Spatial Environmental Economics
Lecture 10: Traffic

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Roadmap

1. Traffic Congestion and Externalities
2. Transportation Infrastructure
3. Urban Planning
   - Road Closure in Paris (Bou Sleiman, 2024)
   - LEZ in Germany (Sarmiento et al., 2023)
   - Congestion Pricing in NYC (Cook et al., 2025)

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Traffic congestion

- Feedback between economic activity and the efficiency of a transportation network
  - **Traffic** is the amount of transportation that passes through each transportation link each given amount of time (e.g. cars/hour)
  - **Traffic congestion** happens if the flows of goods or people or other endogenous variables affect the intensity/cost of the link
- In our model notation, we can for example write

$$\tau_{ij} = \bar{t}_{ij} L_{ij}^{\lambda}$$

  - τ_{ij} is the cost of moving people between locations i and j
  - $\bar{t}_{ij}$ measures the exogenous transportation infrastructure
  - L_{ij} is the traffic on a given link (in this case, number of people)

Estimating congestion

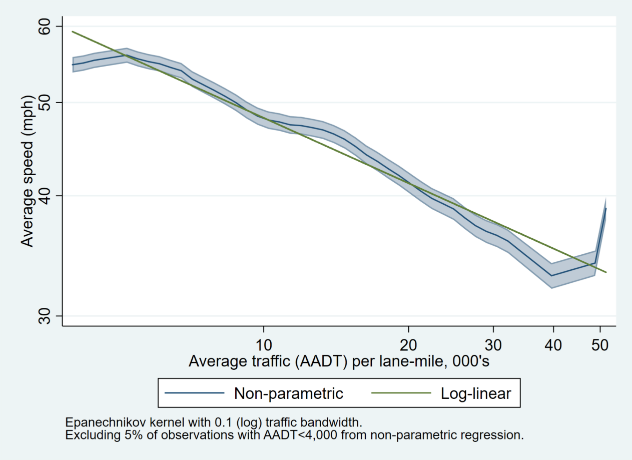
- A large literature estimates

$$\ln speed_{ij} = \lambda_0 - \lambda \ln\left(\frac{traffic_{ij}}{lanes_{ij}}\right) + \varepsilon_{ij}$$

  - $speed_{ij}$ is for example average km/h of vehicles moving through the link
  - $traffic_{ij}$ is the number of vehicles per unit time, e.g. average vehicles per day
  - $lanes_{ij}$ is the number of existing lanes in the link
  - λ is the congestion elasticity
  - λ_0 is the average speed without congestion
  - ε_{ij} measures link-specific unobserved determinants of speed

Estimating congestion

- This log-linear relationship between speed and traffic holds in the data (with $\lambda = 0.226$):



Notes: Speed of travel using a routing API. AADT (Annual average daily traffic) from US Department of Transportation. Source: Arkolakis (2024)

From estimates to model

- Notice that this is consistent with our model if we assume $traffic_{ij} = L_{ij}$ and

$$\tau_{ij} = \frac{distance_{ij}}{speed_{ij}}$$

- Replacing:

$$\tau_{ij} = \underbrace{\frac{distance_{ij}}{\exp\left(\lambda_0 + \varepsilon_{ij}\right) lanes_{ij}^{\lambda}}}_{\bar{t}_{ij}} L_{ij}^{\lambda}$$

External costs of congestion

- Congestion creates several externalities, such as:
  - Time delays
  - Vehicle capital depreciation
  - Accidents
  - **Air pollution**
  - **Noise pollution**

Air pollution and noise pollution

- Heavy traffic often generates poor air quality
  - Estimates from health studies indicate that living within 50m−100m of a major road significantly increases disease health risk and mortality
- Traffic can generate extreme noise levels
  - Alert levels >65-80 dB. Oftentimes measured at 90+ dB
- Recent technological advancements have led to cleaner air and lower noise in big cities
  - E.g. elimination of lead in gas, catalysts, better combustion engines, electrical cars
  - Important factor in re-population of major cities
  - However, ought to be vigilant. Reversal may happen when regulations relax

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Traffic congestion and road investment

- Building more roads may or may not improve congestion
  - People could start using more cars exactly where the road improves
  - Also people could relocate to regions with better infrastructure
- In our model $\tau_{ij} = \bar{t}_{ij} L_{ij}^{\lambda}$:
  - Adding lanes decreases $\bar{t}_{ij}$
  - But L_{ij} responds endogenously, potentially offsetting the change in $\bar{t}_{ij}$
- Duranton and Turner (2011): "the fundamental law of road congestion"
  - Estimate effect of lane kilometers of roads on vehicle-kilometers traveled (VKT) in US cities
  - Find that VKT increase proportionally - no congestion relief!
  - Sources for extra VKT: more driving by current residents, more commercial traffic, migration

