Driving restrictions:
What we know and lessons for climate policy

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Workshop on CO2 pricing and sectoral complementary policies
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The World Bank’s Carbon pricing map
Source: The World Bank, April 2015
Chile’s carbon tax and its political economy

• Approved in September 2014, it applies to power plants greater than 50 MW of thermal capacity starting in 2017
• Industry and transportation not affected
• This tax was approved only because it was a small part of a comprehensive tax reform package (increasing corporate taxes mainly)
• very unlikely these “green” taxes would have been pushed and approved in isolation
• (we had ETS discussion that didn’t advance)
• (Mexico’s CO2 tax of 1-3 US$/ton, approved in Jan 2014, followed similar path, coverage smaller, 40%)
The carbon tax is not enough

• What to do with the transportation sector?
• the sector has its own political economy
• Gasoline taxes?...No, mentioned but immediately disregarded during the tax reform debate
• Scrappage subsidies?....No, too expensive
• Subsidies for EV and hybrids?....Virtually none
• Road pricing? No....it has been proposed for years but face strong opposition in Parliament
• What other policies have been tried in Latin America in the fight against vehicle congestion and local air pollution?
• Driving restrictions!
Vehicle congestion and local air pollution
...driving restrictions: what are they?

- they ban drivers from using their vehicles once a week on the basis of the last digit of the vehicle’s license plate
- some restrictions have followed a drastic implementation: affecting almost all drivers in the city and permanently
- others are more gradual: in place only in days of unusually high pollution (e.g., Beijing); affecting only older vehicles
- some include provisions that exempt new, cleaner cars
- enforcement has been quite effective
- very popular in Latin America (now you also see them in large cities in China and even India tried them for a month last January; and Paris!)
Driving Restrictions: where?
Where do we see them?

• Athens (first introduced in 1982)
• Santiago-Chile (186): \textit{restricción vehicular},
• Mexico-City (1989): \textit{Hoy-No-Circula}
• Sao Paulo-Brasil (1996): \textit{Operacao Rodizio}
• Manila (1996)
• Bogotá-Colombia (1998) and Medellín-Colombia (2005): \textit{Pico y Placa}
• San José-Costa Rica (2005): \textit{Restricción vehicular}
• Beijing (2008), Hangzhou (2011), Chengdu (2012)
• Berlin, Frankfurt, Munich... (2008): Low-Emission zones
• Quito-Ecuador (2010): \textit{Pico y Placa}
• Delhi (January 2016) : an odd-even experiment
• Paris (2014 and 2015): 1 day episodes
Have these restrictions worked?

• More importantly, can it be part of a climate policy package?
• It depends….two pieces of evidence with remarkably different messages
• Mexico-City’s 1989 Hoy-no-Circula (restriction imposed upon all cars)
  • Eskeland and Feyzioglu (WBER 1997)
  • Davis (JPE 2008)
  • Gallego-Montero-Salas (JPubE 2013, EnergyEcon 2013)
• Santiago-Chile 1992 (cleaner cars exempted from restriction)
  • Barahona-Gallego-Montero (wp 2016)
Mexico-City 1989 (Hoy-no-circula)
Figure: CO observations for Mexico-City
Our approach

- Flexible approach including monthly dummies for adaptation:
  \[ y_t = \alpha + \phi y_t^b + \beta T_t + \sum \delta_t d_t + \theta t + \gamma x_t + \epsilon_t \]

- Imposing adaptation process:
  \[ y_t = \alpha + \phi y_t^b + [a + b(t - t_T)]A_t + cT_t(1 - A_t) + \theta t + \gamma x_t + \epsilon_t \]

- \( y_t^b \): background pollution
- \( x_t \): includes fixed effects (day of week, month), weather variables, economic variables
- \( d_t \): dummies for transition months
- \( T_{t=1} \) if \( t > t_T \) (time of policy adoption) and zero otherwise.
- \( A_t = 1 \) if \( t_T < t \leq t_A \) (en of adjustment phase, endogenous using supF method of Quandt, 1960; Andrews, 1993; Hansen, 2000) and zero otherwise.

- Why linear trend \( \theta \)?

