


Predictions of our model vs. exogenous durations

▸ Change in speeds

Consumer surplus, tax revenue and emissions

Policy: uniform toll at peak-hour



(a) Welfare loss and tax revenue **(b)** Implied cost NO_X reduction

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Driving restrictions vs. tolls

Policies at peak-hour only

Driving restriction: ban randomly 50% of the cars

$\rightarrow$ with probability 50%, car at peak hour $\notin$ choice set

Tolls: uniform price or per kilometer

$\rightarrow$ Increase car trip cost by the toll amount, at peak hour

Calibrate policies to get same traffic reduction (39.4%) at peak hour:

- Fixed toll: 2.71€ ($\sim$ 2.3 $\times$ av. driving cost)
- Variable toll: 0.31€/km, av. price = 3.54 €, max. price = 44 €

▸ Modal shift

Driving restrictions vs. tolls: individual surplus

	Driving restriction	Fixed toll	Variable toll
% ΔCS > 0	0.529	0	14.3
% ΔCS < 0	79.2	79.7	65.4
Min ΔCS	-2.49	-2.17	-5.3
Max ΔCS	0.047	0	1.49
Total ΔCS (M€)	-1.27	-1.55	-1.64
ΔCS from speed	0.218	0.249	0.133
ΔCS, constant speed	-1.49	-1.79	-1.77
Tax revenue	0	1.53	1.06
Δ welfare	-1.27	-0.011	-0.577
Δ CO_2 (ton)	-308	-353	-642
Δ eqNO_X (ton)	-1.28	-1.47	-2.66
Implied cost local pollutants (€/ton NO_X)			
w/o redistribution	996,877	1,051,719	615,469
w. redistribution	996,877	7,818	216,500

Notes: ΔCS in €. Total ΔCS, ΔW and tax revenues in million €, computed using survey weights.

Results on durations

Driving restrictions vs. tolls: heterogeneity

	Driving restriction	Fixed toll	Variable toll
Age $\leq$ 18	-0.29	-0.361	-0.137
Age $\in$]18- 25]	-0.21	-0.266	-0.317
Age $\in$]25- 35]	-0.301	-0.362	-0.458
Age $\in$]35- 45]	-0.362	-0.432	-0.575
Age $\in$]45- 60[	-0.362	-0.433	-0.554
Age $\geq$ 60	-0.345	-0.411	-0.461
Estate $\leq$ 110,000	-0.354	-0.425	-0.47
Estate $\in$]110,000-152,000]	-0.378	-0.452	-0.506
Estate $\in$]152,000-205,000]	-0.342	-0.411	-0.448
Estate $\in$]205,000-283,000]	-0.286	-0.35	-0.356
Estate $>$ 283,000	-0.219	-0.278	-0.252
Independent	-0.334	-0.417	-0.542
White collar	-0.373	-0.431	-0.564
Blue collar	-0.309	-0.386	-0.479
Education $\leq$ high school	-0.297	-0.367	-0.144
Education > high school	-0.133	-0.179	-0.227
Family	-0.333	-0.404	-0.423
Single	-0.226	-0.273	-0.319
Average	-0.316	-0.383	-0.406

Notes: $\triangle CS$ in €.

Conclusion

Structural model for individual transportation decisions with endogenous car trip durations

Used to quantify the costs from driving restrictions and road tolls

Model is general and can be applied to predict the effects of various policies, find the optimal policy parameters for given regulator's objectives

Model can be extended to more driving areas, more periods

Queries

Car trip durations (TomTom):

- Queries done in July 2021
- Predictions for Thursday September 16th, 2021
- Peak hour: departure time = 8.30 a.m
- Non-peak hour: departure time = 6.30 a.m

Public transport duration and itinerary (Google Maps):

- Queries done on June 2nd, 2019
- Queries for Tuesday June 4th, 2019
- Departure time = 9.30 a.m

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Public transport overcrowding

- Combination of 3 datasets:
  - Metro card validations at the hour and metro station level
  - Number of trains per hour and line from schedules
  - Metro capacity by line

- Overcrowding by line:

Line	**Non-peak**	**Peak**
3Bis	0.3	0.59
1	0.86	1.43
4	1.13	2.03
13	2.15	2.67
A	1.26	2.81
Average	1.07	1.67

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Estimation results: heterogeneity of preferences

Variable	Est.	Std. err.
Log(duration) × real estate q2	-0.08	0.05
Log(duration) × real estate q3	-0.09	0.05
Log(duration) × real estate q4	-0.13*	0.05
Log(duration) × real estate q5	0	0.06
Log(duration) × Age ∈]18-25]	-0.32**	0.06
Log(duration) × Age ∈]25-35]	-1.06**	0.06
Log(duration) × Age ∈]35-45]	-1.1**	0.06
Log(duration) × Age ∈]45-60[	-0.9**	0.05
Log(duration) × Age ≥ 60	-1.25**	0.12
Non-peak hour × white collar	-0.64**	0.11
Non-peak hour × blue collar	0.19*	0.09
Non-peak hour × education ≤ high school	-1.13**	0.14
Non-peak hour × education > high school	0.03	0.11
Non-peak hour × family	-0.1*	0.05

*Significance level: **1%, *5%, †10%. Reference category is Age < 18, estate ∈ q1, independent worker, single.*

▸ Go back

Estimation results: Value of travel time

- $\text{VOT}_{njt} = \frac{\partial U_{njt}}{\partial \text{duration}_{njt}} \Big/ \frac{\partial U_{njt}}{\partial \text{cost}_{njt}} = \frac{\beta_n^{\text{duration}}}{\beta^{\text{cost}}} \times \frac{1}{\text{duration}_{njt}}$

Note: Estate cost per consumption unit (in €1,000).

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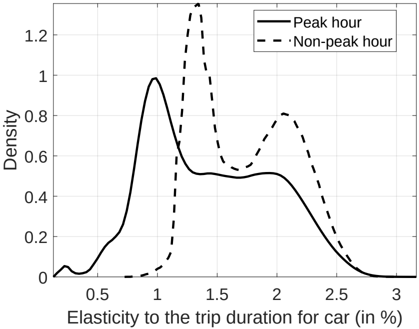
Elasticities to trip duration



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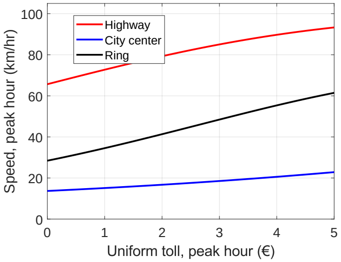
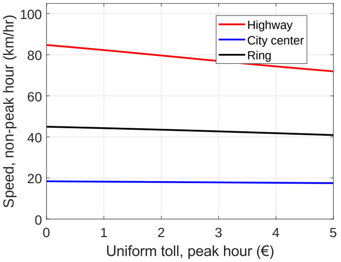
Speeds

Policy: uniform toll at peak-hour



(a) Speeds at peak hour



(b) Speeds at non-peak hour

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Shares of transportation modes

	Initial	Driving restriction	Fixed toll	Variable toll
Bicycle	2.09	2.42	2.42	2.21
Pub. transport, peak	30.3	32.1	32.4	32.9
Motorbike	2.07	2.45	2.47	2.6
Walking	15.8	17.6	17.8	15.9
Car, peak	23	14	14	14
Car, non-peak	12.2	16.1	15.5	16.5
Pub. transport, non-peak	14.6	15.3	15.5	15.8
Total car share	35.2	30.2	29.5	30.5
Total pub. transport share	44.8	47.4	47.8	48.8

Notes: in %.

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Driving restrictions vs. tolls: durations

	Driving restriction	Fixed toll	Variable toll
% Δduration > 0	53.1	54.3	46.9
% Δduration < 0	26.6	25.5	32.8
Min Δduration	-10.5	-12.8	-11.9
Mean Δduration	1	1.07	1.02
Max Δduration	37.9	37.9	78.5
Total Δduration (in 1,000 hrs)	67.4	71.7	68.8
Average speed, peak (km/hr)	33	33.3	35.4
Average speed non-peak (km/hr)	33.5	33.9	32.6

Notes: Durations are in minutes.

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