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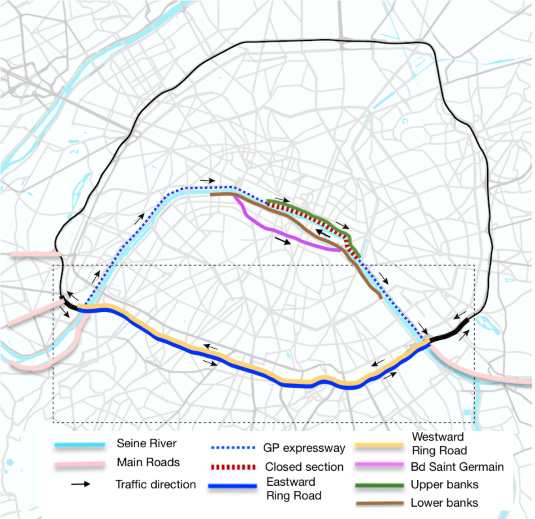
Pedestrianization of urban streets

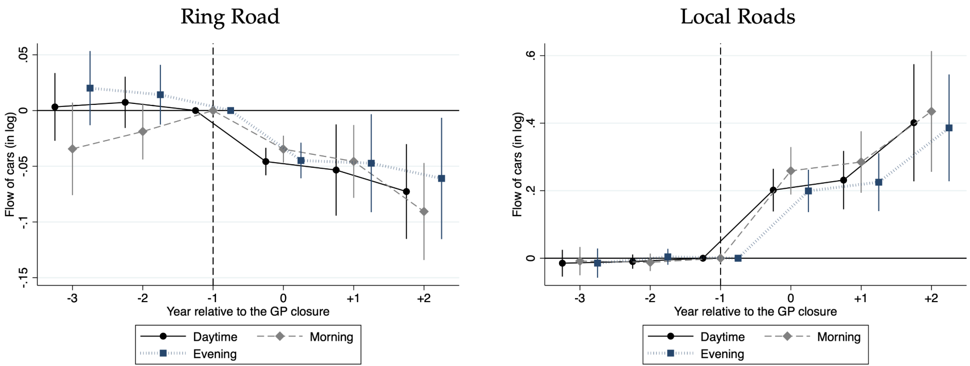
- Road pedestrianization policies
  - Defined as removing or reducing car access to certain roads
  - Used to reduce the external effects of traffic congestion
  - For example, "superblocks" in Barcelona
- Concern: policies may just shift congestion and pollution to alternative areas (leakage!)
- Bou Sleiman (2024) studies one such policy in Paris
  - Permanent closure in 2016 of a 3.3 km segment of an expressway along the Seine's riverbank
  - How did it impact traffic in substitute roads? And pollution?

The Georges Pompidou (GP) expressway and its substitutes



- The GP expressway crossed the city flowing eastward
- How to identify potential substitutes and controls?
- Substitutes: local and ring roads flowing in the same eastward direction
  - Local roads: Boulevard Saint Germain, upper banks
  - The ring road (Boulevard Périphérique)
- Controls: westward counterparts (thus sharing same engineering characteristics)

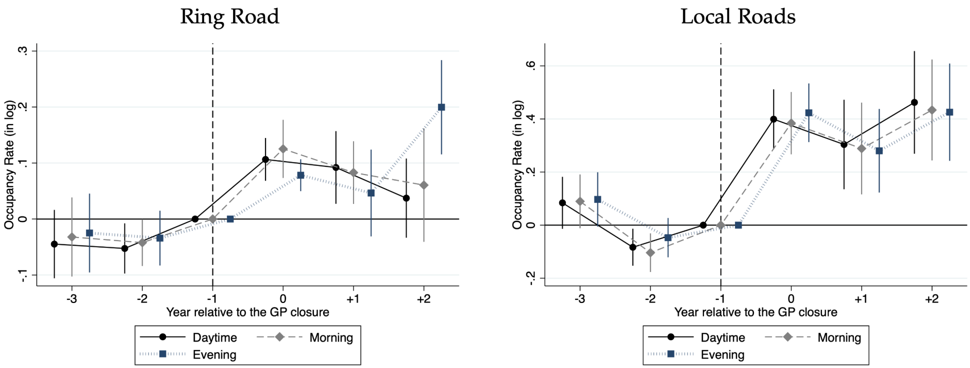
Impact on the flow of cars



Notes: estimates and 95% confidence intervals.