[Links: HNC, TS]
Our results for HNC

<table>
<thead>
<tr>
<th></th>
<th>Mexico-City (HNC)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>short-run</td>
</tr>
<tr>
<td>peak hours (8-9 am)</td>
<td>-11%</td>
</tr>
<tr>
<td>off-peak (12-2 pm)</td>
<td>-9%</td>
</tr>
<tr>
<td>sunday (8-10 am)</td>
<td>+2%</td>
</tr>
</tbody>
</table>
Table: Policy effects by station: HNC

<table>
<thead>
<tr>
<th>Station</th>
<th>Sector</th>
<th>Income per HH (relative to average income)</th>
<th>Short-run effect</th>
<th>Long-run effect</th>
<th>Difference effects</th>
<th>LR-SR effects</th>
<th>Months of adaptation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xalostoc</td>
<td>NE</td>
<td>0.55</td>
<td>11.96%</td>
<td>17.60%</td>
<td>5.64%</td>
<td></td>
<td>12.5 (6.06)</td>
</tr>
<tr>
<td>Tlalnepantla</td>
<td>NW</td>
<td>0.50(^a)</td>
<td>-21.32%(^*)</td>
<td>0.76%</td>
<td>22.08%(^*)</td>
<td></td>
<td>9 (3.10)</td>
</tr>
<tr>
<td>I.M. del Petróleo</td>
<td>NW</td>
<td>0.53</td>
<td>-17.81%(^***)</td>
<td>15.98%</td>
<td>33.79%(^***)</td>
<td></td>
<td>14 (1.91)</td>
</tr>
<tr>
<td>Lagunilla</td>
<td>CE</td>
<td>0.71</td>
<td>-28.21%(^***)</td>
<td>-6.52%</td>
<td>21.69%(^*)</td>
<td></td>
<td>11 (1.78)</td>
</tr>
<tr>
<td>Merced</td>
<td>CE</td>
<td>0.84</td>
<td>-15.27%(^*)</td>
<td>8.07%</td>
<td>23.34%(^**)</td>
<td></td>
<td>12 (1.52)</td>
</tr>
<tr>
<td>M. Insurgentes</td>
<td>CE</td>
<td>0.70</td>
<td>-24.58%(^***)</td>
<td>14.27%</td>
<td>38.85%(^***)</td>
<td></td>
<td>15 (2.33)</td>
</tr>
<tr>
<td>Cerro Estrella</td>
<td>SE</td>
<td>0.54</td>
<td>-17.81%(^**)</td>
<td>20.37%(^*)</td>
<td>38.18%(^***)</td>
<td></td>
<td>11.5 (1.51)</td>
</tr>
<tr>
<td>Taqueña</td>
<td>SE</td>
<td>1.14</td>
<td>-9.48%</td>
<td>22.55%(^**)</td>
<td>32.03%(^***)</td>
<td></td>
<td>15 (2.41)</td>
</tr>
<tr>
<td>Plateros</td>
<td>SW</td>
<td>1.99</td>
<td>-3.31%</td>
<td>-3.31%</td>
<td>0.00%</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Pedregal</td>
<td>SW</td>
<td>1.99</td>
<td>-3.38%</td>
<td>13.78%</td>
<td>17.16%</td>
<td></td>
<td>10.5 (3.06)</td>
</tr>
</tbody>
</table>
Santiago’s driving restriction

- **1985:** prohibition to the import of used cars into the country
- **1986:** driving restriction is introduced in the city of Santiago; but only for days of unusually bad air quality
- **1990:** the restriction becomes, for practical purposes, permanent from April to October; 20% of the fleet off the road during weekdays
- **1992:** cars that complied with a new emissions standard (be equipped with a catalytic converter) would get a green sticker
  - new cars bought in 1993 and after without the green sticker not allowed to circulate in Santiago’s Metropolitan Region
  - a car with a green sticker is exempt from any driving restriction
Evidence #1:

The vehicle fleet in Santiago is cleaner than in the rest of the country because of the driving restriction
Fleet evolution: the data

- our main database consists of a panel of 323 counties/municipalities and 7 years (2006-2012) with detailed information on fleet evolution (number of cars per vintage).

