Adopting a cleaner technology: The effect of driving restrictions on fleet turnover*

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Abstract

In an effort to reduce vehicle pollution and congestion, authorities in different cities have experimented with different forms of driving restrictions. The restrictions in Mexico-City and in Santiago-Chile, for example, ban the use of a car once a week based on the last digit of its license plate, unless the car is relatively new, in which case is exempt from the restriction. Evidence from Santiago's program show that such an exemption can have a large effect on fleet turnover and on houselholds not longer bypassing the restriction with a second high-emitting car. We develop a vertical-differentiation model to study how best to design these driving policies. Calibrating the model's parameters using Santiago's evidence, we find that well design driving restrictions can come close to implement the first-best (i.e., achieve 80% of the first-best welfare gains).

1 Introduction

Air pollution and congestion remain serious problems in many cities around the world, particularly in emerging economies because of the steady increase in car use. Latin American cities have experimented with different policies in an effort to contain such trend and persuade drivers to give up their cars in favor of public transport (EIU, 2010). In

*This is a first draft that collects most of our results so far. It still needs a fair amount of editing and polishing. Comments welcome!

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1986, for example, authorities in Santiago were the first to introduce a driving restriction program. The program, as implemented in 1986, banned drivers from using their vehicles only a few days during the year, those days when pollution reached critical levels. A few years later, authorities in Mexico City introduced a much more comprehensive program, Hoy-No-Circula (HNC), that restricted all drivers from using their vehicles one weekday per week every day and for the entire year. Many cities in Latin American have followed suit: São Paulo in 1996, Bogotá in 1998, Medellín and San José in 2005, Quito in 2010, etc. Cities in China have also seen these restrictions implemented, both Beijing and Tianjin in 2008. Even authorities in Paris have used it; although once (in march last year).

There is obviously a political economy question of why these driving restrictions are so popular relative to more effective ones such as gasoline and congestion charges. We don't attempt to answer this question here. But given that they are so popular, there are good reasons to try to understand how they have actually worked in practice and see whether there is room to design them better. There has been a series of papers looking at the HNC policy including our own work (Gallego-Montero-Salas, GMS, 2013a and 2013b). As implemented in 1989, some believe that HNC had a good start (e.g., Onursal and Gautam 1997; GMS 2013a), but most agree that over the longer term it lead instead to an increase in the number of vehicles on the road and in pollution levels (e.g., Eskeland and Feyzioglu, 1997; Ornasul and Gautam, 1997; Molina and Molina, 2002; Davis, 2008; GMS 2013a). In fact, Davis (2008) documents an increase of 20% in the car fleet due to HNC (the number in GMS (2013b) is smaller but still important and quite fast, within a year). Lin et al (2013) also failed to find air quality improvements from restrictions elsewhere, namely, Bogotá, São Paulo and Tianjin (they did find some improvement for Beijing).

The main take from the existing literature is that driving restriction policies, while they can lead to some pollution reduction in the very short run, over the long run they create perverse incentives for people to buy a second and highly polluting car. A crucial design aspect totally neglected in the literature (and that is present, for example, in later reforms in the programs in Mexico-City and Santiago), however, is that in some restriction programs cleaner cars are not affected by the restriction. In the case of Santiago, 93 and newer models are not affected by the restriction as they are equipped with catalytic converters. Similar reforms were introduced in the program in Mexico-City. In this paper we are particularly interested in how this aspect affects the fleet turnover and whether or not it reduces the perverse incentives to buy a second car to bypass the restriction. To tackle these questions we first look at the evidence from Santiago's program and then develop a novel (vertical-differentiation) model of car use and ownership that we use for policy evaluation. Our model share some aspects of Adda and Cooper (2000) and

Gavazza et al (2014) but it also separates from them in crucial aspects, in particular, our focus on pollution control and policy instruments.

Because a restriction with this exemption element creates incentives to scrap older cars sooner than otherwise, our paper is also closely related to the literature looking at the effects of scrapping subsidies on fleet evolution (e.g., Hahn, 1995; Adda and Cooper, 2000; Mian and Sufi, 2012). It also related to the effects of subsidies on new/greener cars, for example, the "Bonus/Malus" feebate program introduced in France in 2008 (D'Haultfoeuilley et al 2014), which has been terminated because the program entered in a large deficit.

The problem with these scrapping subsidies is that they are used only sporadically, for a few months, so their effects are usually very limited. Besides, we have never seen them implemented in less-developed economies; largely because they are costly to implement for any government. Conversely, driving restrictions are ubiquitous (the Chilean government now wants to extend them to other cities in the country), but more importantly, they remain in place for much longer periods of time (the ones in Mexico-City and Santiago are still in place, like all the others we know). More interestingly, a driving restriction policy with an exemption clause can work very much like a scrapping subsidy without the usual (shadow) cost associated to subsidies.

The rest of the paper is organized as follows. In the next section (Section 2) we explain Santiago's driving restriction and document our main empirical results, namely, (i) that the fleet in Santiago is much cleaner than in the rest of the country (after controlling for income and other factors), (ii) that households did not bypass the restriction with a second car, and (iii) that the restriction has introduced an important price gap in the discontinuity between those cars affected and those that are not. In Section 3 we develop a model of car ownership and use. We derive the no-intervention equilibrium and the first-best outcome (Pigouvian taxation) and explain how subsidies and driving restrictions enter into the model. In Section 4 we calibrate the model to obtain relevant parameter values (about car characteristics, policy intensity, and consumer characteristics). In Section 5 we use these parameter values to run different policy simulation exercise comparing the performance of different driving restrictions and scrapping subsidies. Somehow surprising, well design restriction policies can perform better than subsidy programs (even without including the shadow costs of public funds associated to subsidies) and not too far from the first-best. Conclusions are in Section 6.

2 Santiago's driving restriction

The first restriction was implemented in 1986, when 20% of the fleet was banned from circulation on any day that air pollution was expected to reach a critical level. Restriction episodes were called ever more often and by 1990 it applied to almost every week-day from April to December. In 1991, however, a new decree was promulgated which required any 1993 and later models registered in Santiago and surrounding areas to be equipped with a catalytic converter (otherwise they could not be registered in Santiago nor enter the city). In addition, these new models would be automatically exempted from any driving restriction. Older cars, not equipped with the converter, could continue circulating in Santiago, but subject to a restriction of one week-day a week between 6.30 am and 8.30 pm.

