Low Emission Zones: Transition Technologies and the Value of Commitment

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- Initiated in Germany in 2008 (Berlin, Cologne, and Hanover)
- Increasingly popular policy instrument to accelerate adoption of EVs and hybrids:
  - today, more than 500 LEZs across Europe
  - also seen in Shangai, Beijing, Haifa, Seoul, Jakarta, etc.
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  - Madrid's LEZ covers just 5 km^2, but restricts all gasoline and diesel cars

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- Significant variation in their design:
  - Berlin's LEZ spans 88 km^2 and restricts not all gasoline and diesel cars
  - Madrid's LEZ covers just 5 km^2, but restricts all gasoline and diesel cars
- Why so much variation?
  - Should some cars be restricted more than others?
  - Should some cars (the transition technologies) be restricted later than others?
  - Ultimately, what is the optimal LEZ design?
  - And does it require of planner's commitment?

Links (and contributions) to the literature on...

- modeling (new and/or second-hand) car markets, e.g., Adda and Cooper (2000), Gavazza et al (2014), Gillingham et al (2022), Grieco et al (2024)
- estimating LEZ impacts, e.g., Wolff (2014), Galdon-Sanchez et al (2023)
- comparing price-based instruments (e.g., taxes, emissions trading) vs command-and-control (CAC) instruments (e.g., emission and technology standards), e.g., Ellerman et al (2000), Montero (2005)
  - but LEZs are a distinctive CAC instrument: its inefficient (proportional) rationing gives rise to convex welfare functions (see also Barahona et al, 2020)
  - this may introduce time-inconsistency problems, as in Coase (1972)

Motivating evidence: Madrid's LEZ or Madrid Central

- Madrid Central: announced in May 2018 and enforced in November 2018
- Hybrids and EVs are exempt...was it a good idea?

Roadmap

- Reduced-form empirical analysis
  - Impact of Madrid Central mainly on greater adoption of hybrids
- A simple dynamic model of car choice
  - First-best solution (useful benchmark)
  - Optimal LEZ design (size and exempt technologies)
  - What makes (or not) hybrids a transition technology in a LEZ context
  - Does it require commitment from the social planner?

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  - What makes (or not) hybrids a transition technology in a LEZ context
  - Does it require commitment from the social planner?
- Structural analysis
  - estimation: in progress
  - policy-design counterfactuals: in progress

Empirical analysis: Data (sales of new units, 2015-2020)