Figure: Evolution of the car fleet at the country level
Preliminary evidence: Santiago vs the rest of the country

- compelling evidence that the fleet in Santiago is cleaner than in the rest of the country
- but how much is explained by income? (Santiago is richer)

Figure: Fleet in 2006

Figure: Fleet in 2012
explaining the ”Santiago effect” for 92/93

of the total number of cars of vintage $\tau$ in the country in year $T \geq \tau$, how many go to municipality $i = 1, ..., 323$?

$$\log(c_{i\tau}) = \beta_T \text{Santiago}_i + \alpha_T \log(\text{Pop}_i) + \gamma_T \log(\text{Income}_i) + ...$$

$$... + \delta_T + \psi \mathbf{X}_i + \epsilon_{i\tau}$$

where

- $\text{Pop}_i$: is the population in municipality $i$ for that year sample
- $\text{Income}_i$: is the income per capita in county $i$
- $\text{Santiago}_i$: takes the value of 1 for municipalities in the city of Santiago
- $\delta_T$: vintage fixed effect
- other controls included (see table 1)
a few of observations...

**Figure:** Sample 2006 corrected
Evidence #2:

The driving restriction has created a price differential between 5 and 18% for otherwise similar cars (this is also indication that the restriction is well enforced)
price effects in the used-car market

- evident discontinuity in used-car prices between vintages 1992 and 1993

**Figure:** Price of used car Toyota Corolla by vintage
Table 3: Effect of driving restriction on prices (1993-2000)

<table>
<thead>
<tr>
<th></th>
<th>Fiat Uno</th>
<th>Honda Accord</th>
<th>Honda Civic</th>
<th>Mazda 323</th>
<th>Peugeot 205</th>
<th>Peugeot 505</th>
<th>Toyota Corolla</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catalytic</td>
<td>0.0458***</td>
<td>0.162***</td>
<td>0.0633***</td>
<td>0.0459***</td>
<td>0.0378***</td>
<td>0.149***</td>
<td>0.180***</td>
</tr>
<tr>
<td></td>
<td>(0.006)</td>
<td>(0.008)</td>
<td>(0.007)</td>
<td>(0.006)</td>
<td>(0.007)</td>
<td>(0.008)</td>
<td>(0.009)</td>
</tr>
<tr>
<td>Age f.e.</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Offer date f.e.</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Observations</td>
<td>4136</td>
<td>5980</td>
<td>5530</td>
<td>5796</td>
<td>3396</td>
<td>6788</td>
<td>5764</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.930</td>
<td>0.966</td>
<td>0.924</td>
<td>0.950</td>
<td>0.937</td>
<td>0.934</td>
<td>0.941</td>
</tr>
</tbody>
</table>

Notes: OLS regressions with age and date fixed effects. Standard errors clustered by offer date in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
prices in the used-car market

- another test: some ads reported some Honda Accord models prior to 1993 having catalytic converters
- the effect only shows up for cars made before 1993

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Catalytic</td>
<td>0.223***</td>
<td>0.189***</td>
<td>0.0206</td>
<td>-0.00487</td>
</tr>
<tr>
<td></td>
<td>(0.059)</td>
<td>(0.040)</td>
<td>(0.036)</td>
<td>(0.026)</td>
</tr>
<tr>
<td>Constant</td>
<td>15.60***</td>
<td>15.68***</td>
<td>15.96***</td>
<td>16.40***</td>
</tr>
<tr>
<td></td>
<td>(0.031)</td>
<td>(0.026)</td>
<td>(0.023)</td>
<td>(0.009)</td>
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<tr>
<td>Observations</td>
<td>47</td>
<td>53</td>
<td>58</td>
<td>49</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.245</td>
<td>0.309</td>
<td>0.006</td>
<td>0.001</td>
</tr>
</tbody>
</table>

Standard errors in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

- cars with a carburetor engine couldn’t be equipped with a catalytic converter
Evidence #3:

The clean-car exemption has eliminated the incentives to bypass the restriction with old high emitting cars.
purchasing a second (old) car

- using data from household-level surveys we look at whether households in Santiago are more likely to own more than one car.

Figure: Number of cars (1998)

Figure: Number of cars (2006)
Buying a second car?