Our main database to study the impact of the restriction and its exemption on cleaner cars consists of a panel of 323 counties and 7 years (2006-2012) with detailed information on fleet evolution (number of cars per vintage in every county). Figure 1 shows the stock of cars that are found at the national level for every vintage in each year. Those bars in red correspond to cars from vintage 1992 and older, while bars in green correspond to newer cars with catalytic converter. There are some interesting facts that arise. First, the fleet has been growing quite fast in the last 7 years (this may be in part explained by a poorly public transport reform implemented in early 2007; see GMS 2013a for an empirical evaluation). It is interesting that, since importing used cars to Chile is not allowed, one can see fewer models for years of low economic growth (e.g. 1983-1985, 1999-2002, 2008). Finally, one cannot help but notice that non-catalytic cars are now a relatively small portion of national fleet.

*** INSERT FIGURE 1 HERE OR BELOW ***

Exploiting this database and using demographic information at the household and county level collected from the Socioeconomic Characterization Survey (CASEN) we found several interesting effects of the driving restriction on fleet evolution, decision to buy a second car to bypass the restriction (as opposed to a newer car), and the price of cars. We now document each of them in that order.

2.1 Is the fleet cleaner?

To understand the effect that driving restriction may have had in car fleet composition we start comparing Santiago's Metropolitan Region's fleet with that of the rest of the country. In Figure 2 we can see that comparison for years 2006 and 2012. It gives some preliminary evidence that the fleet in Santiago is cleaner than in the rest of the country. However, this evidence must be taken carefully, since there are many differences between Santiago and other places that can be inducing this composition. Santiago is, for instance, richer and this could be leading people to drive newer cars. The differences could be explained by some counties located in Santiago that concentrate the richest households.

*** INSERT FIGURE 2 HERE OR BELOW ***

In a first attempt to control by income, Figure 3 shows the share of old cars[1] at the county level, where the red dot indicates a county in Santiago There is a clear indication, that regardless of income, there is a smaller fraction of old cars in the municipalities that are in Santiago.

*** INSERT FIGURE 3 HERE OR BELOW ***

There may still be different reasons behind the higher fleet turnover in Santiago. One is that it could be that the driving restriction have in fact lead drivers to have a larger fraction of cleaner cars. But it could also be because the faster turnover in the higher-income municipalities have accelerated the turnover in middle and low-income municipalities within the same the city. In other words, people get rid of a 92 car not because it is dirty but because it is old.

To test for this second possibility we look at the share of 92 and 93 cars, so let

$$92/93_{it} \equiv \frac{q_{1992}}{q_{1992} + q_{1993}}$$

be the 92/93 ratio in municipality i in sample year t. Figure 4 shows the value of this ratio for all municipalities in the 2006 sample. The results are even stronger, supporting the idea that there is an important difference in the number of cars from 1993 related to those from 1992 that are found in counties in Santiago. Since 1992 and 1993 cars are similar in terms of age and quality, the idea of people getting rid of a 92 car because it is old does not seem plausible. This preference for 1993 cars over 1992 ones in Santiago can only be attributed to the driving restriction.

*** INSERT FIGURE 4 HERE OR BELOW ***

If the story of 1992 cars getting away from Santiago is true, we should not expect to find the same results in other vintages. We repeated the exercise calculating the ratio for different contiguous vintages and found that the effect only shows up for the 92/93 ratio. Results are shown in Figure 5.

[1] An old car is a vintage-1992 car or older.

*** INSERT FIGURE 5 HERE OR BELOW ***

In order to formalize these results a bit further we ran the following regression

$$ratio_i = \beta Santiago_i + \gamma X_i + \varepsilon_i$$

where $ratio_i$ is the ratio calculated for different contiguous vintages in every county, $Santiago_i$ is a dummy variable that takes the value of 1 if the county is located in Santiago and X_i is a vector of different characteristics from county i including income per capita, distance to Santiago, income dispersion, a urbanization ratio and two dummies indicating whether the county is northern from Santiago or it is located in regions I or XII (the most far away regions from Santiago).

As it can be seen in Table 1, the coefficient of *Santiago* is negative and significant only for 92/93 ratio. For other ratios it is not statistically different from zeros, meaning that there is no difference for these ratios between a county in Santiago and the rest of them.

*** INSERT TABLE 1 HERE OR BELOW ***

Another interesting result of the latter exercise are the coefficients of (Distance to Santiago) and (Distance to Santiago)^2 which tells us that there is a quadratic relationship between 92/93 ratio and the distance from the county to Santiago. It suggest that the highest value of the ratio is not located in counties close to Santiago, nor those far away. This result is consistent with a story of cars moving from Santiago to other regions. However, counties that are close to Santiago use their cars often enough to go to Santiago and therefore are indirectly affected by the restriction. Counties that are too far, on the other hand, are places hard to reach by car and sell a vehicle to these countries may be difficult.

So far we have found a big discontinuity in car quantities for counties located in Santiago. Nevertheless we have not explore yet whether the discontinuity is produced by a lack of old cars in Santiago or a surplus of new ones relative to the rest of the country. By using a more flexible model we can get a better idea of the mechanisms operating behind this policy. We ran the following panel regression that explains the number of cars from every vintage that were used in a particular municipality in year 2006.

$$\log(c_{i\tau}) = \beta_\tau Santiago_i + \alpha_\tau \log(Population_i) + \gamma_\tau \log(Income_i) + \delta_\tau + \psi X_i + \varepsilon_{i\tau}$$

where $c_{i\tau}$ is the number of cars from vintage τ that are used in county i. $Population_i$ is the population in municipality i, $Income_i$ is the income per capita in county i, $Santiago_i$ takes the value of 1 for municipalities in Santiago, δ_τ is a vintage fixed effect and X_i is a vector of controls also used in Table 1. The main advantage of this model is that it allows one to calculate different coefficients for different vintages, as β_τ, α_τ and γ_τ are allowed to vary across vintages.

Figure 6 shows the coefficients of *Income* and *Santiago* and their intervals of confidence. *Income* coefficients increase gradually as we move to more recent vintages, consistent with a story of similar vintages having similar cars and that higher income should explain a larger fraction of new cars. That *Income* is significant for most vintages also indicates that there are more cars overall in richer counties.