- Cars/hour fell by 6% on the ring road and increased by 26% on local roads
- Why the sign difference? If congested enough, adding more vehicles to a road can reduce speed and therefore flows

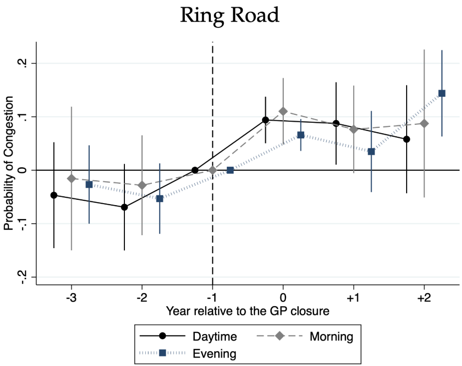
Impact on the occupancy rate

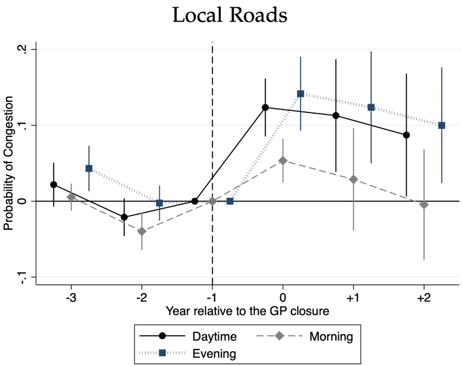


Notes: estimates and 95% confidence intervals.

- Occupancy rate: % of the day that a segment of the road is occupied by vehicles
- Occupancy rates increase by 11.2% on the ring road and by 34% on local roads

Impact on the probability of congestion

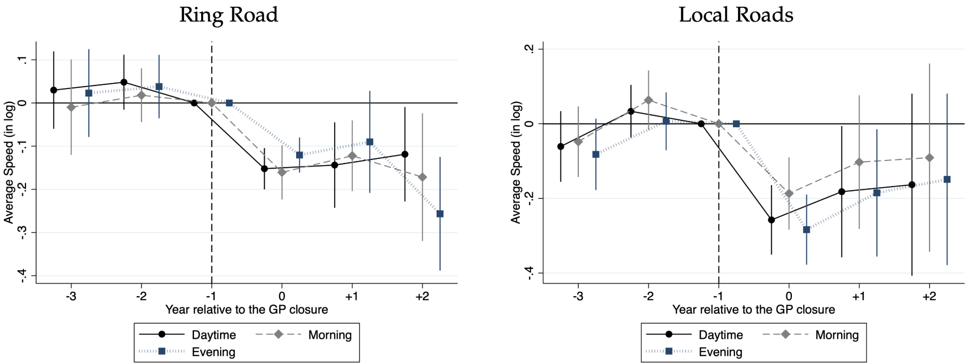




Notes: estimates and 95% confidence intervals.

- Congested if occupancy exceeds occupancy level where the flow of cars starts to fall
- Probability of congestion increased by 21% and 50% for ring and local roads, respectively

Impact on the average speed



Notes: estimates and 95% confidence intervals.

- Average speeds fall by 16.5% on the ring road and 17.5% on local roads
- Consistent with congestion worsening in all substitute roads

Impact on air pollution

	(1)	(2)	(3)	(4)
	NO_2 emissions (in log)			
	Ring Roads			
Speed (in log)	-0.293***	-0.275***	-0.346***	-0.256***
	(0.019)	(0.018)	(0.021)	(0.022)
Flow (1000 v/h)	0.043***	0.034***	0.077***	0.073***
	(0.003)	(0.003)	(0.006)	(0.006)
Constant	6.053***	5.502***	5.579***	5.214***
	(0.100)	(0.100)	(0.104)	(0.108)
Observations	75,51	7,551	7,551	7,551
R^2	0.249	0.349	0.406	0.417
	Upperbanks			
Speed (in log)	0.062***	0.064***	-0.084***	-0.091***
	(0.023)	(0.022)	(0.020)	(0.020)
Flow (1000 v/h)	0.361***	0.367***	0.357***	0.290***
	(0.010)	(0.010)	(0.017)	(0.017)
Constant	5.440***	5.181***	5.376***	5.470***
	(0.076)	(0.079)	(0.069)	(0.068)
Observations	10,170	10,170	10,170	10,170
R^2	0.336	0.373	0.536	0.559
Weather Characteristics	Yes	Yes	Yes	Yes
Month of Sample FE	No	Yes	Yes	Yes
Hour FE	No	No	Yes	Yes
Day of the week FE	No	No	No	Yes