Figure: Trends of EVs and hybrids adoptions: Madrid vs. rest of Spain

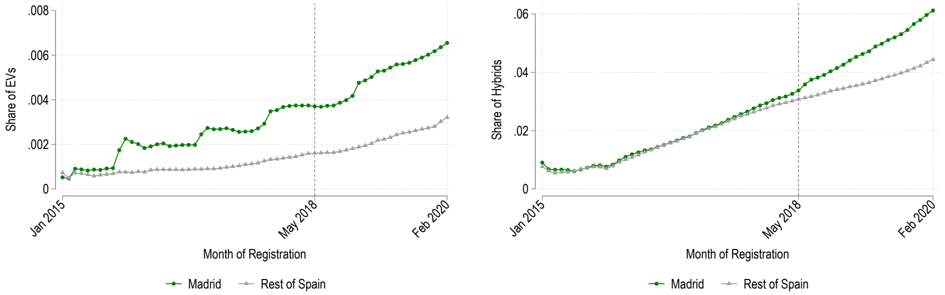

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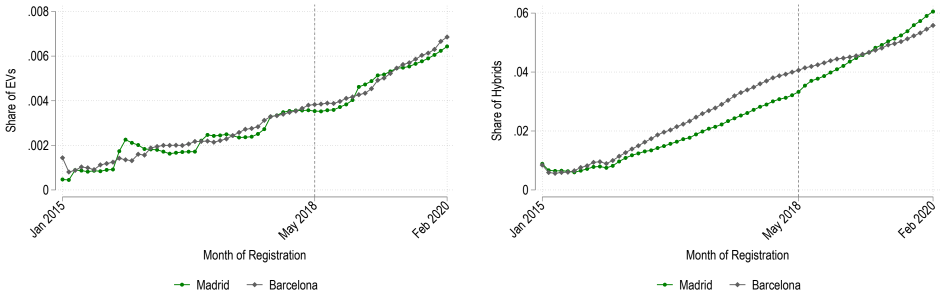
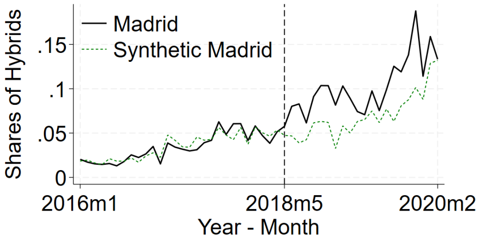
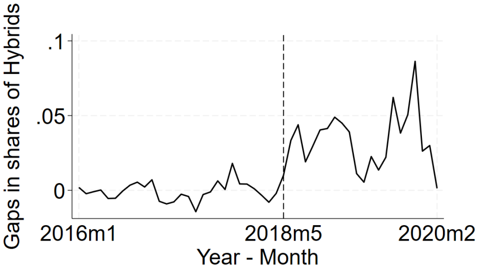
Figure: Trends EVs and hybrids: Madrid vs. Barcelona



It appears that Madrid Central accelerated the adoption of hybrids
...but did it? And EVs?

Empirical analysis: Synthetic control for hybrids





Weights: Barcelona 0.5; Araba/Alava 0.3; Almeria 0.1; Sevilla 0.1

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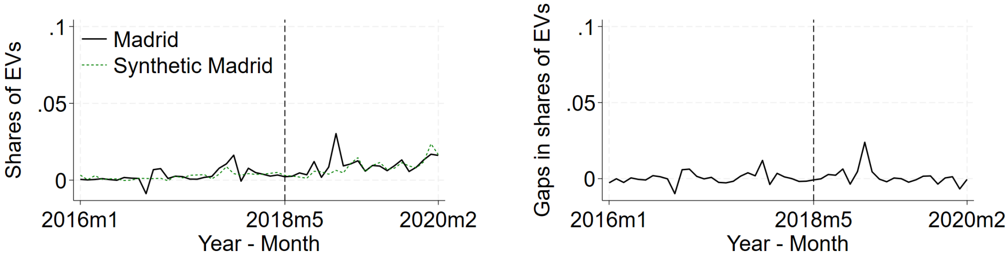
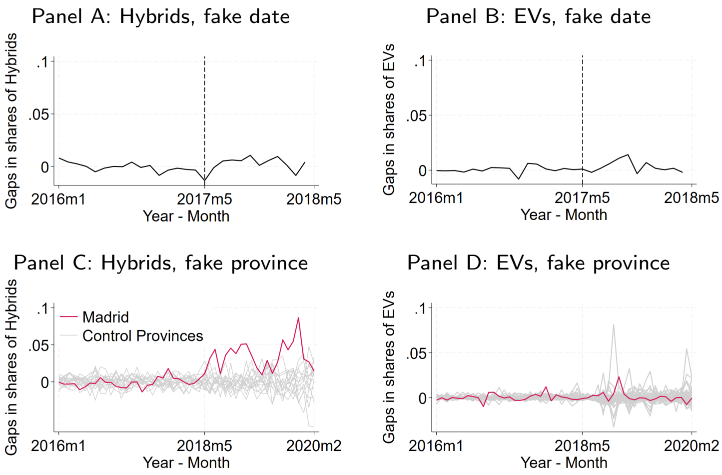


Weights: Barcelona 0.7; Almeria 0.2; Sevilla 0.1

Empirical analysis: Placebo effects



Questions that emerge from the reduced-form analysis

- Was it a good idea to have also hybrids exempted?
- ...perhaps they should have been to some extent, say, subject to a smaller LEZ, i.e., smaller than that for gasoline/diesel cars
- ...or better: why not to have treated hybrids as a "transition technology": exempted today but restricted tomorrow, at a date announced today?
- ...but, does this transition-technology design require of planner's commitment?