*** INSERT FIGURE 6 HERE OR BELOW ***

The evolution of *Santiago* coefficient, contrary to *Income*, shows a significant discontinuity around the 92 and 93 vintages. It also shows that old cars were not displaced from Santiago uniformly. The effect is big for cars from vintage 1992 and closely below, while for very old cars the effect gets smaller. This result is consistent with a model of vertical differentiation, where some individuals decide between a car from vintage 1992 or 1993 and prefer the ones from 93. Other individuals, however, are deciding between using a car from vintage 1985 or 1986 and therefore don't move to a 93 car since it is too far from their willingness to pay. Another plausible explanation to the negative slope of the coefficients on the left side of the discontinuity is that car drivers in Santiago are not only bypassing the driving restriction policy by moving to cleaner cars, but also by buying a second an older car, as it happened in the case of Mexico-City (HNC). Both alternative explanations will be discussed in greater depth in other sections (we will come back to this picture after the model has been developed).

So far we have learned that the driving restriction had a significant impact on fleet composition. Old and dirty cars moved from Santiago to other places in the country were air pollution was less of a problem. This encouraged a faster fleet turnover and allowed the technology of catalytic converters to spread faster in Santiago than it would have been otherwise.

2.2 Do people buy a second car?

Previous literature has emphasized the perverse incentives that driving restrictions might create to the purchase of a second and older vehicle (Davis, 2008; GMS et. al. 2013a and 2013b). These findings, however, have been under a framework in which all cars were exposed to the driving restriction and therefore bypassing it by buying a clean car was not possible. The Socioeconomic Characterization Survey (CASEN) for years 1998 and 2006 ask households whether they have a car or not and, if having any, whether they have more than one. Unfortunately there is no data available for a year before the restriction was implemented, nevertheless we can still arrive at some conclusions with the data we have.

Figure 7 shows the histogram of households having zero, one or more than one car. The majority of households do not have any car and less than 5% of the households have more than one, both in Santiago's Metropolitan Region and in the rest of the country. At simple sight one can also notice that the proportion of households having more than one car in Santiago doubles the proportion of households in the rest of the country with multiple vehicles. Differences in households characteristics in different places do not allow us to arrive at any conclusion from these illustrations.

*** INSERT FIGURE 7 HERE OR BELOW ***

The idea is to model how living in Santiago affects the number of cars owned by a household. We estimate models that control for household characteristics related to income, assets, age, gender and employment status of the head of the household, the composition of the household (in terms of number of members and also number of employed members), and the size of the county in which the household is located. The "treatment" effect is living in Santiago's Metropolitan Region.

The main econometric challenge has to do with the discrete nature of the data. Households typically have either 0, 1, or 2 cars in the sample. Moreover, due to data constraints we can just have three categories in the two surveys we use: either the households owns zero, one, or more than one car. This corresponds to a right-censoring of the count data but empirically does not have much of an empirical implication as the share of household having more than two cars is really insignificant.

There are three general ways of modelling this kind of problems. First, we can think of the choice between 0, 1, and 2 cars as coming from a multionomial choice model in which households sort into the three ordered categories. This implies that an ordered model like logit or probit could be a good fit for the data (e.g., Matas and Raymond, 2008). Second, we can think of the choice about the number of cars as a process with counts (e.g. a Poisson process), in which the number of cars is a realization of, for instance, a Poisson or a Negative Binomial process (e.g., Huang and Yao, 2014). We can also think of a mixture of the two previous models, in which a discrete choice process determines the extensive margin (the decision to own or not a car) and then a count model is used to explain the intensive margin (whether having 1 or more than 1 car).

The different approaches in general imply differences in the underlying data-generation-process (DGP). As we do not necessarily have a good idea of the true DGP we estimate several models. In addition, we estimate these models for household surveys in both 1998 and 2006. The first cross-section of households corresponds to a situation closer to the initial implementation of the driving restriction we study in this paper. The second cross-section corresponds to the year for which we have information on the total number of cars by different cohorts. In all cases we present marginal effects. We also present "naive-models" in which we just run regressions of a dummy that takes a value of one if a household has more than one car conditional on having at least one car (i.e. $P[y \geq 2|y \geq 1]$). Results are presented in Table 2.

*** INSERT TABLE 2 HERE OR BELOW ***

In Panel A we present the results from the "naive-models" using OLS and a probit model. The result from this regressions shows that living in Santiago doesn't change the probability of having more than one car conditional on having already one, after controlling for relevant variables. This means that the differences seen in Figure 7 between Santiago and the rest of the country were probably driven by other households characteristics.

In Panel B we estimate marginal effects on probability using ordered logit and probit models. The results show a very small effect, close to zero and even slightly negative. It says again that living in Santiago doesn't change the probability of having more than one car, and if anything, households in Santiago are less likely to have two or more cars.

Panel C presents the results of a Poisson model in which the probability of having another car is lower for households in Santiago. Mixing both strategies by using a hurdle poisson-logit model again give non significant results on the intensive margin.

We also test for other econometric issues and find no evidence of overdispersion in the data, so results using Poisson and Negative Binomial models are similar. Therefore only Poisson models are shown in the table. We also didn't find any evidence that right-censoring in two cars is relevant for the estimations. When estimating the model for 2006 using a non-censoring model, in which there is full information of the numbers of cars per household, the results keep the same.

In all, there is no evidence that the driving restriction has resulting in households owning more cars. The number of households having multiple cars is very low and controlling for relevant variables the differences between households living in Santiago and other places disappear.

2.3 How much do car prices react?

This is important not only as a robustness check but also as it provides an estimate of the cost of the restriction on individuals. A driving restriction reduces the value of a car within the area of the restriction but not beyond that area. This differences in valuation between a catalytic and a non-catalytic car should not only be reflected in cars moving from one place to another, but it could also may have some impact in the used-car market and their prices. As Santiago's Metropolitan Region concentrate 40% of country's population a policy that affects some used-car's valuation can have a great impact in the used-car market prices.

To analyze how prices changed with the driving restriction, we collected a rich panel data from 1988 to 2000 with offers of different car models that were published on Chile's main newspaper on the first Sunday of every month. Figure 8 shows some of the results that can be found in the dataset using ads with posted prices for Toyota Corolla models. Every scatter of the plot represents an ad with the vintage of the car and its respective price (in logarithms). In order to use comparable data we show prices from ads in October, November or December from 1991, 1995 and 1997.