- controlling for different household’s characteristics we estimate the effect of living in Santiago on having more than one car

| Panel A: marginal effects on probability of having two cars conditional on having at least one |
|-----------------|-----------------|
| OLS              | 0.0018 (0.006)  | 0.00999 (0.0144) |
| probit           | -0.00076 (0.001) | 0.0031 (0.0107) |

| Panel B: marginal effects on probability of having an extra car |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                  | \(\frac{\delta P[y=0]}{\delta x}\) | \(\frac{\delta P[y=1]}{\delta x}\) | \(\frac{\delta P[y\geq 2]}{\delta x}\) | \(\frac{\delta P[y=0]}{\delta x}\) | \(\frac{\delta P[y=1]}{\delta x}\) | \(\frac{\delta P[y\geq 2]}{\delta x}\) |
| ordered logit    | 0.0279*** (0.01) | -0.0258*** (0.009) | -0.0021*** (0.0007) | 0.0206* (0.011) | -0.0192* (0.0104) | -0.0014* (0.0007) |
| ordered probit   | 0.0318*** (0.01) | -0.0299*** (.0103) | -0.002*** (0.0007) | 0.0212* (0.012) | -0.01998* (0.0112) | -0.00126* (0.00067) |

| Panel C: marginal effects on having an extra car using count data models |
|-----------------|-----------------|
| poisson         | -0.0185*** (0.0058) | -0.0181*** (0.0065) |
| hurdle poisson-logit | 0.062 (0.081) | -0.01216 (0.0968) |

Standard errors in parentheses
* \(p < 0.05\), ** \(p < 0.01\), *** \(p < 0.001\)
A model of car ownership and use

- There are three agents in this model: **car producers**, **car dealers** and **drivers**.

- The cost of producing a new car is $c$ (price at which producers sell new cars to car dealers).

- The (annual) rental price at which a car of vintage $\tau = \{1, 2, 3, \ldots\}$ is rented to drivers is denoted by $p_{\tau}$.

- The probability that a vintage-$\tau$ car is still in the market for the next period as a vintage-$(\tau + 1)$ car is $\gamma_{\tau} \in (0, 1)$.

- A car can be scrapped at any time, getting a value of $v$ for its parts.
There is a continuum of drivers of mass 1 that vary in their willingness to pay for the quality of the car (they consider at most one car; see empirical result 3).

A consumer that rents a vintage-$\tau$ car obtains utility:

$$u(\tau, x, \theta) = \frac{\alpha}{\alpha - 1} \theta s_\tau x^{1 - \frac{1}{\alpha}} - \psi x - p_\tau$$

where $\theta$ is the consumer’s type, $s_\tau$ is the quality of the car, $x$ is a measure of car use during the period, $\psi$ is unit cost of using the car (e.g., parking, gasoline, etc), $\alpha > 1$ is a parameter that captures decreasing returns in car use, and $p_\tau$ is the rental price including insurance, inspections, and any other fixed cost.
Since a consumer $\theta$ that rents an age $\tau$ car anticipates that she will drive

$$x(\theta) = \left( \frac{\theta s_{\tau}}{\psi} \right)^{\alpha}$$  \hspace{1cm} (1)

her utility from renting a vintage-$\tau$ car reduces to

$$u(\tau, x(\theta), \theta) = k (\theta s_{\tau})^{\alpha} - p_{\tau}$$  \hspace{1cm} (2)

where $k = [(\alpha - 1)\psi^{\alpha-1}]^{-1}$.

Our formulation captures with a single parameter two empirical regularities:

- people that value quality more tend to drive newer cars and
- newer cars are, on average, run more often.
Consumers are distributed according to the cdf $F(\theta)$ over the interval $[\underline{\theta}, \bar{\theta}]$.

A consumer that doesn’t rent a car gets its outside utility $u_0$ (e.g., utility from using public transport).

The quality of a car falls with age (higher maintenance costs, more likely to break down, etc), according to

$$s_{\tau+1} = \beta s_{\tau}$$

with $\beta \in (0, 1)$. The quality of a new car is denoted by $s_0$.

All agents discount the future at $\delta \in (0, 1)$.
HOUSEHOLDS RENTING DIFFERENT VINTAGE CARS
At the beginning of any given year $t$ there will be some stock of used cars $Q^t = \{q^t_1, q^t_2, \ldots\}$.