* p<.10, ** p<.05, *** p<.01

- First estimate the elasticity of Nitrogen Dioxide (NO_2) with respect to the average speed (table)
- Then combine it with impacts on speed to calculate change in pollution
- Find: NO_2 concentration increased by 5.8% near ring road and 1.5% near local roads

Bou Sleiman (2024): additional results and discussion

- Additional results
  - Housing prices fall 5% within 700m radius of the periphery (captures other pollutants, noise)
  - Higher-income commuters bear 60% of time cost, lower-income 90% of pollution cost
  - Most commuters live outside the jurisdiction responsible for the closure
- Discussion
  - How should we value the amenity benefits of the closure? Tourism benefits?
  - What was the impact on accidents?
  - What about part-time closures?

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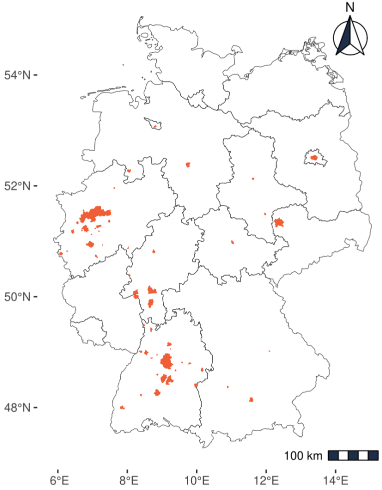
Low emission zones (LEZ)

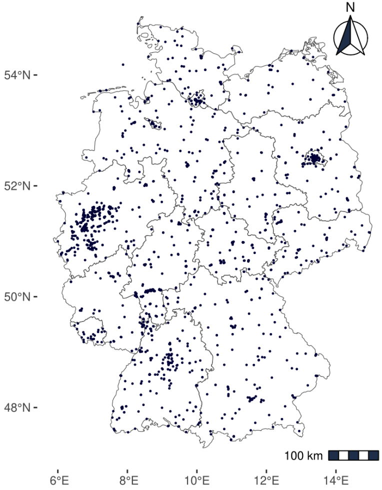
- LEZ are an increasingly popular policy tool for reducing traffic-related emissions in cities
  - They restrict vehicle access to certain geographical areas based on emission intensity
  - Between 2019-22, the number of active LEZs in Europe increased from 228 to 320 (+40%)
- The **health benefits** of reduced traffic-related pollution are well understood
- However, this may be too narrow a **scope** for evaluating these policies
  - Effect on overall air quality beyond traffic-related pollution?
  - Impacts on air pollution in unregulated areas (i.e., spatial spillovers)?
  - Well-being costs associated with restricted mobility?

Sarmiento et al. (2023) widen the scope

- Question: What is the impact of LEZ on
  - pollution,
  - health outcomes, and
  - self-reported well-being?
- Setting: LEZ introduced between 2008 and 2018 across German cities
- Data: units of observation are either
  - air-pollution measurement stations or
  - individuals from the Socio-Economic Panel Study (SOEP)

Spatial distribution of LEZs and pollution monitors





Notes: LEZ introduced between 2008 and 2018 (left) and air pollution monitors active in the period 2005-2018 (right).

Challenges in estimating the impact of LEZ, and how they address them

1. **Staggered adoption** means it is not obvious which units we would want to use as control
   - They use the CS difference-in-differences (DID) estimator (Callaway and Sant'Anna, 2021)
   - This estimator compares, in each period, "Treated"-"Not Yet Treated" and "Treated"-"Never-Treated" units
   - Prevents issues with a naive DID regression ("two-way fixed effects estimator")
     - ⋆ Which implicitly also compares "Treated"-"Earlier Treated" units
     - ⋆ Would bias the estimates towards zero because e.g. pollution falls in "Earlier Treated" units
2. **Spatial spillovers** would mean that untreated units are also affected by the LEZ
   - Buffer design: exclude all controls within 25 km of LEZs
3. **Comparability** of treatment and control units
   - Doughnut design: restrict outer edge of control group to 75 km

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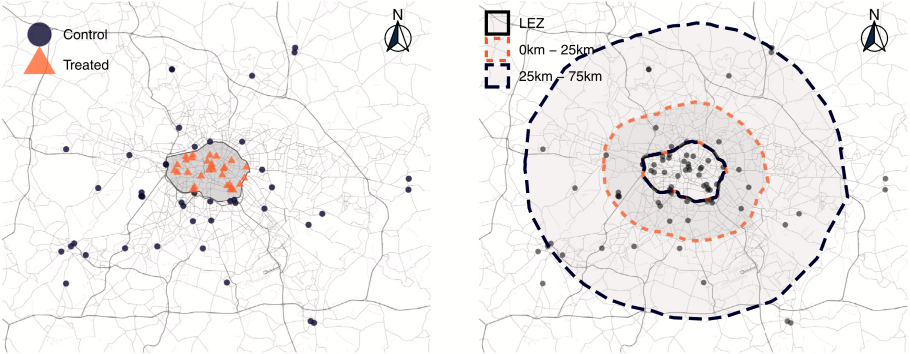
Example: treated and control groups in Berlin LEZ