*** INSERT FIGURE 8 HERE OR BELOW ***

In the figure it can be noticed a log-linear relationship between prices and vintages. Nevertheless, there is a big gap between prices of cars from 1992 and 1993. Again, following the idea behind an RD methodology, prices of cars from similar vintages should have similar prices. In Table 3 the results of Figure 8 are formalized. Panel A shows the coefficient of a model in which car depreciation is linear in age. The coefficient of the dummy $Post_{1992}$ shows that, controlling for age, a car with a catalytic converter is between 17% and 25% more expensive that one without it. Panel B calculates the same coefficient, relaxing the assumption of a linear relation. Running an RDD the coefficients are even larger now.

*** INSERT TABLE 3 HERE OR BELOW ***

Another interesting exercise that can be made to understand how driving restrictions affect prices is exploiting a particularity that happened with Honda Accord models. Some cars equipped with catalytic converter started to be imported to the country before 1993. These are also exempted from the driving restriction. Honda Accord is the case, in which some people reported in ads that the car was equipped with a converter. Running a simple regression where the independent variable is a dummy when a car reported to have a catalytic converter for different car vintages we found a significant difference in prices only for cars made before 1993. We used cars offer from newspapers of October, November and December from year 1995 to do this exercise. Every column shows the regression using cars from different vintages.

*** INSERT TABLE 4 HERE OR BELOW ***

For cars from vintage 1991 and 1992, having a catalytic converter was a desirable attribute and therefore reporting it allowed one to receive a higher price for it. Cars from vintages 1993 and 1994, however, had to be equipped with the converter. Everyone of these cars then was exempted from restriction and reporting them to have a catalytic converter has no effect in prices.

This alternative exercise shows again a premium of 20% in prices for cars that have a catalytic converter and therefore are exempted from driving restrictions, consistent with the previous exercise using Toyota Corolla and a different empirical strategy.

So far we have shown three main empirical results from driving restrictions. First of all, its effects were big and had consequences in terms of fleet composition, cleaning the car fleet from Santiago by moving older and dirtier cars to other regions of the country were air pollution was less of a problem. Second, we didn't find any evidence of perverse incentives generated by this driving restriction to buy a second car in order to bypass the policy. This incentive was probably replaced by the incentive of buying a newer and cleaner car. Third of all, the driving restriction not only had a big effect in terms of car stocks, but also had a great impact in used-car prices. As drivers valued more a car that could be used every day of the week, prices of clean cars were up to 20% higher.

3 A model of fleet turnover

To understand better how driving restrictions and alternative instruments work we develop a theoretical model that we then calibrate with parameter values using the evidence from Santiago's restriction.

3.1 Notation

There are three agents in this economy: car producers, car dealers and drivers or households. They all discount the future at $\delta \in (0, 1)$. The cost of producing a new car is c, which is also the price at which perfectly competitive producers sell new cars to car dealers. There is a large number of car dealers that buy new cars from car producers and rent them together with used cars to drivers.[2] The (annual) rental price for a car of age $\tau = \{0, 1, 2, ...\}$ at date t is denoted by $p_{\tau t}$ ($\tau = 0$ corresponds to a new car). Note that the rental price is not invariant to time as it depends on the stock of used cars which can vary in response to policy shocks, which are the only shocks we consider in our model. Cars exit the market at some exogenous rate due to crush, fatal malfunctioning, etc. This rate may vary with age, so the probability that a age τ car is still in the market next period is $\gamma_\tau \in (0, 1)$, with $\gamma_\tau \geq \gamma_{\tau+1}$ (to simplify notation we will assume throughout the

[2]The renting assumption is also in Bento et al (2009).

rest of this section that $\gamma_\tau = \gamma$ for all τ). All surviving cars at time t are (endogenously) scrapped at age T_t for a value of v. This latter can be seen, for example, as the price a dealer gets for an old vehicle when exported to another country or, more importantly for the purposes of this paper, as the subsidy in a government's scrappage program.

Similar to the vertical model in Gavazza et al (2014), there is a continuum of households/drivers of mass 1 that vary in their willingness to pay for quality but also in how much they drive. A driver that rents car τ obtains a per-period utility of (to save on notation in many places we will omit the the subscript "t" unless is strictly necessary)

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

where θ is the consumer's type, $s_\tau > 0$ is the quality of the car, x is a measure of car use during the period, ψ is unit cost of using the car (e.g., parking, gasoline, etc.),[3] $\alpha > 1$ is a parameter that captures decreasing returns in car use, and p_τ is the rental price including insurance, inspections, and any other fixed cost. The quality of a car falls with age, i.e., $s_{\tau+1} < s_\tau$, either because older cars are more likely to break down or because they lack the latest technological advances. The quality of a new car is denote by s_0.[4]

A consumer θ that rents an age τ car anticipates that she will drive

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

so, her utility from renting a vintage-τ car reduces to

$$u(\tau, x(\theta), \theta) = k\left(\theta s_\tau\right)^\alpha - p_\tau \tag{2}$$

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

Our formulation captures with a single parameter two empirical regularities: that people that value quality more tend to drive newer cars and that newer cars are, on average, run more often. Consumers are distributed according to the cdf $F(\theta)$ over the interval $[\underline{\theta}, \bar{\theta}]$, with $0 \leq \underline{\theta} < \bar{\theta}$. A consumer θ that doesn't rent a car obtains an outside utility equal to u_0, which we interpret as the utility from using pollution-free public transport.

3.2 The market equilibrium

At the beginning of any period, say year t, there will be some stock of used cars $\mathbf{S}_t = (q_{1t}, q_{2t}, ...)$. As a function of that stock, the market equilibrium for the year must satisfy

[3] This may also include (socially optimal) congestion charges which we don't model explicitely.

[4] Our model is different than Gavazza's et al (2014) in at least two dimensions. First, we only deal with households that at best own one car (the empirical evidence of the previous section support this assumption; our results shouldn't change; very few households own more than one car, if at all). And second we incorporate vehicle use which is crucial when dealing with externalities.