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- ...but, does this transition-technology design require of planner's commitment?
- is Madrid's LEZ too small?
- ....perhaps it would have been better to have no LEZ, or a much bigger one
- answers to these questions follow a "bang-bang" logic

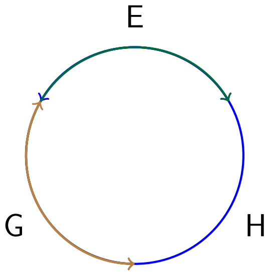
Theory: A dynamic model with infinitely-lived drivers

- Three type of vehicles: electric (E), hybrid (H) and gasoline (G)
- Offered in three distinct and equidistant points on a unit circle
- Drivers are uniformly distributed on the circle
- A driver located at $x \in [0, 1]$, who at the beginning of a given period holds a car of type $j = E, H, G$ and age $a = 1, 2, ..., T_j$, derives a per-period surplus from driving

$$u_a^j(x) = v_a^j - \gamma|x - x^j|,$$

  where:
  - T_j: (endogenous) age of oldest car
  - $v_a^j > v_{a+1}^j$
  - $x^E = 0$, $x^H = 1/3$ and $x^G = 2/3$
  - $\gamma > 0$: (per-period) horizontal-differentiation parameter
- The market is fully covered: all individuals drive a car in equilibrium

Consumer preferences



Pollution

- Vehicles also differ in how much they pollute
- Gasoline vehicles emit $e_a^G = e_a$ units of pollution, with $e_{a+1} \geq e_a$
- Hybrids emit $e_a^H = \alpha e_a$, with $\alpha \in (0, 1)$
- EVs are emission-free, i.e., $e_a^E = 0$
- The per-unit social cost of a unit of emissions is $1 \rightarrow$ emissions = social cost of pollution

No-intervention outcome

- Let U_a^j be the lifetime utility flow of an individual located at x with a car of type j and age a.
- Bellman equations that must hold in equilibrium

$$
\begin{aligned}
U_1^j(x) &= u_1^j(x) - p_1^j + \delta U_2^j(x) \\
& \dots \\
U_a^j(x) &= u_a^j(x) + \delta U_{a+1}^j(x) \\
& \dots \\
U_{T_j}^j(x) &= u_{T_j}^j(x) + \delta U_1^j(x) + \delta z^j
\end{aligned}
$$

  where:
  - $\delta < 1$: the discount factor
  - p_1^j: price of a new (i.e., age 1) car
  - z^j its scrap value (received at the end of T_j or beginning of $T_j + 1$).
- no need to trade second-hand cars

Lifetime value of holding a car for T periods

- Lifetime value of holding a car of type j for an individual located at x

$$U_1^j(x) = \frac{1}{1-\delta^{T_j}}\left[\sum_{a=1}^{T_j} \delta^{a-1} u_a^j + \delta^{T_j} z^j - p_1^j\right] \tag{1}$$

- In turn, the price of a second-hand car ($a > 1$) can be obtained from the indifference condition

$$U_1^j(x) = U_a^j(x) - p_a^j$$

- Scrapping age: if it is optimal to scrap cars at age 3 ($T_j = 2$), for example, then it must must hold

$$v_2^j > \frac{1}{1+\delta}\left(v_1^j + \delta v_2^j + z^j - p_1^j\right) > v_3^j$$

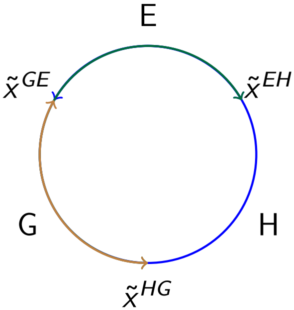
Demand for new (age 1) cars

- Let $\tilde{x}^{jk}$ be the indifference location between cars j and $k \neq j$: $U_1^j(\tilde{x}^{jk}) = U_1^k(\tilde{x}^{jk})$
- Drivers located between $\tilde{x}^{jk}$ and $\tilde{x}^{jl}$, with $l \neq j, k$, will own a type-j vehicle, so from eq (1)

$$q_1^j = \frac{1}{3} + \frac{1}{2\Gamma}\left(2(V_j + Z_j - P_j) - (V_k + Z_k - P_k) - (V_l + Z_l - P_l)\right)$$

  where:
  - $\Gamma = \gamma/(1-\delta)$
  - $V_j = \sum_{a=1}^{T_j} \delta^{a-1} v_a^j/(1-\delta^{T_j})$
  - $Z_j = \delta^{T_j} z^j/(1-\delta^{T_j})$, and
  - $P_j = p_1^j/(1-\delta^{T_j})$
- demand is decreasing in P_j and increasing in V_j and Z_j,
- but is increasing in P_k and P_l, and decreasing in V_k, V_l, Z_k and Z_l.