(a) Raw **(b)** Spatial Restrictions

Fig. 7. Definition of treated and control stations in the CS-DD design (Berlin low emission zone).
Notes: The left panel shows the raw design's definition of treated and control stations. The right panel illustrates the two restriction areas we use to refine the econometric specification. In the buffer design, we exclude all controls within 25 km of LEZs to avoid spatial spillovers threatening the validity of SUTVA. In the doughnut design, we increase the comparability of treatment and control units by restricting the outer edge of the control group to 75 km. The buffers in the map are on a scale of 1-to-4.

LEZ impact on air pollutants

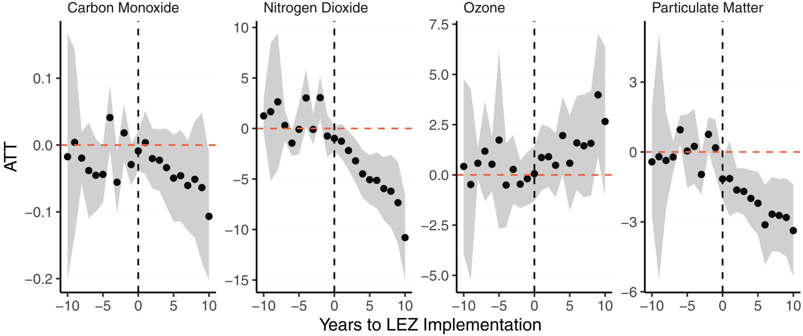


Fig. 8. Event-time ATTs.
Notes: Event-time CS-DD estimates for the impact of LEZs on annual air pollutant concentrations. Event time is measured in years before/after policy implementation. Treated stations are inside the zones. Control stations are between 25 and 75 km from the zones' borders. Gray ribbons represent 95% confidence intervals. We cluster standard errors at the municipality level. Ozone (O_3), nitrogen dioxide (NO_2), and coarse particulate matter (PM_{10}) reported in micrograms per cubic meter (μg/m^3) and carbon monoxide (CO) in milligrams per cubic meter (mg/m^3).

- LEZs decrease the concentrations of PM_{10} and NO_2, and effectiveness increases over time
- But they increase ozone (O_3) concentrations!

Spillovers in air pollution concentration outside LEZs

Spillovers across different control samples.

(a) Carbon monoxide (CO)

	Raw	Buffer	Doughnut	CAAP
	0.032*	0.036*	0.028*	0.045**
	(0.015)	(0.015)	(0.013)	(0.016)
N.Obs	1252	1075	878	874
N.Stations	185	149	122	119
N.Groups	8	8	8	8
N.Periods	14	14	14	14

(b) Nitrogen dioxide (NO_2)

	Raw	Buffer	Doughnut	CAAP
	−0.068	0.048	−0.035	0.916
	(0.641)	(0.664)	(0.726)	(0.894)
N.Obs	4423	3622	2873	2507
N.Stations	418	342	266	237
N.Groups	8	8	8	8
N.Periods	14	14	14	14

(c) Ozone (O_3)

	Raw	Buffer	Doughnut	CAAP
	1.485*	1.494*	1.561*	1.411+
	(0.640)	(0.663)	(0.704)	(0.817)
N.Obs	3379	2718	2148	1523
N.Stations	313	254	199	148
N.Groups	8	8	8	8
N.Periods	14	14	14	14

(d) Coarse particulate matter (PM_{10})

	Raw	Buffer	Doughnut	CAAP
	−0.338	−0.246	−0.053	0.044
	(0.366)	(0.399)	(0.426)	(0.524)
N.Obs	3897	3212	2612	2211
N.Stations	387	317	253	224
N.Groups	8	8	8	8
N.Periods	14	14	14	14

Notes: CS-DD estimates for the impact of LEZs on annual air pollution concentrations for stations between 0 and 25 km from the zones' borders. We provide estimates of four different specifications of the control group. The raw control sample contains all stations further away than 25 km. The buffer excludes all stations within a 25 km buffer zone. The doughnut further excludes from the buffer sample all stations further away than 100 km from LEZs. And the CAAP only considers stations in CAAP cities. Standard errors clustered at the municipality level. Significance levels denoted by $^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$; $^{+}p < 0.10$. Ozone (O_3), nitrogen dioxide (NO_2), and coarse particulate matter (PM_{10}) reported in micrograms per cubic meter (µg/m^3) and carbon monoxide (CO) in milligrams per cubic meter (mg/m^3).