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 $\{\theta_{0t}, \theta_{1t}, ...\}$ that precisely determine the prices at which consumers are renting which cars. Denote by $\theta_{\tau t}$ the consumer that that at time t is indifferent between renting a car of age τ at price $p_{\tau t}$ and one of age $\tau+1$ at a lower price $p_{\tau+1,t}$, that is

$$k\left(\theta_{\tau} s_{\tau}\right)^{\alpha} - p_{\tau} = k\left(\theta_{\tau} s_{\tau+1}\right)^{\alpha} - p_{\tau+1} \tag{3}$$

for all $\tau = 0, 1, ..., T-1$, where T is the age of the oldest car that is rented. Consumers of type $\theta \geq \theta_{\tau}$ rent age-τ vehicles or newer while consumers of type $\theta < \theta_{\tau}$ rent pre-τ vehicles (or not at all for θ's sufficiently low). As in any vertical differentiation model, an obvious corollary from (3) is that a higher valuation consumer obtains strictly more surplus than a lower valuation consumer.

From (3), equilibrium rental prices can be expressed as a function of p_0 and the series of cutoff levels as follows

$$p_{\tau} = p_0 - k s_0^{\alpha}(\beta^{-\alpha} - 1)\sum_{i=0}^{\tau-1}(\theta_i \beta^i)^{\alpha}$$

for all $\tau = 1, ..., T$. In turn, the series of cutoff levels must be consistent with the population of drivers and the existing stock of used cars $\mathbf{S}_t$ and the new cars coming to the market this year (q_0). Hence, it must also hold that

$$q_0 = 1 - F(\theta_0) \text{ and } q_{\tau} = F(\theta_{\tau}) - F(\theta_{\tau+1}) \tag{4}$$

for all τ that are rented in equilibrium.

Since car dealers have always the option to scrap an old car and receive v, in equilibrium they must also be indifferent between renting an age T vehicle today (and scrap it tomorrow, if the vehicle still exits) and scrapping it today, i.e.,

$$p_T + \delta\gamma v = v \tag{5}$$

In general, only a fraction of vintage-T vehicles will be scrapped in equilibrium (while all pre-T vehicles will), so

$$F(\theta_{T-1}) - F(\theta_T) \leq \gamma_{T-1} q_{T-1} \tag{6}$$

where $\gamma_{T-1} q_{T-1}$ is the number of age T vehicles that survived from last period.[5]

[5]Note that because quality drops discretely with age, it can happen that in equilibrium all $T-1$ vintage are rented but all T vintage are scrapped, then the relevant scrapping condition is not (5) but

$$p_{T-1} + \delta\gamma v > v > p_T + \delta\gamma v \tag{7}$$

where p_T is the hypothetical price for the rental of a T vehicle. One way to mitigate these corners is by working with periods of shorter length, say a month instead of a year; the problem is that our empirical analysis is based on more aggregate data.

In addition, in equilibrium (competitive) car dealers must break even, so the evolution of rental prices must satisfy

$$c = \sum_{i=0}^{\Gamma} (\gamma\delta)^i p_i + (\gamma\delta)^{\Gamma+1} v \tag{8}$$

where Γ is the age at which a car bought today, i.e., at date t, is expected to be retired (or rented for the last time). Note that both Γ and T depend on the existing stock $\mathbf{S}_t$ and in steady-state $\Gamma = T$.

One last condition that must hold in equilibrium is that the lowest-valuation household to rent a car today, θ_T, obtains its outside utility

$$k\left(\theta_T s_T\right)^{\alpha} - p_T = u_0 \tag{9}$$

If (9) does not hold, a dealer would be strictly better off by renting a T vehicle at a price slightly above p_T instead of scrapping it.[6]

Conditions (3)–(9) determine the unique equilibrium for any given stock of used cars $\mathbf{S}_t$, that is, rental prices of new and used cars and sales of new cars for any given stock of used cars $\mathbf{S}_t$. Unlike other papers, we are not only interested in the steady-state equilibrium, but also in the equilibrium during the transition phase after a policy shock. Transitions can be particularly long in car markets, so despite they can be computationally demanding they cannot be neglected in policy evaluation and design.

Definition 1 *Let the no-intervention steady-state equilibrium be denoted by the scrappage age* T^n*, rental prices* $\mathbf{p}^n = \{p_0^n, p_1^n, ..., p_T^n\}$*, sales of new cars* q_0^n*, and the stock of used cars* $\mathbf{S}^n = \{q_1^n, q_2^n, ..., q_T^n, 0, ...\}$ *at the beginning of each year.*

3.3 The social optimum

If cars pollute the market equilibrium described above (Definition 1) is not socially optimal. Suppose that cars emit pollutants at a rate e per mile, which is increasing with age, that is, $e_{\tau+1} > e_\tau$. Denote by h the harm from pollution, so the cost to society of a vintage-τ car running for x miles is $e_\tau x h$. If the social planner can monitor emissions, $e_\tau x$, he can restore the social optimum by levying a Pigouvian tax equal to h on each unit of pollution. This will affect decisions on car use and ownership, i.e., will affect (1) and (2) in the following way

$$x^*(\theta) = \left(\frac{\theta s_\tau}{\psi + e_\tau h}\right)^{\alpha} \tag{10}$$

[6]The same logic applies if we are in the corner (7) of the previous footnote: given the fixed supply of vintage $T-1$ vehicles, a dealer owning a $T-1$ vehicle could slightly raise its rental price above p_{T-1} and still find demand for it.

and

$$u(\tau, x^*(\theta), \theta) = k_\tau \left(\theta s_\tau\right)^\alpha - p_\tau \tag{11}$$

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

In anticipation to our calibration and simulation exercises, assume the following

A1 new cars are relatively clean ($e_0 \approx 0$), and

A2 a car's pollution rate deteriorates faster than its quality when is young but less so as it ages; formally, $s_{\tau+1}^\alpha e_{\tau+1} - s_\tau^\alpha e_\tau > 0$ for low τ's and $s_{\tau+1}^\alpha e_{\tau+1} - s_\tau^\alpha e_\tau \approx 0$ for higher τ's.

Assumption A1 is supported by the data and assures that new car are always rented in equilibrium for any h. According to Molina and Molina (2002) almost a third of 1998 emissions in Mexico-City came from very old cars that represented no more than 5% of the fleet. Assumption A2 implies that taxing pollution widens the price differential (i.e., $p_\tau - p_{\tau+1}$) for newer vehicles but closes it for older ones. With those assumptions, we can establish.