Market shares



No intervention: symmetric case

Welfare

- Since cars survive until they are scrapped, total welfare, in present value terms, is

$$W = \sum_{j=E,H,G} \left((V_j + Z_j - C_j - \mathcal{E}_j) q_1^j - \int_{\tilde{x}^{jk}}^{\tilde{x}^{jl}} \Gamma |x - x^j| dx \right),$$

  where:
  - $C_j = c^j / (1 - \delta^{T_j})$ is j's (lifetime) production cost, and
  - $\mathcal{E}_j = \sum_{a=1}^{T_j} \delta^{a-1} e_a^j / (1 - \delta^{T_j})$ is its (lifetime) emissions harm.
  - note that cars can have different lifetimes
- Policy interventions affect terms in W differently
- e.g., taxes, scrappage subsidies, low-emission zones

Two policy interventions: Pigouvian taxes and LEZs

- Pigouvian taxes: $\tau_a^j = e_a^j$ (first-best intervention, used as benchmark)
- (we assume that taxes are returned to individuals in a lump-sum fashion; no shadow cost of public funds)
- Low Emission Zones (LEZ)s:

$$v_a^j \to (1 - s_a^j) v_a^j$$

  where s_a^j is the "size" of the LEZ for that vehicle
- These two policies work quite differently: efficient vs inefficient (proportional) rationing
- A LEZ works through the intensive margin by destroying welfare from inframarginal consumers, those who continue holding restricted cars
- In contrast, taxes work at the margin without affecting inframarginal consumers (besides the tax payment)

Some simplifying assumptions and organization

- Since our focus is on correcting the environmental externality, we assume that cars are sold at cost or with a constant, uniform markup.
- As with any intervention in a durable-good market, it takes time for the car fleet to adjust to its new (steady-state) equilibrium.
- To facilitate the exposition, we proceed sequentially:
  - first, the case of "short-lived" vehicles, lasting only one period so the fleet adjusts instantly to a policy shock (also the case under a discriminatory LEZ!)
  - then, the case of "long-lived" vehicles, lasting for two periods
- Without loss of generality, cars are assumed symmetric except for their pollution levels: same production cost c, service value v_a, and scrap value z.
- Finally, we assume that pollution is age-independent, i.e., $e_a = e$ for all a (ok for global pollutants but not for local pollutants)

First-best solution with short-lived vehicles

Proposition

Consider the following emission thresholds:

$$e_G^{FB} \equiv \frac{2\gamma}{3(2-\alpha)} \text{ and } e_H^{FB} \equiv \frac{\gamma}{2\alpha}$$

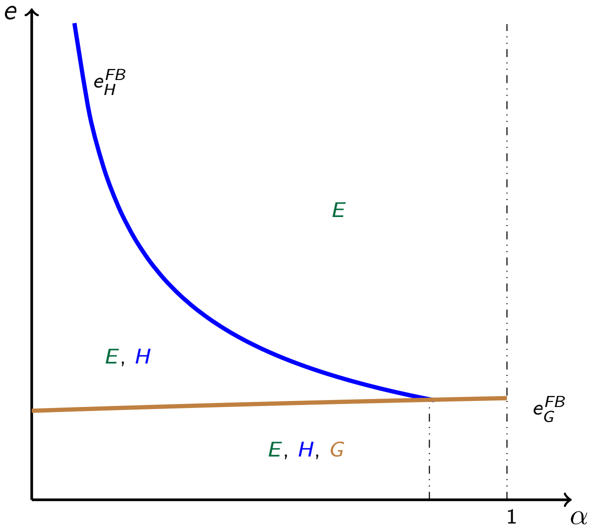
Under the FB intervention:

(i) *all three vehicle types are sold in equilibrium if* $e \leq e_G^{FB}$

(ii) *only EVs are sold in equilibrium if* $e \geq \max\left\{e_G^{FB}, e_H^{FB}\right\}$

(iii) *otherwise, only hybrids and EVs are sold in equilibrium*

First-Best solution with short-lived vehicles



LEZ solution with short-lived vehicles

Proposition

Consider a LEZ of size s and the following emission thresholds:

$$e_G^{LEZ}(s) \equiv \frac{2\gamma - 3v_1 s}{3(2-\alpha)} < \frac{2\gamma}{3(2\alpha - 1)} \equiv e_H^{LEZ}$$