- Increases in the concentration of O_3 and CO outside the zones' borders
- Suggestive evidence of increases in PM_{10} and NO_2

LEZ impact and spillovers on overall air quality

Effectiveness and spillovers of LEZ introduction on the air quality index (AQI).

	Inside LEZ	Outside LEZ			
		Raw	Buffer	Doughnut	CAAP
	−5.438***	−0.635	−0.677	−0.475	−0.584
	(1.349)	(0.941)	(1.042)	(1.108)	(1.256)
N.Obs	2968	4814	3970	3118	2679
N.Stations	276	447	366	283	249
N.Groups	8	8	8	8	8
N.Periods	14	14	14	14	14

Notes: CS-DD estimates for the impact of LEZs on annual average AQI values for stations inside and outside LEZs. For inside stations, treated units are inside the zone and controls between 25 and 75 km from the zones' borders. For outside stations, treated units are between 0 and 25 km from the zones' borders and we provide results for four different specifications of the control group. The raw sample contains all stations further away than 25 km, the buffer excludes all stations within a 25 km buffer zone, the doughnut further excludes from the buffer sample all stations further away than 100 km from LEZs, and the CAAP only considers stations in CAAP cities. Standard errors clustered at the municipality level. Significance levels denoted by $^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$; $^{+}p < 0.10$.

- Even with the rise in O_3, AQI increases
- Spillovers: AQI falls, but the impacts are imprecisely estimated

LEZ impact on life satisfaction

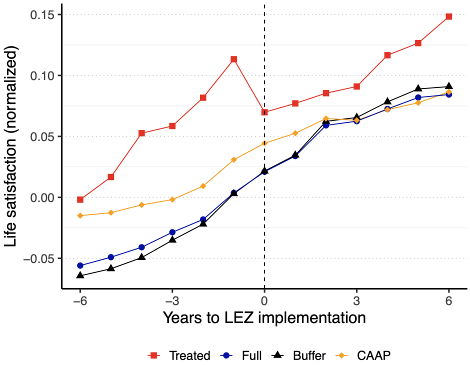


Figure A.6: Average life satisfaction of treated and control individuals

Notes: This figure shows annual averages of life satisfaction between treated individuals and different control groups. The vertical axis contains the average of life satisfaction, expressed in terms of standard deviations, and the horizontal axis the time to treatment in years to LEZ implementation. The treated group contains all individuals residing inside LEZs. The full control group control group includes all individuals residing outside LEZs, the buffer sample restricts the control group to individuals living further away than 25km from LEZs, and the CAAP sample further restricts the control group to persons living in cities with a CAAP but no LEZ. Each data point corresponds to the average value of all possible event-time combinations across treatment and control groups six years around policy adoption.

LEZ impact on life satisfaction

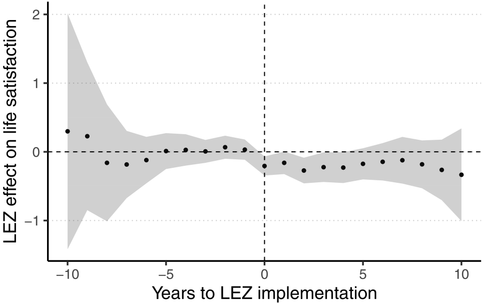


Fig. 12. Dynamic effects on life satisfaction.
Notes: Dynamic CS-DD point estimates and 95% confidence bands on the impact of LEZs on the life satisfaction of individuals living inside a LEZ. The sample of control individuals is restricted to residences further than 25 km away from the nearest LEZ. Standard errors clustered at the household level.

- Life satisfaction of individuals living inside a LEZ decreases by 0.2 points after policy adoption (approx. 20% of the effect of becoming unemployed)
- Drop in life satisfaction is immediate, lasts for several years, but is ultimately transient
- Also find evidence of improvement in health outcomes (hypertension cases)

Spillovers on well-being and health

LEZ spillovers in well-being and health.

	LS	Doctor visits	Hypertension	Cancer
ATT	-0.196^{***}	0.493	0.003	-0.002
	(0.044)	(0.475)	(0.010)	(0.005)
N.Obs	32782	32671	32782	32782
N.Individuals	10518	10508	10518	10518
N.Groups	4	4	4	4
N.Periods	5	5	5	5

Notes: CS-DD estimates of the impact of LEZs on the life satisfaction and health outcomes of individuals living between 0 and 25 km from LEZs. The control group consists of individuals living further away than 25 km away from the nearest LEZ. Standard errors clustered at the household level. Significance levels denoted by $^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$, $^{+}p < 0.1$.