Proposition 1 *Relative to the no-intervention steady-state of definition 1, the social optimum steady-state can be characterized as follows: (i) $\theta_T^* > \theta_T^n$,(ii) $x_\tau^*(\theta) < x_\tau^n(\theta)$ for all τ, (iii) $T^* \leq T^n$,(iv) $p_0^* > p_0^n$, and (v) $q_0^* > q_0^n$.*

Proof. To prove (i) note that the last consumer to rent a car under the steady-state social optimum is θ_T^*, which obtains $k_T \left(\theta_T^* s_T\right)^\alpha - p_T = u_0$, where $p_T = v(1 - \delta\gamma)$ as derived from (5). When $h \to 0$, $T^* = T^n$ but $\theta_T^* > \theta_T^n$ because $k_T < k$ (this is regardless of possible changes in q_0). As we increase h, T^* can in principle go down or up (shortly we will show that A2 ensures that $T^* \leq T^n$). Consider first the case in which $T^* > T^n$. If so, θ_T^* must be strictly greater than θ_T^n; otherwise $k_T \left(\theta_T^* s_T\right)^\alpha - p_T < u_0$ because both k_T and s_T have dropped. Consider now the case in which $T^* < T^n$. To simplify the exposition we will provide a proof for a two-period model (the full proof is in the online appendix). Suppose that $e_0 = 0$ and $T^n = 1$, which implies that (3) reduces to

$$k(\theta_0^n s_0)^\alpha - p_0^n = k(\theta_0^n s_1)^\alpha - p_1^n$$

where $p_0^n = c - \delta\gamma v$ and $p_1^n = (1 - \delta\gamma)v$. In addition, we know from (9) that

$$k(\theta_1^n s_1)^\alpha - p_1^n = u_0 \tag{12}$$

(note that parameters must be such that $\theta_1^n < \theta_0^n$ (and $\theta_1^n > F^{-1}[1 - q_0^n(1 + \gamma)]$). The first-best is to have only new cars around because $e_1 > 0$ and h too big. If so, $p_0^* = p_0^n$ and

$$k(\theta_0^* s_0)^\alpha - p_0^* = u_0 \tag{13}$$

We need to prove that $\theta_0^* > \theta_1^n$. Substracting (12) from (13) and plugging the definitions of $p_0^n = p_0^*$ and p_1^n yields

$$(\theta_0^* s_0)^\alpha - (\theta_1^n s_1)^\alpha = (\theta_0^n s_0)^\alpha - (\theta_0^n s_1)^\alpha = (c - v)/k > (\theta_1^n s_0)^\alpha - (\theta_1^n s_1)^\alpha$$

because $\theta_0^n > \theta_1^n$; hence, $\theta_0^* > \theta_1^n$. The proof of (ii) is straightforward. A driver θ renting a vintage-τ car will now drive according to (10), which is obviously less than (1).

The proofs of (iii), (iv) and (v) are more involved in that they require assumption A2. Consider first the case $T^* = T^n = T$ ($h \to 0$). Rewrite the break-even condition (8) as follows

$$\begin{aligned} c \;=\; & (p_0^* - p_1^*) + (1 + \gamma\delta)(p_1^* - p_2^*) + ... + (1 + \gamma\delta + ... + \gamma^{T-1}\delta^{T-1})(p_{T-1}^* - p_T^*) \\ & + (1 + \gamma\delta + ... + \gamma^T \delta^T) p_T + (\gamma\delta)^{T+1} v \end{aligned} \tag{14}$$

where

$$p_\tau - p_{\tau+1} = \theta_\tau (k_\tau s_\tau^\alpha - k_{\tau+1} s_{\tau+1}^\alpha) \tag{15}$$

from (3) and (11). We know that p_T is fixed and that $\partial p_{T-1}/\partial h|_{h=0} < 0$ because of A2. This implies both that $p_{T-1}^* < p_{T-1}^n$ and $p_{T-1}^* - p_T^* < p_{T-1}^n - p_T^n$. The question now is how prices and price differentials evolve backward from $\tau = T - 1$ to $\tau = 0$. Conditions (8) and (14) require that both prices and prices differentials must eventually go above the no-intervention levels. Assumptions A1 and A2 assure that $p_0^* > p_0^n$ and that $p_0^* - p_1^* > p_0^n - p_1^n$. ■

Some parts of the proposition are quite intuitive but others are not. For example some readers may argue that because now cars are on average more expensive to use than public transport, the total number of cars should drop. The proposition says that intuition is wrong and the reason is that we can not see a car as single product but as a collection of different products providing different services. Newer cars have become relatively cleaner than older cars so their demand has increased. The overall effect is that there are more cars coming to the market but lasting fewer periods.

3.4 Real-world policy interventions

Since Pigouvian taxation is rarely feasible, policy makers tend to rely on imperfect instruments (e.g., Fullerton and Gan 2005, Parry et al 2007). We consider two that we see quite often: scrapping subsidies and driving restrictions. The way a scrapping subsidy enters into our model is by simply increasing v. On the other hand, the way a driving restriction enters into the model is more complicated because it depends on the specific design which must specify the extent of the restriction and the car vintages that are affected. The extent of the restriction is captured by the parameter $R_\tau < 1$, which tells you that vintage-τ cars can only be used a fraction R of the time, for example, 4 days a week. In other words, the actual travel of household θ on a vintage-τ car that faces restriction R_τ will be

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

and its utility

$$u(\tau, x(\theta), \theta, R_\tau) = R_\tau k \left(\theta s_\tau \right)^\alpha - p_\tau \tag{16}$$

We now use the model to recover relevant parameters and then use those parameter to run a series of policy exercises.

4 Calibration

Using the data from the country's car fleet we estimated the most relevant parameters of our model, so as to simulate and compare different policies. We assume that a period in the model was 4 years. Some other parameters were also collected from other sources, such us c, which was assumed to be equal to US\$16000, consistent with new car prices from the database collected from the newspapers. The scrappage value v was given a value of US\$700 and δ was given a value of 0.656, a value that corresponds to a 4 years period discount factor of 0.9.

