Zero fare, cleaner air? The causal effect of Luxembourg's free public transportation policy on transport emissions

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Introduction

- In March 2020, Luxembourg became the first country to implement ***free public transport for everybody across all modes***

  $\longrightarrow$ Intention: reduce car density and associated negative externalities

- **RQ:** What are the effects of this policy on transport emissions?
- Identification challenges:
  1. Luxembourg is special
  2. COVID-19 - and associated variation in mobility patterns
- Data on emissions: IPCC-sector 1.A.3.b Grided emission data from EDGAR
- Unit of analysis: NUTS 2 level
- Method: Synthetic Difference in Differences (SDID) (Arkhangelsky et al., 2021)
- **Results**: ATT of around $-$**6% on CO_2** transport emissions

Policy Background

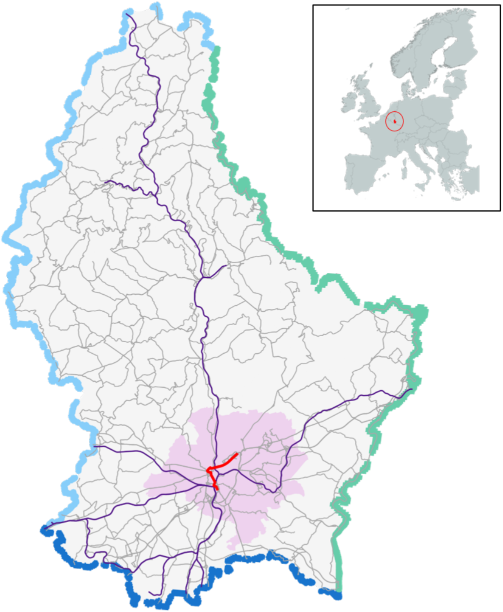
Intention of free-fares: reduce car density and associated negative externalities

Before the free-fare policy:

- Annual ticket revenues ∼41 Mio. EUR (∼8% of operating costs)
- Differentiated fares based on the duration and length of travel
- Special rates for children and the elderly were available
- Short-term tickets (2 hours): 2 EUR
- Long-term tickets for 1, 2, and 3 days ranged from 4 to 12 EUR
- Annual subscriptions: 440 EUR

Luxembourg's public transport system:

- Buses are predominant mode. 400 bus lines connect the country.
- Trains connect LU in a star-like network with neighbouring countries, originating from Luxembourg City.
- One tram line in Luxembourg City

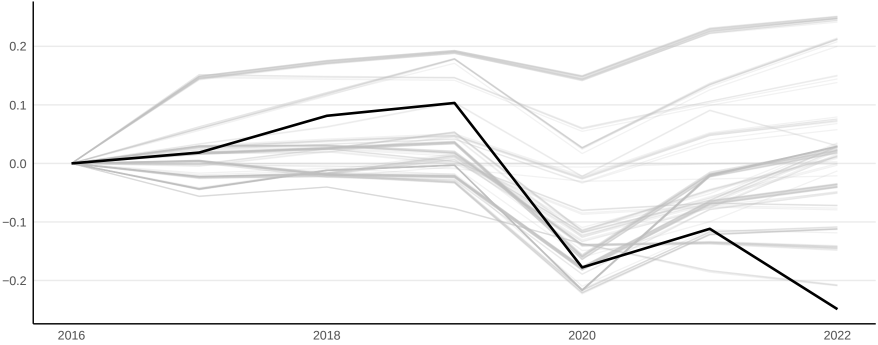


tram extensions

Literature

- Tallinn 2013
  → Cats et al. (2017) find increased PT usage, limited effect on car usage.
- 9-EUR ticket (2022) in DE
  → Aydin and Kürschner Rauck (2023) and Gohl and Schrauth (2024) find improvements in air quality during weekdays, when commuting activity is highest.
  → Liebensteiner et al. (2024) find increased train travel during leisure hours, only marginal reduction in car use.
- "Deutschlandticket" (2023, successor of 9-EUR ticket)
  → Ariadne-Projekt (2025) shows car kilometers reduced by around 5%; Krämer and Korbutt (2026) find a reduction in car use of 8.8% in the greater Hamburg area.
  → Daniel et al. (2026) only find a short-term effect on car use.
- Evidence for China shows
  → that lower fares improve air quality (Liang & Wang, 2025), while
  → higher fares worsen it (Yang & Tang, 2018).