As a function of that stock, the market equilibrium for the year $t$ must satisfy several conditions.

First, it must be true that in equilibrium consumers of higher types rent newer cars. There will be a series of cutoff levels $\{\theta^t_0, \theta^t_1, \ldots\}$ that precisely determines which consumers are renting which cars.

Denote by $\theta^t_\tau$ the consumer that is indifferent between renting a car of vintage $\tau$ at price $p^t_\tau$ and one of vintage $\tau + 1$ at a lower price $p^t_{\tau+1}$, that is

$$k (\theta^t_\tau s^t_\tau)^\alpha - p^t_\tau = k (\theta^t_\tau s^t_{\tau+1})^\alpha - p^t_{\tau+1}$$

for all $\tau = 0, 1, \ldots, T - 1$, where $T$ is the age of the oldest car that is rented.
The series of cutoff levels must be also consistent with the population of drivers and the existing stock of used cars $Q^t$ and the new cars coming to the market this year ($q_0^t$).

$$q_0 = 1 - F(\theta_0)$$
$$q_T = F(\theta_{T-1}) - F(\theta_T)$$

Car dealers have always the option to scrap an old car and receive $v$. Denoting by $T^t$ the age at which cars are being scrapped, in equilibrium dealers must be indifferent between renting an age $T$ vehicle today (and scrap it tomorrow, if the vehicle still exits) and scrapping it today.

$$p_T + \delta \gamma v = v$$
In general, only a fraction of age $T$ vehicles will be scrapped in equilibrium, so

$$F(\theta_{T-1}) - F(\theta_T) \leq \gamma q_{T-1}$$

Note that because quality drops discretely with age, it can happen that in equilibrium all vintage-$(\tau - 1)$ are rented but all vintage-$\tau$ are scrapped. Then the relevant scrapping condition is:

$$p_{T-1} + \delta \gamma v > v > p_T + \delta \gamma v$$
In addition, in equilibrium (competitive) car dealers must break even, so today’s and future’s rental prices must satisfy

\[ c = \sum_{i=0}^{T} (\gamma \delta)^i p_i + (\gamma \delta)^{T+1} v \]

where \( T \) is the age at which a car bought today, i.e., at \( t \), is expected to be retired from the rental market.

One last condition that must hold in equilibrium is that the lowest-valuation consumer to rent a car today, \( \theta_T \), obtains no surplus, i.e., it gets the surplus from using public transport, which we normalize to zero.

\[ k (\theta_T s_T)^\alpha - p_T = u_0 \]
Suppose that cars emit pollutants at a rate $e$ per mile, so that $e_{\tau+1} > e_\tau$. Denote by $h$ the harm from pollution, so the cost to society of a vintage-$\tau$ car running for $x$ miles is $e_\tau x h$.

The social planner can restore the social optimum by levying a Pigouvian tax equal to $h$ on each unit of pollution and so change consumer’s driving decision to

$$x^*(\theta) = \left(\frac{\theta s_\tau}{\psi + e_\tau h}\right)^\alpha$$

and its utility to

$$u(\tau, x^*(\theta), \theta) = k_\tau (\theta s_\tau)^\alpha - p_\tau$$

where $k_\tau = \left[(\alpha - 1)(\psi + e_\tau h)^{\alpha-1}\right]^{-1}$. 

real-world policy interventions

- Since Pigouian taxation is not feasible, policy makers must rely on alternative and imperfect policy instruments:
  - scrapping subsidies
  - driving restrictions, etc.

- The way a scrapping subsidy enters into our model is by simply increasing $v$.

- Driving restriction is captured by the parameter $R_\tau < 1$, which tells you that vintage-$\tau$ cars can only be used a fraction $R$ of the time, so that

$$x(\theta) = R_\tau \left( \frac{\theta s_\tau}{\psi} \right)^\alpha$$

and driver’s utility

$$u(\tau, x(\theta), \theta, R_\tau) = R_\tau k (\theta s_\tau)^\alpha - p_\tau$$
obtaining relevant parameter values to feed the model