4.1 Parameter values

To estimate the parameters of the model we group all municipalities in 60 electoral districts and cars into 6 different vintages in the following way:

1981-1984 1985-1988 1989-1992 1993-1996 1997-2000 2001-2004

Assuming perfect arbitrage in the used car market we can assume that rental prices p_τ are the same in every district. Therefore, equations (**??**) and (18) must be satisfied for every district i and vintage τ.

$$\theta_{i\tau} = \left(\frac{p_{\tau+1} - p_\tau}{R_{i\tau+1} k s_{\tau+1}^\alpha - R_{i\tau} k s_\tau^\alpha} \right)^{\frac{1}{\alpha}} \tag{17}$$

$$q_{i\tau} = F_i(\theta_{i\tau-1}) - F_i(\theta_{i\tau}) + \varepsilon_{i\tau}$$

where $k = [(\alpha - 1)\psi^{\alpha-1}]^{-1}$, s_τ comes from parameters s_0 and β as described in the model, $R_{i\tau}$ equals R if a car from vintage τ is exposed to restriction in district i and 1 if not, p_τ is the estimated rental price from a car of vintage τ, $q_{i\tau}$ is the number of cars from vintage τ per household that can be found in district i, $F_i(.)$ is the cdf of θ in district i and $\varepsilon_{i\tau}$ is an error term.

To capture the estimated rental prices p_τ we used the car offers collected from the newspapers. We first estimated the following regression in order to get real car prices as a function of car vintage and year.

$$\log(P_{i\tau ym}) = \alpha + \phi_\tau + \psi_y + \eta_m + \mu_{i\tau ym} \tag{18}$$

where $P_{i\tau ym}$ is the price of offer i in year y of a car model m from vintage τ and ϕ_τ, ψ_y and η_m are vintage, year and model fixed effects.

Using equation (18) we then estimated the rental price of a representative car of vintage τ for one period (i.e. 4 years) as follows.

$$p_\tau = e^{\hat{\alpha}+\hat{\phi}_\tau+\hat{\psi}_y+\hat{\eta}_m} - \delta e^{\hat{\alpha}+\hat{\phi}_\tau+\hat{\psi}_{y+4}+\hat{\eta}_m}$$

To estimate $F_i(\theta)$ we approximated the function by a third degree Taylor polynomial expansion as a function of vector $x_i = (a_i, b_i, c_i, d_i)$, where $F_i(x) = a_i + b_i x + c_i x^2 + d_i x^3$. Each parameter varies in every district and depends on different district characteristics such as per capita income and urbanization ratio.

$$x_i = \phi_x^1 + \phi_x^2 Income_i + \phi_x^3 Urb_i + \eta_i \tag{19}$$

for each $x_i \in \{a_i, b_i, c_i, d_i\}$.

The parameters to be estimated are

$$\{R, \beta, s_0, \alpha, \psi, \phi_a^1, \phi_a^2, \phi_a^3, \phi_b^1, \phi_b^2, \phi_b^3, \phi_c^1, \phi_c^2, \phi_c^3, \phi_d^1, \phi_d^2, \phi_d^3\}$$

Imposing the following moments:

$$\frac{1}{N}\sum_{i=1}^{N} \varepsilon_{i\tau} = 0 \quad , \quad \frac{1}{N}\sum_{i=1}^{N} Santiago_i \times \varepsilon_{i\tau} = 0,$$
$$\frac{1}{N}\sum_{i=1}^{N} Income_i \times \varepsilon_{i\tau} = 0 \quad , \quad \frac{1}{N}\sum_{i=1}^{N} Urb_i \times \varepsilon_{i\tau} = 0$$

for every vintage τ. R represents the impact of driving restriction as implemented in Santiago, β and s_0 are the parameters defining quality s_τ, α and ψ determine the utility function of car drivers and ϕ_x^n are used to determine the cdf $F_i(\theta)$. This gives a total of 17 parameters to be estimated imposing 24 moments to be zero. $\varepsilon_{i\tau}$ is the error term from equation (**??**). The final estimated values of the parameters are:

$$\{R = 0.9419; \beta = 0.8452; s_0 = 19.83; \alpha = 1.504; \psi = 0.2230\}$$

4.2 Survival rate of cars

Other important parameter that needs to be estimated is the survival rate of cars γ_τ. We used the panel data of car stocks from 2006 to 2012. As it is forbidden to import used cars, the number of cars at the national level for a certain vintage is reduced every year. By dividing the numbers of cars from vintage τ in year t by the number of cars from the same vintage in year $t-1$ we can get the value of γ_τ^t. Then, using ordinary least squares and imposing that $\gamma_\tau \leq 1$ and $\gamma_{\tau+1} \leq \gamma_\tau$ we got the following values for γ_τ:

Age	1-4	5-8	9-12	13-16	17-20	21-24	25-28	29-32	33-36
γ_τ	0.9966	0.9966	0.9966	0.9434	0.8267	0.7226	0.5828	0.5242	0.5242

4.3 Emissions and social damage

To estimate the externalities from a τ-vintage car use we exploited two different sources. Our first source comes from Parry and Strand (2012), where local tailpipe emissions damage in Chile is estimated to be US$0.06 per mile for Santiago and US$0.007 per mile for regions outside Santiago.

The second source of information comes from Molina and Molina (2002) and relates the emissions contribution of cars with their respective vintages for Mexico. This relation is shown in Table 5.

*** INSERT TABLE 5 HERE OR BELOW ***

Using our data from chilean car fleet we can compare the fleet composition of Chile with the one of Mexico and see that there are not big differences. Therefore, Mexico's data seems to be a reasonable way to infer emissions contribution of different vintages cars in Chile. In Table 6 we can find the fleet percent share out of the total number of cars from the vintages of interest found in Chile in year 2006.

*** INSERT TABLE 6 HERE OR BELOW ***

We are interested in estimating the externalities produced in a year by each car. Average annual miles driven by passenger cars is estimated to be around 12,000 miles (NHTSA, 2006). Using this information and Parry and Strand (2012) estimation we get an average damage of US$720 per car per year for Santiago and US$84 for other regions. This, however, is an average and it is important to see how it chanegs for cars of different vintages. To do this, we used the relation between fleet share and emissions contribution from Molina and Molina (2002) and calculated the damage externalities produced by a representative car of every set of vintages in order to keep average car damage constant and consistent with Parry and Strand's (2012) estimate.