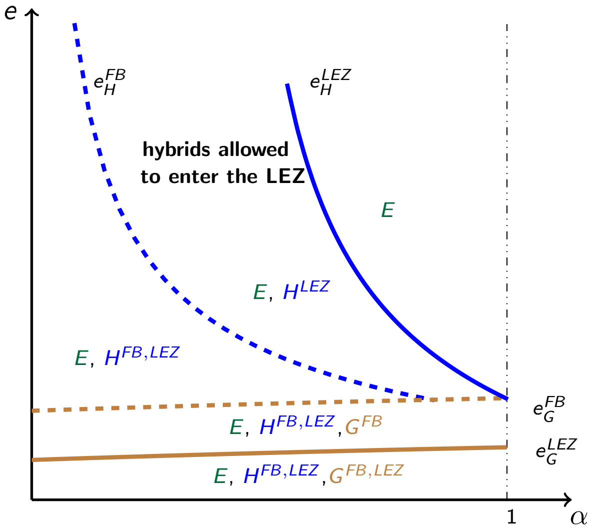
Then, it is optimal to

(i) *restrict no vehicle if* $e \leq e_G^{LEZ}$

(ii) *restrict only gasoline cars if* $e_G^{LEZ} < e \leq e_H^{LEZ}$*, and*

(iii) *restrict both gasoline and hybrid vehicles if* $e > e_H^{LEZ}$

LEZ solution with short-lived vehicles



Optimal LEZ with short-lived vehicles: Bang-bang design

Proposition

Let $\bar{s} \leq \gamma/3v_1$ *be the largest (politically feasible) LEZ. Define the thresholds* $\tilde{s}(e)$ *and* $\underline{e}$*:*

$$e_G^{LEZ}(\tilde{s}) = e \text{ and } \underline{e} \equiv e_G^{LEZ}(\gamma/3v_1) = \frac{\gamma}{3(2-\alpha)}$$

Then, it is optimal to have:

(i) *no LEZ if either* $e \leq \underline{e}$ *or* $\underline{e} < e \leq e_G^{LEZ}$ *and* $\bar{s} < \tilde{s}(e)$

(ii) *a LEZ of the maximum possible size* $\bar{s}$ *and only restrict gasoline vehicles if* $e_G^{FB} < e \leq e_H^{LEZ}$ *or* $\underline{e} < e \leq e_G^{FB}$ *and* $\bar{s} \geq \tilde{s}(e)$

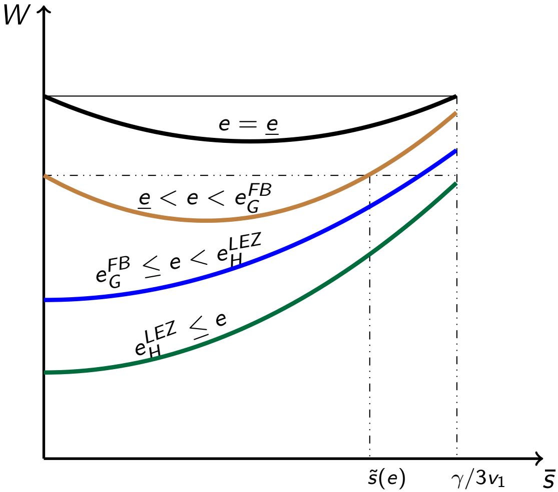
(iii) *a LEZ of the maximum possible size* $\bar{s}$ *and restrict gasoline vehicles and hybrids if* $e > e_H^{LEZ}$

Optimal LEZ with short-lived vehicles: Bang-bang design

- Welfare is decreasing in e
- Welfare is **convex** in s:
  - The smaller s the higher the share of G and hence, as s goes up, restricting G destroys utility

Optimal LEZ with short-lived vehicles: Bang-bang design

- Welfare is decreasing in e
- Welfare is **convex** in s:
  - The smaller s the higher the share of G and hence, as s goes up, restricting G destroys utility
- **Main takeways:**
  - Better not to have LEZ if e small or if max. feasible size is small enough
  - If having LEZ is optimal, make it as large as possible
  - (hybrids should be treated no different when restricted)



More Bang-bang: Hybrids equally restricted or not at all

Corollary

If it is possible to set $s^H \in [0, s^G]$, *then the optimal LEZ involves either* $s^H = s^G$ *or* $s^H = 0$.