- We use the 2006 car fleet sample
- We aggregate our fleet data from the county level (320) to the electoral district level (60).
- We group vintages in four-year groups
- Given that the used-car market between Santiago and the rest of the country is well arbitrated, the equilibrium equations to be estimated are

\[ R_{i\tau} k ((\theta_{i\tau} + \varepsilon_{i\tau}) s_{\tau})^\alpha - p_\tau = R_{i\tau+1} k ((\theta_{i\tau} + \varepsilon_{i\tau+1}) s_{\tau+1})^\alpha - p_{\tau+1} \]

\[ q_{i\tau} = F_i(\theta_{i\tau-1}) - F_i(\theta_{i\tau}) \]

where \( R_{i\tau} \) indicates whether a car of vintage-group \( \tau \) in district \( i \) faces a restriction (\( R < 1 \)) or not (\( R = 1 \)), \( p_\tau \) is the rental price, \( q_{i\tau} \) is the number of cars per capita, and \( \varepsilon_{i\tau} \) is an county-vintage specific shock in preferences.
obtaining parameter values

- To obtain values for $p_{\tau}$ we collected data of used-car prices from newspaper ads between years 1988 and 2000.
- We used a fixed effects regression model to predict the price of a standard car in every year of the panel.
- The difference of the predicted net present values of the cars in a 4 year period was assumed to be the rental price $p_{\tau}$.
- $F_i(\theta|x_i)$ is the distribution function of $\theta$ which is approximated by a cubic function (bounded between 0 and 1) captured by the vector $x_i = (a_i, b_i, c_i, d_i)$, where each parameter depends on the district’s characteristics:

$$x_i = \phi_x^1 + \phi_x^2 Income_i + \phi_x^3 Urb_i + \phi_x^4 Distance_i + \eta_i$$
We then imposed that the correlation between \((\varepsilon_{i\tau} - \varepsilon_{i\tau+1})\) and the district’s observable variables is zero:

- a dummy that took the value of 1 if the district is located in Santiago and three variables corresponding to the average income of the district, its distance to Santiago and its urbanization ratio.

Parameter values obtained:

\[
\{ R = 0.9666; \beta = 0.8911; \alpha = 2.1014; \psi = 0.36822 \}\]
obtaining parameter values

Figure: Distribution function $F_i(\theta | x_i)$ for different districts
The survival rate of cars of different vintages, \( \gamma \), was computed directly by looking at how many of the vintage-\( \tau \) cars in year \( t \) were still around in year \( t + 1 \).

We did this for many years and vintages to obtain:

\[
\begin{array}{ccccccc}
\text{vintage group} & 1-4 & 5-8 & 9-12 & 13-16 & 17-20 \\
\gamma & 0.9966 & 0.9966 & 0.9966 & 0.9434 & 0.8267 \\
\text{vintage group} & 21-24 & 25-28 & 29-32 & 33-36 \\
\gamma & 0.7226 & 0.5828 & 0.5242 & 0.5242 \\
\end{array}
\]
other parameter values: pollution damages

- To estimate the pollution damage from a $\tau$-vintage car we relied on two different sources.

- Following Parry and Strand (2012), we assume that the damage of local tailpipe emissions is US$0.06 per mile in Santiago and US$0.007 outside Santiago.

- We assume a passenger car runs about 12,000 miles per year (NHTSA, 2006)

- We take Mexico’s values from Molina and Molina (2002) for the relation between emissions contribution and vintages

<table>
<thead>
<tr>
<th>Car vintage</th>
<th>Fleet Percent Share</th>
<th>Emissions Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1993-2001</td>
<td>60%</td>
<td>15%</td>
</tr>
<tr>
<td>1985-1992</td>
<td>28%</td>
<td>30%</td>
</tr>
<tr>
<td>1980-1985</td>
<td>7%</td>
<td>25%</td>
</tr>
<tr>
<td>1979 &amp; older</td>
<td>5%</td>
<td>30%</td>
</tr>
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</table>
In our model, average damage generated by a vintage-$\tau$ car is given by

$$\frac{\int_{\theta_{\tau}}^{\theta_{\tau-1}} \left( \frac{\theta s_{\tau}}{\psi} \right)^{\alpha} e_{\tau} h f(\theta) d\theta}{\int_{\theta_{\tau}}^{\theta_{\tau-1}} f(\theta) d\theta}$$

where $f(.)$ is the pdf of parameter $\theta$.