- Similar-sized reductions in life satisfaction for individuals dwelling near a LEZ
- Health outcomes for these individuals show no significant changes
- $\Rightarrow$ bear the costs of restricted mobility but do not benefit from improvements in air quality

Heterogeneous LEZ effects

- Declines in life satisfaction are especially pronounced for owners of diesel cars
  - The engine class facing the most stringent restrictions
- Larger reductions in life satisfaction for working-age individuals
- Older people also accrue most of the health benefits
- Public transport quality and accessibility may mitigate the negative life satisfaction effects

Sarmiento et al. (2023): summary

- Study life satisfaction and air quality impacts of low emission zones (LEZs)
- LEZs improve air quality despite increases in ozone and pollution spillovers
- LEZs cause transitory yet long-lasting reductions in life satisfaction
- Well-being effects of restricting mobility may outweigh those of improved health

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Congestion pricing

- We have discussed extensively how Pigouvian taxes can address externalities
  - Congestion externalities arise because each extra vehicle slows down every other vehicle
  - In addition, there are environmental externalities
  - A congestion tax or price can help internalize these externalities
- But congestion pricing faces opposition, typically with two kinds of concerns:
  1. It will not change traffic flows in the long run
  2. It will induce harmful economic impacts, including unfair burdens on lower-income individuals
- Still, congestion pricing is implemented in cities such as London, Stockholm, and Milan
- We will discuss the effects of congestion pricing in New York City (NYC)

Cook et al. (2025): "the short-run effects of congestion pricing in NYC"

- In January 2025, NYC became the first US city to implement congestion pricing
  - Applied to vehicles entering the central business district (CBD)
  - Passenger vehicles are assessed a $9 toll during peak hours
  - Higher prices for vans and trucks
  - Lower prices for taxis and during the remaining off-peak hours
- Question: how did the policy affect road speeds, travel times, and emissions throughout the NYC metropolitan area?
- Approach:
  - Use data from Google Maps Traffic Trends spanning Sept. 2024 - Feb. 2025
  - Compare traffic conditions with 5 most similar US cities
  - Evaluate the impact on roads segments with high "co-occurrence" with the CBD

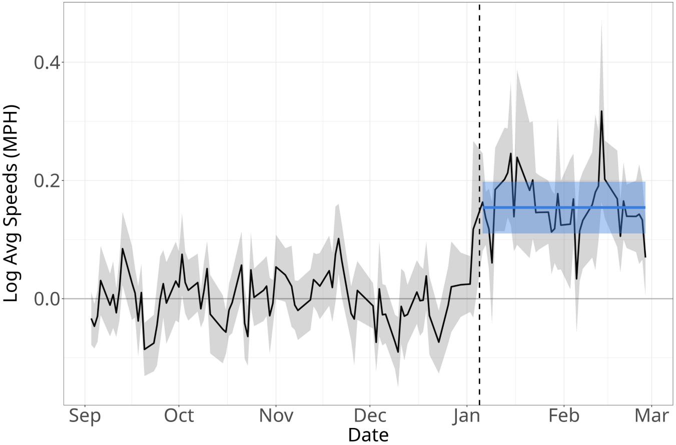
Synthetic control

- We could compare outcomes before and after the congestion price was implemented
- But that conflates the impact of the policy with any time trends in traffic patterns
  - In other words, a causal interpretation requires assuming that absent the policy, NYC traffic conditions after January would have been similar to earlier periods
- To address this, the authors build a **synthetic control** formed from other cities
  - Use 5 similar cities: Philadelphia, Boston, Chicago, Atlanta, and Baltimore
- Intuition:
  - Average outcomes between cities to construct a "synthetic NYC"
  - Weights in the average are chosen so NYC and "synthetic NYC" are as similar as possible pre-policy

Measuring impacts beyond the CBD

- Ex-ante, the direction of possible spillovers on non-CBD road segments is ambiguous
  - Positive if it reduces the total number of trips throughout the city
  - Negative if non-CBD roads are used as substitutes for driving to/from the CBD
- As in Bou Sleiman (2024), we want a way to identify roads that may be indirectly affected
- Cook et al. (2025) do this by calculating each road segment's pre-policy **co-occurrence**
  - Co-occurrence = what fraction of cars passing through a segment eventually enter the CBD
  - E.g., a segment has co-occurrence of 50% if half of the cars that typically traversed it prior to the policy eventually entered the CBD
- Co-occurrence is then a continuous measure of non-CBD roads' exposure to the policy