Evolution of CO_2 road transport emissions from LU



LU reduction over period 2020 to 2022: 20.5%.

How much because of free fares?

grids

Luxembourg is special

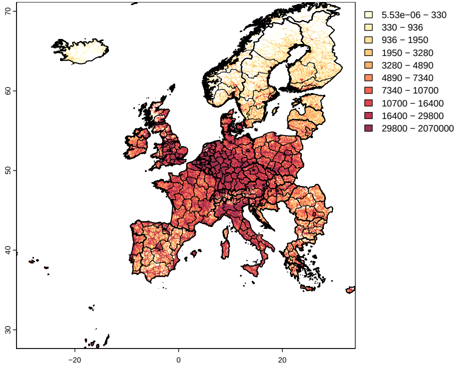
- Size: 2,586.4 km^2
- Population: $\approx$ 660,000
- GDP/capita: $\approx$ 140,000 USD (highest in EU)
- Car density: $\approx$ 700 cars per 1,000 inhabitants (highest in EU)

Solution:

- Unit of analysis: NUTS 2 level
- Use SDID, which combines characteristics of both SC and DID. Advantage:
  - → no comparable levels assumption in any stage
  - → time weights

Road transport emission data

- Data at NUTS 2 level: The European Database Global Atmospheric Research (EDGAR) database provides annual sector-specific grid maps expressed in tons substance with a spatial resolution of 0.1 degrees $\times$ 0.1 degrees.



Set up

Sample

- 45 NUTS 2 units: predominantly Urban NUTS 2 units + balanced panel + excluding bad controls ▸ details
- pre-treatment period 2016 to 2019; post-treatment period 2021-2022

Main threat: COVID-19

$\longrightarrow$ Has mobility behavior in LU changed differently compared to other regions?

- COVID-19 cases ▸ details
- Working from home ▸ details
- Omit 2020

Other threats

- Fuel prices, energy efficiency of new vehicles, freight volume
- Commuting inflows and relative fuel prices ▸ details

Synthetic DiD

Synthetic DiD combines features of both DiD and SC methods.

- Like DiD, it is invariant to additive unit-level shifts
- Like SC, it weighs and matches pre-treatment trends to reduce reliance on parallel-trends assumption

Synthetic DiD re-weighs **both units and time periods.**

- Unit weights to match pre-treatment trends between exposed and unexposed units.
- Time weights assign higher weights to pre-treatment time periods that are similar to post-treatment time periods.

Synthetic DiD

$$\left(\widehat{\tau}^{sdid}, \widehat{\mu}, \widehat{\alpha}, \widehat{\beta}\right) = \underset{\tau,\mu,\alpha,\beta}{\arg\min} \left\{ \sum_{i=1}^{N} \sum_{t=1}^{T} (Y_{it} - \mu - \alpha_i - \beta_t - W_{it}\tau)^2 \widehat{\omega}_i^{sdid} \widehat{\lambda}_t^{sdid} \right\}$$

Synthetic Control

$$\left(\widehat{\tau}^{sc}, \widehat{\mu}, \widehat{\beta}\right) = \underset{\tau,\mu,\beta}{\arg\min} \left\{ \sum_{i=1}^{N} \sum_{t=1}^{T} (Y_{it} - \mu - \beta_t - W_{it}\tau)^2 \widehat{\omega}_i^{sc} \right\}$$

DiD

$$\left(\widehat{\tau}^{did}, \widehat{\mu}, \widehat{\alpha}, \widehat{\beta}\right) = \underset{\tau,\mu,\alpha,\beta}{\arg\min} \left\{ \sum_{i=1}^{N} \sum_{t=1}^{T} (Y_{it} - \mu - \alpha_i - \beta_t - W_{it}\tau)^2 \right\}$$