We assume the following emission rate function $e_{\tau}$:

$$e_0 = 0$$
$$e_{\tau} = (1 + \omega)e_{\tau-1} + \omega$$

Running an OLS we estimate $\omega$ and $h$, so that $\omega = 1.52$ and $h = 0.012$ for cars in Santiago and $h = 0.001$ for cars outside Santiago.
other parameter values: cost, scrap value and discount factor

- we let $c = 16,000$, as it was the average price of new cars used in the rental price estimations
- for the scrap value we use initially $v = 600$.
- for the discount value we use $\delta = 0.656$, a value that corresponds to a 4 years period discount value of 0.9.
a two-city model

- we now split the country into two different regions, Santiago and the rest of the country.

Figure: Car fleet with no intervention
a two-city model: first best

- it is first best that older cars go to the rest of the country where pollution is less of a problem

Figure: Car fleet under Pigouvian taxes

- let us again normalize welfare gains under the first best to 100.
a two-city model: driving restriction

- when a restriction is applied to all cars in Santiago, this latter’s fleet gets even older.

![Graphs showing fleet under driving restriction to all vehicles](image)

(a) Santiago  
(b) Rest of country

**Figure:** Fleet under driving restriction to all vehicles

- in this case, welfare gains amount to $-20.7$. 

![Steady state — Driving restriction (all) (Santiago)](image)

![Steady state — Driving restriction (all) (other regions)](image)
a two-city model: driving restriction

- exempting cleaner cars improve things substantially

![Graph](image_url)

(a) Santiago

(b) Rest of country

**Figure:** Fleet under driving restriction upon older vehicles only

- in this case, welfare gains get to 12.6.
a two-city model: driving restriction

- we can also compare the model’s prediction to the coefficients estimated in the empirical part.

(a) Model prediction  
(b) Empirical estimation

Figure: Model prediction and empirical estimation when cleaner cars are exempted
we can then calculate welfare under an optimal scrappage subsidy of $2,980.

Figure: Car fleet under an optimal scrappage subsidy

in this case, welfare gains amount to 68.6.
a two-city model: optimal driving restriction

- or the optimal driving restriction where old cars are forbidden in Santiago.

![Steady state — Driving restriction (best) (Santiago)](image1)

![Steady state — Driving restriction (best) (other regions)](image2)

**(a) Santiago**

**(b) Rest of country**

**Figure:** Car fleet under an optimal driving restriction

- in this case, welfare gains amount to 90.2.
now driving restrictions behave even better than subsidies, as they can be focused on a particular city.

they get very close to the first best.

Table: Welfare calculations in a two cities model

<table>
<thead>
<tr>
<th>Contrafactual</th>
<th>Welfare (US$)</th>
<th>Rel. welfare</th>
</tr>
</thead>
<tbody>
<tr>
<td>No intervention</td>
<td>7697</td>
<td>0</td>
</tr>
<tr>
<td>First best</td>
<td>9028</td>
<td>100</td>
</tr>
<tr>
<td>Subsidy US$2980</td>
<td>8610</td>
<td>68.6</td>
</tr>
<tr>
<td>Driving restriction $R = 0.966$</td>
<td>7421</td>
<td>-20.7</td>
</tr>
<tr>
<td></td>
<td>$\forall \tau$</td>
<td></td>
</tr>
<tr>
<td>Driving restriction $R = 0.966$</td>
<td>7866</td>
<td>12.7</td>
</tr>
<tr>
<td></td>
<td>$\tau &gt; 3$</td>
<td></td>
</tr>
<tr>
<td>Driving restriction $R = 0$</td>
<td>8898</td>
<td>90.2</td>
</tr>
<tr>
<td></td>
<td>$\tau &gt; 4$</td>
<td></td>
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</tbody>
</table>
Conclusions

- we find a great impact on the evolution of the car fleet as a result of the driving restriction policy implemented in Santiago.
- older cars were exported from Santiago to the rest of the country, where local pollution is less of a problem (what about global pollution?).
- we also find no evidence of people bypassing the policy by purchasing a second (older) car.
- we built a model to better understand how different driving restrictions (and other policies) work and how close they can take us to the first best.
- well designed driving restrictions can work reasonably well (for fighting air pollution not congestion)