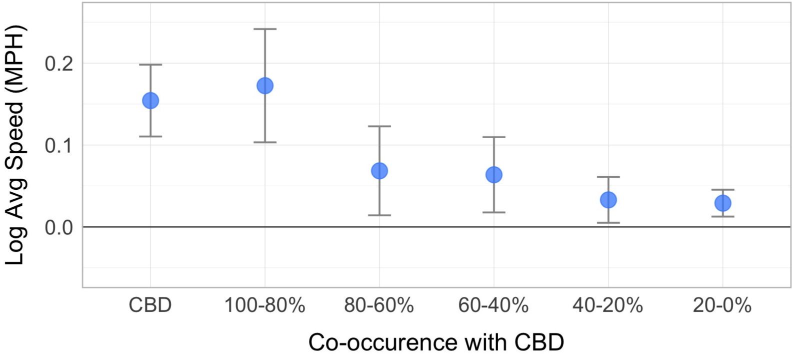
Speeds within the CBD



Notes: Difference in peak-hour weekday speeds, relative to the synthetic control. Shade is 95% confidence interval.

- Congestion pricing led to an immediate and persisting increase in average speeds

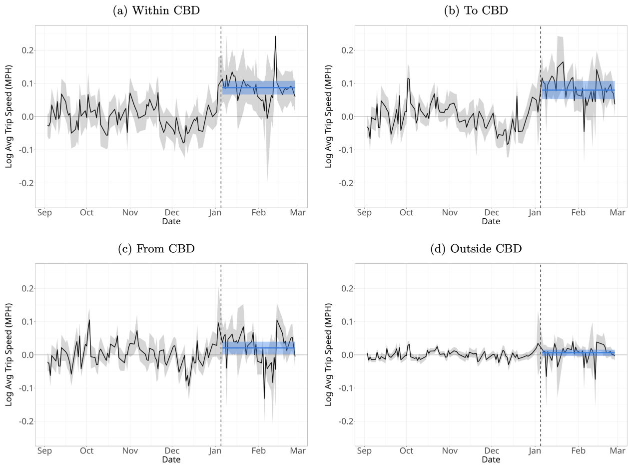
Spillovers on non-CBD roads



Notes: Estimates split by levels of co-occurrence. Vertical lines are 95% confidence intervals.

- Positive spillovers on speeds throughout the NYC metropolitan area

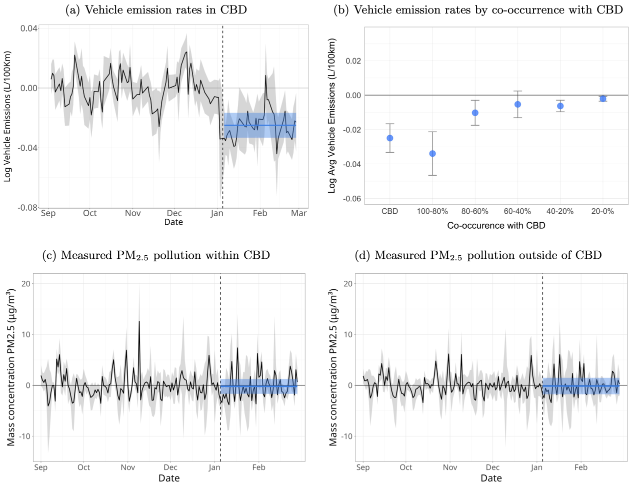
Effect on trip speeds



Notes: Estimates split by origin-destination category. Only "to CBD" are taxed.

- Gains in road speeds add up to meaningful drops in travel times, even for untaxed trips

Effect on emissions



Notes: CO_2 intensity inputed with engineering model for standard mid-size sedan.

- CO_2 emissions drop in CBD and high-co-occurrence roads, but no change in $PM_{2.5}$

Additional results and discussion

- Distributional effects?
  - They find that the increase in speeds is similar for every income quintile
  - Neighborhoods closer to the CBD benefit the most
- How much should we trust the impacts on emissions?
  - They do not observe vehicle types
  - Emission-reduction benefits may materialize in the longer term if fleet composition adjusts (recall LEZ effects on air pollutants in Sarmiento et al., 2023)
- How is congestion pricing different from driving restrictions and car-free zones (e.g. LEZ, pedestrianization)?
  - It raises revenue, that can be used to fund public transit (Almagro et al., 2024)
  - It is less likely to be poorly targeted

Appendix

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