Unit weights are computed to align pre-treatment trends between treated and control units:

$$\left(\widehat{\omega}_0, \widehat{\omega}^{sdid}\right) = \underset{\omega_0 \in \mathbb{R}, \omega \in \Omega}{\arg\min} \sum_{t=1}^{T_{pre}} \left(\omega_0 + \sum_{i=1}^{N_{co}} \omega_i Y_{it} - \frac{1}{N_{tr}} \sum_{i=N_{co}+1}^{N} Y_{it} \right)^2 + \zeta^2 T_{pre} ||\omega||_2^2.$$

Time weights are computed to align pre- and post-treatment periods of control units:

$$\left(\widehat{\lambda}_0, \widehat{\lambda}^{sdid}\right) = \underset{\lambda_0 \in \mathbb{R}, \lambda \in \Lambda}{\arg\min} \sum_{i=1}^{N_{co}} \left(\lambda_0 + \sum_{t=1}^{T_{pre}} \lambda_t Y_{it} - \frac{1}{T_{post}} \sum_{t=T_{pre}+1}^{T} Y_{it} \right)^2 + \zeta^2 N_{co} ||\lambda||^2.$$

- N_{co} and N_{tr} are the number of untreated and treated units.
- T_{pre} and T_{post} are the number of pre- and post-treatment periods.
- ζ is a regularization parameter to increase dispersion and ensure unique weights as defined in Arkhangelsky et al. (2021)

Handling covariates

We apply syhthetic DiD to **emissions adjusted** for covariates

Handling covariates in this setting is treated as a **pre-modelling approach**. Model with fixed effects is estimated only for **control regions** as suggested by Kranz (2022):

$$Y_{it}^{co} = \alpha_i + \gamma_t + X_{it}^{co}\beta + u_{it}, \tag{1}$$

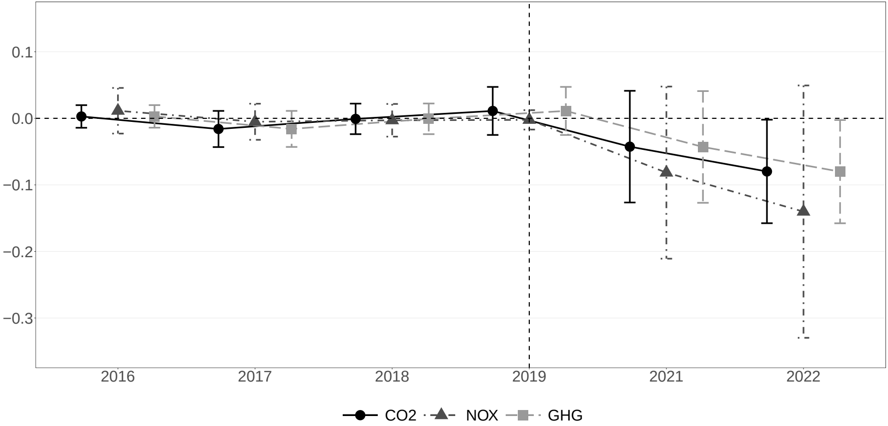
$$\widehat{Y}_{it}^{adj} = Y_{it} - X_{it}\hat{\beta}. \tag{2}$$

- GDP per capita (real)
- daily COVID cases and stringency index
- working from home
- emission intensity of new vehicles
- fuel price controls
- cross-border commuting inflows
- relative fuel price and cross-border commuting inflows interaction

Projected

Results - Event Study

- ATT of -6% for CO_2



weights ATTs inference robustness

Traffic counts: Data

Sources — automatic road traffic counters (motorways & major roads)

Countries

- **LU:** Administration des Ponts et Chaussées (open data portal)
- **DK:** Dataudveksleren (National Access Point)
- **NL:** National Road Traffic Data Portal (NDW)
- **FI:** Fintraffic Digitraffic TMS

Sample restrictions

- Full daily hours reported
- $\geq$90% of days covered per year
- $\leq$14 consecutive missing days
- Criteria met throughout **2019–2023**