Equilibrium with long-lived vehicles

- Denote time/periods by $t = 1, 2, 3....$
- Cars last for two periods, regardless of their type and policy in place
- Two possible LEZ designs announced at $t = 1$
  - Time-invariant LEZ: Cars face same restriction status throughout
  - Evolving LEZ: A car restriction status can change at $t = 2$ (**transition technology**)
  - (both designs may require commitment, which is assumed for now)
- In this two-period cycle, it takes at most three periods for the fleet to reach its new steady-state (two under a time-invariant design).
- Therefore, the planner's welfare function can be written as

$$W = \sum_{t=1}^{\infty} \delta^{t-1} W_t = W_1 + \delta W_2 + \frac{\delta^2}{1-\delta} W_3 \qquad (2)$$

- To simplify notation, $\delta = 1/2$.

Time-invariant LEZ with long-lived vehicles

Proposition

Consider a time-invariant LEZ of size $s < \bar{s} \leq \Gamma/3V = \gamma/(2v_1 + v_2)$ *introduced at* $t = 1$ *and the following emission thresholds:*

$$\hat{e}_G^{LEZ}(s) \equiv \frac{4\gamma(v_1 + v_2) - (2v_1 + v_2)^2 s}{3(2v_1 + v_2)(2 - \alpha)} < \frac{4\gamma(v_1 + v_2)}{3(2v_1 + v_2)(2\alpha - 1)} \equiv \hat{e}_H^{LEZ}.$$

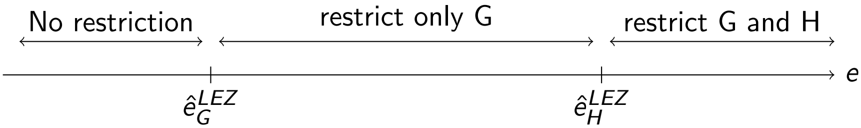
Then, it is optimal to:

(i) *restrict no vehicle if* $e \leq \hat{e}_G^{LEZ}$*,*

(ii) *restrict only gasoline cars if* $\hat{e}_G^{LEZ} < e \leq \hat{e}_H^{LEZ}$*, and*

(iii) *restrict both gasoline and hybrid vehicles if* $e > \hat{e}_H^{LEZ}$*.*

Time-invariant LEZ



Time-evolving LEZ

Hybrids may emerge as a transition technology (TT)

Proposition

Consider a LEZ of size $s < \bar{s}$, introduced at $t = 1$, and the emission thresholds:

$$\hat{e}_{TL}^{LEZ} \in \left[\hat{e}_{G}^{LEZ}, \hat{e}_{H}^{LEZ}\right) \text{ and } \hat{e}_{TH}^{LEZ} > \hat{e}_{H}^{LEZ}$$

Then, it is optimal to:

(i) *restrict no vehicle if $e \leq \hat{e}_{G}^{LEZ}$;*

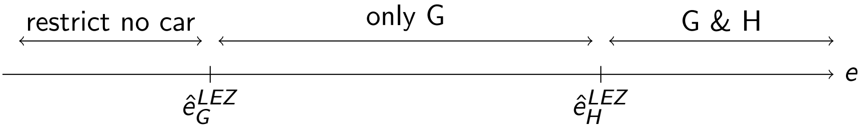
(ii) *restrict only gasoline cars from $t = 1$ onward if $\hat{e}_{G}^{LEZ} < e \leq \hat{e}_{TL}^{LEZ}$;*

(iii) *restrict gasoline cars from $t = 1$ onward, and treat hybrids as a transition technology (TT) if $\hat{e}_{TL}^{LEZ} < e \leq \hat{e}_{TH}^{LEZ}$:*
- *treat hybrids as EVs during $t = 1$ (no restriction),*
- *treat hybrids as gasoline cars from $t = 2$ onward (full restriction)*

(iv) *restrict both gasoline and hybrids from $t = 1$ onward if $e > \hat{e}_{TH}^{LEZ}$*

Time-evolving LEZ with transition technologies (TT)