Variable: monthly means of total daily traffic volumes for passenger-car-like vehicles, aggregated to NUTS 2 level via station metadata

Traffic counts: Loop Detectors

Figure: DK

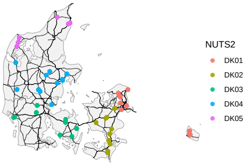


Figure: FI

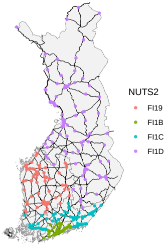


Figure: LU

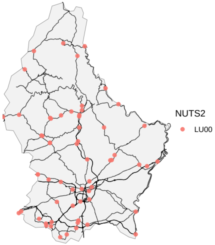
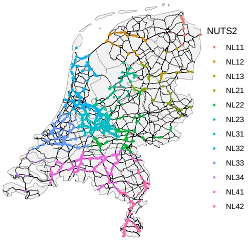
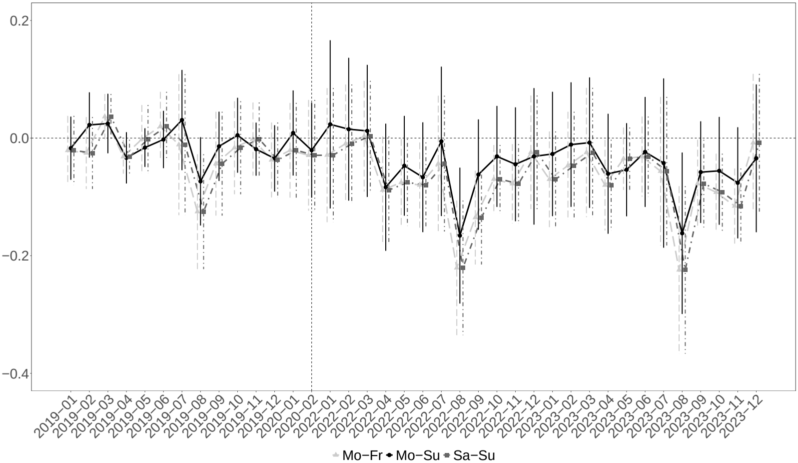


Figure: NL



Traffic counts: Event Study

- Mo−Su and Mo-Fr ATT of around 4.5%; ATT for weekend of around 6.9%



Discussion

Recap

- We estimate an *ATT of around* -6% *for* CO_2
- Results hold against robustness checks
- Analysis of traffic counts (and air quality) from station level data support our results

Mixed evidence on reduced fares need not be contradictory

- 9-Euro ticket did not lead to a substantial displacement of car usage
  $\longrightarrow$ plausibly because its short duration limited households' willingness to reorganize established mobility routines
- Findings on the effect of the more permanent "Deutschlandticket" are more mixed
  $\longrightarrow$ supply side constraints, uncertainty about future prices might play a role (introduced at EUR 49, then 58, now 63).

Permanent, cost-free access may provide the necessary **duration and certainty** for new transit habits to take root and remain resilient.

▸ back-of-the-envelope

Thank you

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https://eibinget.github.io

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Tram extensions

Table: Luxembourg's tram line expansions

Year	Type	Description
2017	New line	Opening of Luxembourg City tram line; 8 stations (3.5 km)
2018	Extension	3 additional stations (+1.6 km)
2020	Extension	4 additional stations (+2.0 km); December opening
2022	Extension	2 additional stations; September opening
2024	Extension	5 additional stations; July opening
2025	Completion	2 final stations added; direct link to Luxembourg Airport established

Note: The tram network currently spans 16 km, serves 24 stations, and includes 10 major interchanges (Luxtram, 2025).

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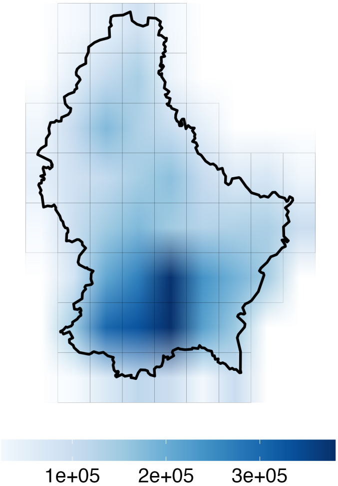
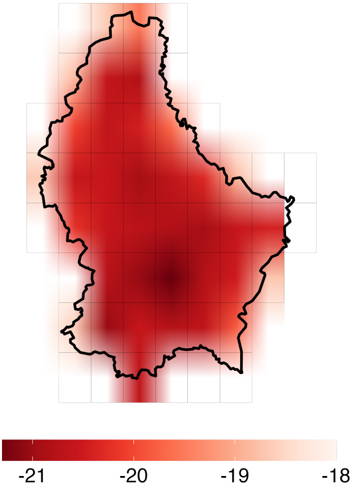
Evolution of road transport emissions from LU



((a)) Average Emissions 2016–2019



((b)) %-Change 2020–2022 vs. 2016–2019

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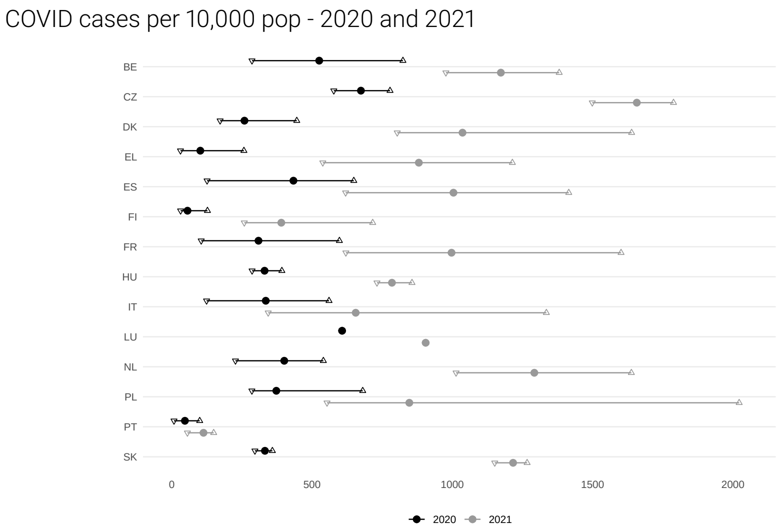
COVID-19: cases



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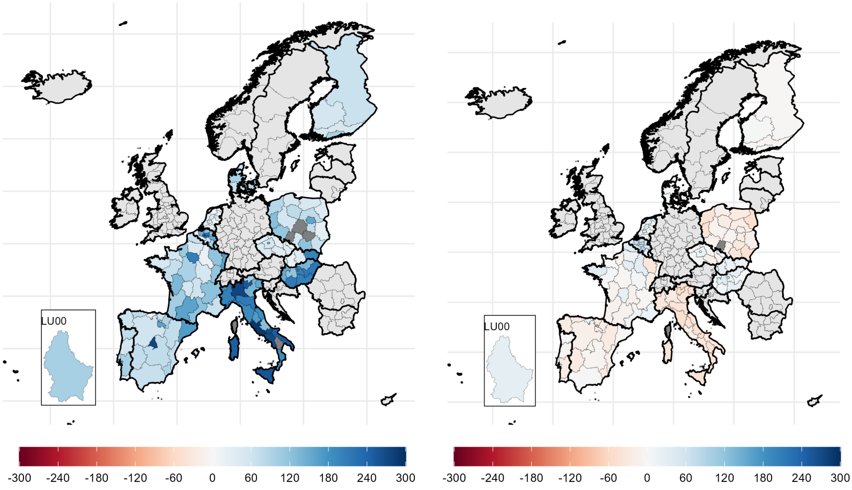
COVID-19: wfh

Change (%) usually wfh in country of residency: 2019-2020 and 2020-2021



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Relative fuel prices

Table: Pre- and post-treatment averages of relative fuel prices for Luxembourg

	Diesel		Petrol	
	Pre-Avg	Post-Avg	Pre-Avg	Post-Avg
BE	0.8171	0.8560	0.8829	0.9186
DE	0.8560	0.8834	0.8417	0.8503
FR	0.7972	0.8464	0.8239	0.8451

Note: Relative fuel prices of LU with respect to its neighboring countries. Pre-Avg are relative fuel prices based on time-weighted pre-treatment fuel prices, where time weights are taken from the SDiD main specification. Post-Avg are relative fuel prices based on post-treatment fuel prices.