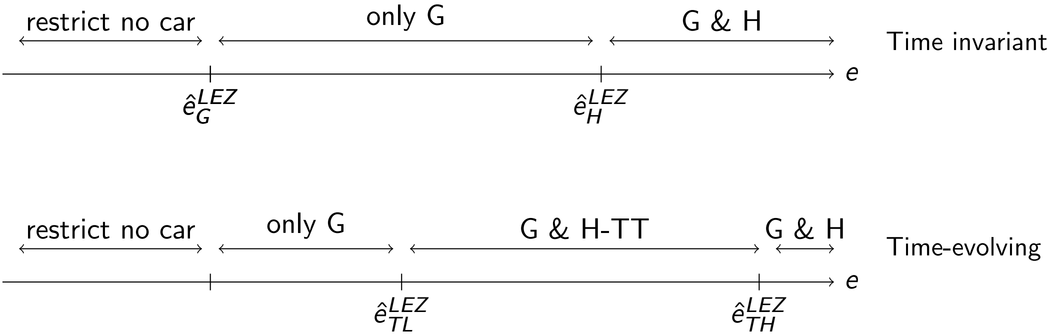
The commitment case



Time invariant

Time-evolving LEZ with transition technologies (TT)

The commitment case



Why does a transition technology (TT) emerge?

- Announcing at $t = 1$ that hybrids will be restricted in the future has immediate and future effects.
- It has an immediate impact on car choice: in anticipation of their lower future value, some individuals switch right away from hybrids
- As a result, there will be fewer inframarginal consumers driving hybrids tomorrow
- With fewer (second-hand) hybrids on the road tomorrow, it becomes less costly to announce today a future restriction on them
- the mere announcement that hybrids will be restricted in the future brings the LEZ instrument closer to a price instrument...
- affecting consumer choices at the margin in $t = 1$ without destroying value for inframarginal consumers in $t = 1$

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- the mere announcement that hybrids will be restricted in the future brings the LEZ instrument closer to a price instrument...
- affecting consumer choices at the margin in $t = 1$ without destroying value for inframarginal consumers in $t = 1$
- our notion of transition technology departs sharply from alternative notions—that EVs are still too expensive or unfamiliar to serve as a viable outside option

Time-evolving LEZs with no commitment

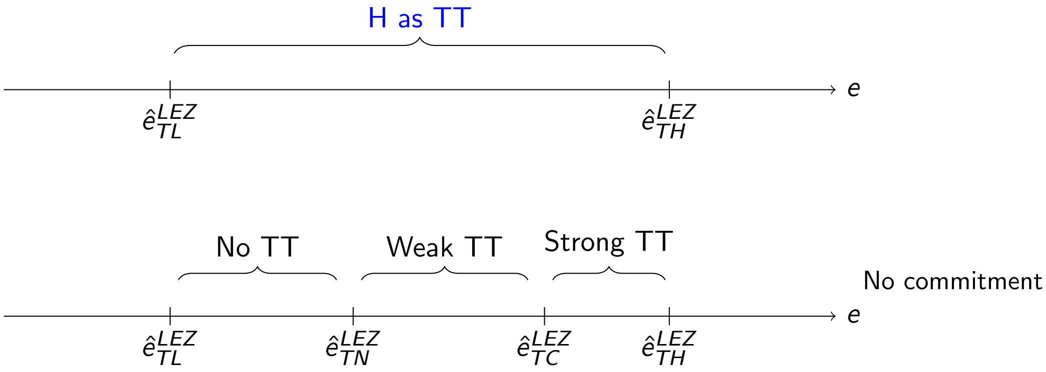
- there is no time-inconsistency problem if no car is restricted, if only gasoline cars are restricted, or if both gasoline and hybrids are restricted from $t = 1$ onward. Why?
- there is a time-inconsistency problem if the LEZ design treats hybrids as a transition technology, whenever

$$\hat{e}_{TL}^{LEZ} < e \leq \hat{e}_{TC}^{LEZ} \in \left(\hat{e}_{TH}^{LEZ}, \hat{e}_{TH}^{LEZ} \right)$$

- Why? At $t = 2$ there are too many second-hand hybrids around to place a restriction on them
- discounting, however, made it optimal for the planner to announce their restriction at $t = 1$
- no commitment requires departing somewhat from the bang-bang logic, placing some restriction on hybrids at $t = 1$: $s_1^H < s_2^H = s^G$
- it is nevertheless an incomplete solution to the planner's commitment problem....