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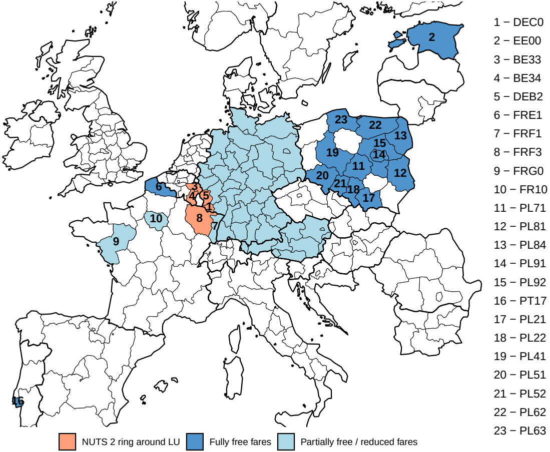
Bad comparisons and spillovers (2016-2022)

- Exclude NUTS 2 ring around LU
- Exclude regions that introduced fully free fares during sample period (2016-2021)



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Covariates projected

	(1) CO_2		(2) NO_x		(3) GHG	
	Coef.	SE	Coef.	SE	Coef.	SE
log(gdp)	0.4371***	(0.1255)	0.4020*	(0.2192)	0.4355***	(0.1256)
asinh(cases)	−0.0164**	(0.0070)	−0.0218***	(0.0060)	−0.0165**	(0.0069)
stringIndex	−0.0017***	(0.0006)	−0.000045	(0.0008)	−0.0017***	(0.0006)
log(some_wfh)	−0.2355**	(0.1024)	−0.2440	(0.1583)	−0.2360**	(0.1021)
log(usual_wfh)	−0.0354***	(0.0075)	−0.0229*	(0.0115)	−0.0353***	(0.0075)
ei	0.0052***	(0.0006)	0.0047**	(0.0021)	0.0051***	(0.0006)
log(dsl)	−0.8934***	(0.1244)	−1.0954***	(0.1004)	−0.8928***	(0.1242)
log(petrol)	0.5392***	(0.1212)	1.0221***	(0.1772)	0.5400***	(0.1208)
log(freight)	0.0201	(0.0116)	0.0152	(0.0328)	0.0201	(0.0116)
log(rel_diesel)	0.2545	(0.1952)	0.0255	(0.1580)	0.2549	(0.1948)
cb_inflow75	0.0020	(0.0092)	−0.0032	(0.0145)	0.0020	(0.0092)
cb_inflow75:log(rel_dsl)	−0.7050**	(0.3116)	−0.3069	(0.9579)	−0.7041**	(0.3112)
Obs	315		315		315	
N	45		45		45	

Notes: Dependent variable is $lco2cap$, standard errors are clustered at the regional level.

$^{***}p < 0.01; ^{**}p < 0.05; ^{*}p < 0.10$

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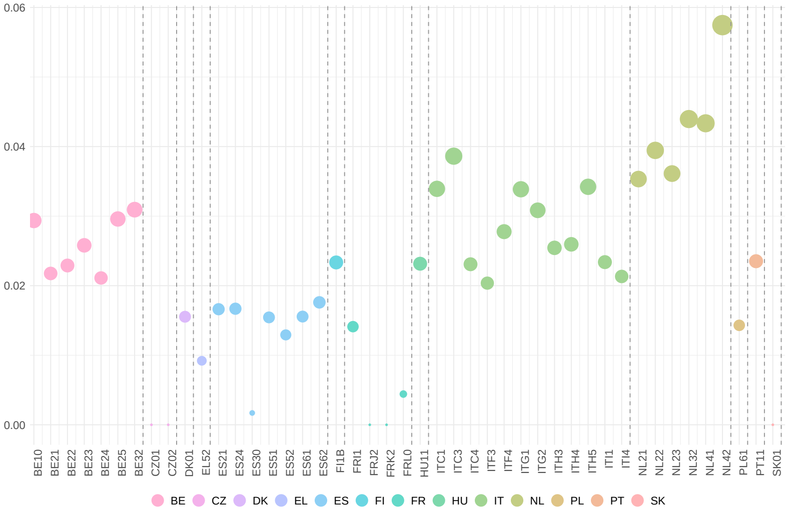
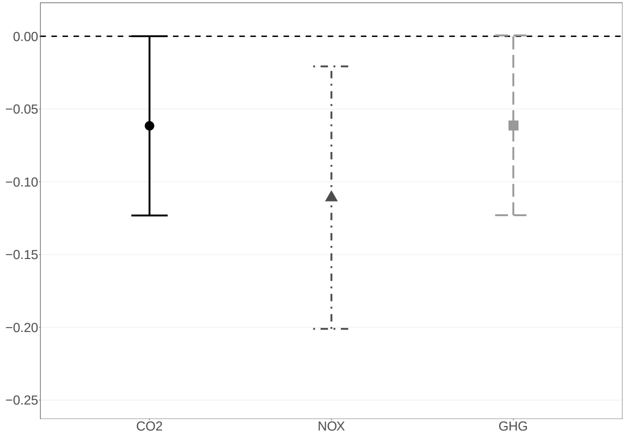
Weights for CO_2 specification



Time weights: 2016: 0.494, 2017: 0.063, and 2018: 0.443 back

Results: ATTs



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Placebo Inference

$\widehat{\tau}^{sdid}$ is asymptotically normal $\longrightarrow$ conventional CIs can be used if the asymptotic variance can be consistently estimated. $\tau \in \widehat{\tau}^{sdid} \pm z_{\alpha/2}\sqrt{\widehat{V}_\tau}$.

With $N_{tr} = 1$, we can use **placebo based inference**:

- Replace the exposed unit with unexposed units
- Randomly assign those units to a placebo treatment
- Compute a placebo ATT
- Repeat many times to obtain a vector of placebo ATTs

Event-study inference can be conducted by estimating:

$$d_t = (\bar{Y}_t^1 - \bar{Y}_t^0) - (\bar{Y}_{base}^1 - \bar{Y}_{base}^0).$$

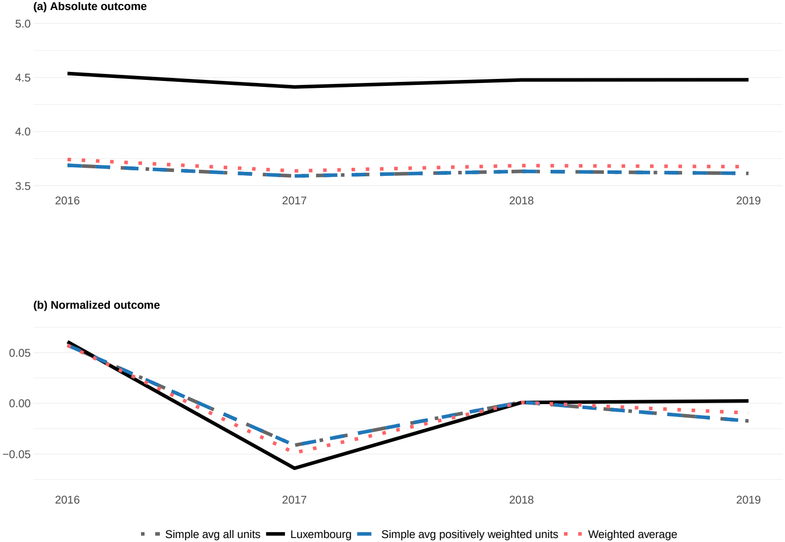
Confidence bands around these estimates can be generated with a placebo-based approach (Arkhangelsky et al., 2021; Clarke et al., 2024). back

Robustness

- Pre-trend with sdid weights ▸ details
- In-time placebo: 2018 treatment ▸ details
- Leave one out ▸ details
- Other sectors ▸ details
- Broader sample