Restoring some commitment in a time-evolving LEZ

It may vary with drivers' beliefs



Structural Model

- We estimate a flexible demand model
- Every quarter, consumers choose whether to buy a new car or not
- The utility that consumer i gets from buying car j in quarter t and city c is given by

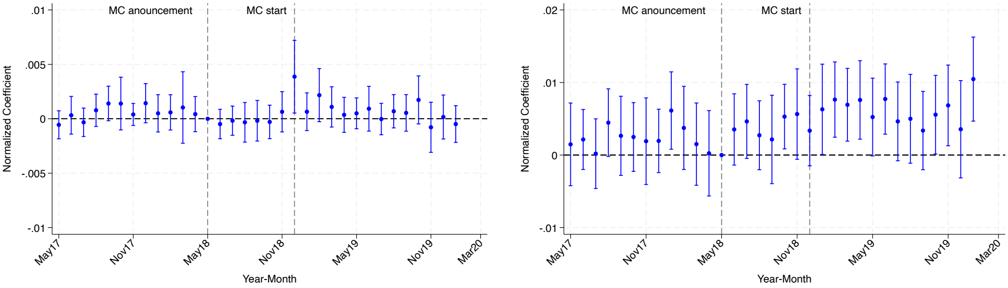
$$u_{ijtc} = -\alpha_i p_{jt} - \beta_i X_j + \delta_j + \delta_t + \delta_c + \xi_{jtc} + \epsilon_{ijtc}$$

where $\alpha_i = \pi_\alpha INC_{m(i)}$, $\beta_i = \pi_\beta INC_{m(i)} + \psi LEZ_{m(i),t}$, and $\epsilon_{ijt} \sim EVI$

  - $X_j \in \{G, H, E\}$: vehicle type (gas, hybrid, electric).
  - $INC_{m(i)}$: average income of zip-code $m(i)$ where i lives.
  - $LEZ_{m(i),t}$: indicator variable for zip-codes close to Madrid Central post-policy.
  - $\delta_j, \delta_t, \delta_c$: car model, quarter, and city fixed effects.

The effect of income on EVs and hybrids adoption

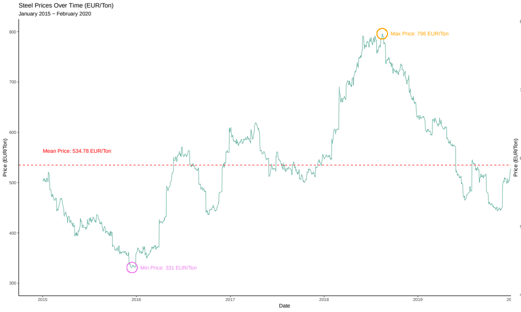
Figure: Event study estimates of income on EVs (left) and hydrids (right) adoption



Structural Model: Identification

- We estimate the model following BLP (1995) and Petrin (2002)
- Instruments for prices:
  1. Real exchange rate between Spain and manufacturing country (Grieco et al 2023)
  2. Price of Lithium, Neodymium, and Steel interacted with the car's weight
- **Micro-moments:**
  - $[i$ chooses car with $\{p_{jt} > \bar{p}\} \,|Inc]$,
  - $[i$ chooses car with $\{X_j = x\} \,|Inc]$ for $x \in \{G, H, E\}$,
  - $[i$ chooses car with $\{X_j = x\} \,|LEZ]$ for $x \in \{G, H, E\}$.

Price of Steel and Neodymium



Counterfactuals

- Estimating the value of having transition technologies
- ...and of commitment

Estimating the value of transition technologies and commitment

What would be the effects on car sales and welfare if...

1. ... **hybrids were also restricted** from entering the LEZ?
   - We can modify ψ so that the cost induced to gasoline cars also applies to hybrid cars
2. ...the **LEZ area were larger** (LEZ indicator active for other zipcodes)?
   - We can modify ψ so increase the penalty that LEZ imposes on owners of restricted cars
3. ...there were **higher subsidies for EV** adoption? How does the LEZ policy and subsidies compare in effectiveness/welfare impacts?
   - We can reduce prices p_{jt} for EVs and eliminate the penalty for restricted cars

Final remarks

- Empirical evidence on Madrid Central (Madrid's LEZ):
  - It only accelerated the adoption of hybrids, not of EVs
  - Good news? Bad news?
- Theory:
  - LEZs give rise to convex welfare functions (seems very general)
  - hybrids could be treated as transition technologies in a LEZ context, as EVs during some time, and as gasoline cars thereafter
  - this transition-technology LEZ design may require commitment from the social planner
  - more generally, how to optimally design a LEZ (size, vehicles restricted)
- **Ongoing work:**
  - Structural estimation to recover preferences and responses to changes in prices and policies (i.e., the introduction of the LEZ)
  - Counterfactual analysis: Bigger and more restrictive LEZs, with and without transition technologies, with and without commitment