▸ back

Trend comparisons - normalized



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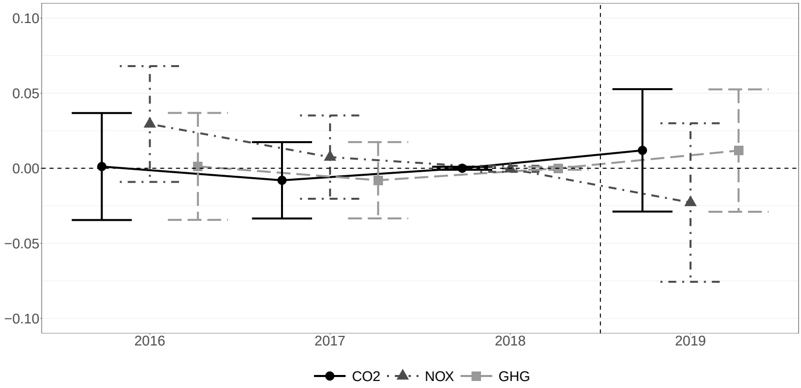
In-time placebo



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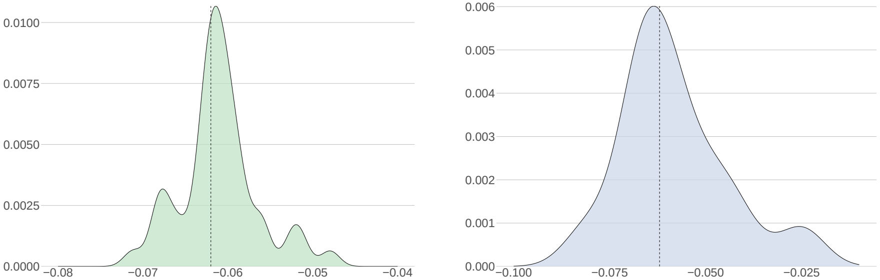
Leave one out



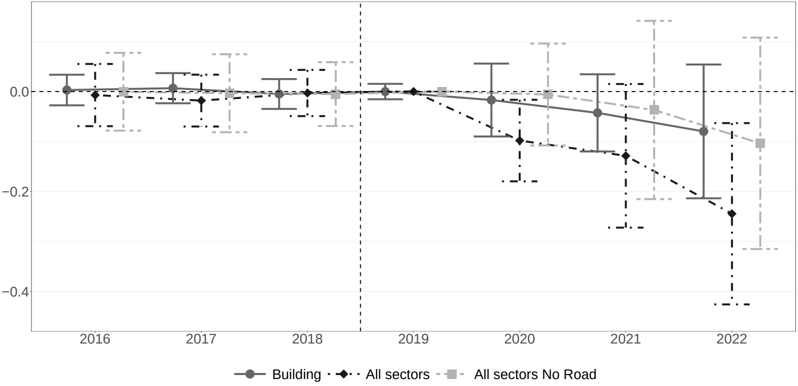
((a)) Dropping a region from the donor pool

((b)) Dropping a country from the donor pool

Figure: Distribution of ATT: leave one out analysis

▸ back

Other sectors



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Back of the envelope calculations

1. Effect size discussion

- Following figures from the Department of Transport, Directorate for Mobility Planning (2017), let us assume a modal split for private vehicles and public transport of around 82% and 18%
- Assume emission reduction is due to a modal change from private vehicles to public transport
  $\longrightarrow$ Estimated increase of public transport: $(\hat{\tau}\frac{82\%}{18\%}) \approx 27\%$.
- In line with LuxMobile survey: 34% increase in public transport usage due to the free-fare policy

2. Marginal abatement cost of carbon

- Foregone revenue from ticket sales of around 41 Mio. Euros
- Compare to CO2 abated according to our estimates:
  $\frac{1}{T_{post}} \sum_{t=T_{pre}+1}^{T} CO2_t^{tr} / (1 - \hat{\tau})$ $\longrightarrow$ EUR 155 per ton of carbon.

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