In Table 7 we can find the average car damage for different vintages that are consistent with the information provided above.

*** INSERT TABLE 7 HERE OR BELOW ***

In our theoretical model, car's damage according to $xe_\tau h$. Then, average damage generated by a vintage-τ 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 θ.

We imposed the following structure to emission function e_τ so that:

$$\begin{aligned} e_0 &= 0 \\ e_\tau &= (1+\omega)e_{\tau-1} + \omega \end{aligned}$$

Using OLS we estimated ω and h, so that $\omega = 1.52$ and $h = 0.012$ for cars driven in Santiago and $h = 0.001$ for cars driven in other regions of Chile.

5 Simulations

With the parameters already identified we can now start to simulate some counterfactual situations and compare different outcomes and policies.

5.1 Car fleet in a closed city and first best

Lets start analyzing how different policies work in a framework were there is only one city isolated from other places. This is similar as thinking on a policy that is applied to the whole country or as thinking in solving a problem of global pollution. We assume that the damage function is the one estimated for Santiago so that $h = 0.012$. All other parameters are the ones estimated in the section above.

Figure 9 shows the steady state of the car fleet in a world without intervention. Every bar represents a vintage[7] and its height the number of cars from that vintage per household that are on the road. It can be seen that cars last 32 years before being scrapped, and every period an amount of 0.1 of cars per household are bought by car dealers and enter into the market.

[7] From now on we will refer as a vintage to a group of four contiguous vintages

*** INSERT FIGURE 9 HERE OR BELOW ***

This model not only allows us to simulate different situations in order to infer the stock of cars that there would be in every setting. It also let one to calculate the net present value of social welfare that is produced by the car market. Car drivers obtain high consumer surplus when driving new cars, since they are high quality cars and are also driven by consumers with the highest valuation for rides. Old cars, however, pollute in high amount when driven and therefore welfare is diminished when this cars are used. Drivers don't take into account this negative externalities and so welfare is not optimal. Under a setting with no intervention the welfare calculated in our model is of US$5897,8 per household. We will set this value in 0 in order to facilitate future comparisons.

In an ideal world, the regulator could charge drivers with a Pigouvian tax. Doing so, he would obtain the first best allocation in terms of fleet composition and car use. Figure 10 (a) shows the car fleet that is obtained under the first best allocation in steady state. Now cars last only 24 years and are driven less (driven miles are not shown in the figure). It is also important to notice that q_0 is bigger now than in the case with no intervention, as it was predicted by Proposition 1.

*** INSERT FIGURE 10 HERE OR BELOW ***

Figures 13 (b), (c), and (d) show the dynamics of q_0, p_τ and θ_τ when the regulator charges Pigouvian taxes. At the beginnig, the stock of old cars is lower than it should be in the steady state equilibrium. To cover the excess of demand car dealers have to buy more new cars, augmenting the value of q_0 above its steady state level. After a few years the model converges to the steady state. Net present value of social welfare under the first best is US$7451,5 per household. We will set this value to 100.

5.2 Restrictions and subsidies in a one-city model

We consider now alternative instruments. In many countries policy makers have implemented programs of scrappage subsidies that aim to accelerate the retirement of old vehicles (Cash for Clunkers, USA 1992 and 2009; Balladur and Jupé, France 1992 and 1995). By increasing the value of v car dealers are encouraged to retire their vehicles sooner from the market.

Figure 11 shows the outcome of a scrappage subsidy of US$1000. The policy successfully retires cars earlier than in a world with no intervention making them last only 24 years. The welfare obtained under this framework is US$7451,5 reaching 60,5% of the first-best gains.

*** INSERT FIGURE 11 HERE OR BELOW ***

Consider now a driving restriction. As we will see, its design matters a great deal. Many countries have implemented driving restrictions in different formats. Santiago (1986) and Mexico-City (1989) started with a driving restriction that was applied to every car of the fleet. In Figure 12 we simulated this situations using a value of $R = 0.94$ estimated in the calibration section.

*** INSERT FIGURE 12 HERE OR BELOW ***

Welfare under this intervention is US$5066,9, lower than under no intervention; a 32,35% reduction the first-best gains. What is happening here is that new cars are not used as much because of the restriction, which is socially suboptimal given their low emissions

Driving restrictions, however, can be design in a more intelligent way. One can, for instance, exempt cleaner cars from it as done in Santiago since 1992 or in Mexico-City since 1994. In Mexico-City cars of less than 8 years old are exempted from restriction, different from Santiago, when cars from vintage 1993 or after are exempted. This makes the Mexican restriction an interesting case to evaluate since it is in constant renovation. A driving restriction as the one from Santiago will end up with the same steady state as a world without intervention.

Figure 13 shows a case similar to the driving restriction implemented in Mexico-City in 1994. We simulated a situation where cars with more than 12 years are exposed to a driving restriction with $R = 0.94$ while newer cars are exempted from restriction. Welfare in this case reaches US$6492,6, 23,16% of the first-best gains.

*** INSERT FIGURE 13 HERE OR BELOW ***

5.3 Optimal interventions in a one-city model

After understanding how subsidies and driving restriction may operate, we can use our model to optimize both policies. In Figure 14 one can see the results under the application of an optimal scrappage subsidy of US$5050 per every scrapped vehicle. Cars now last even less than in the first best. Since scrappage subsidies don't allow the regulator to control for the distance driven by a specific car, cars need to be retired sooner that they would be under a Pigouvian taxation scheme. In the first best allocation, cars between 16 and 20 years old were still in the fleet because they were not driven too much and therefore the negative externality produced by them was low. Using scrappage subsidies the intensive margin is not under control and therefore it is necessary to scrap vehicles earlier. Welfare under this optimal policy is US$8076,5 and reaches 84,83% of the gains from the first best.

*** INSERT FIGURE 14 HERE OR BELOW ***

When optimizing driving restrictions we find interesting results. It is easy no notice from equation (16) that driving restriction parameter R_τ enters lineal to the utility function of drivers. Then, if consumer surplus of driving a car is higher than de damage caused by the same car, then the optimal driving parameter takes the value of $R_\tau = 1$. If not, then the optimal value is $R_\tau = 0$, getting always to a corner solution where polluting cars are forbidden while cleaner cars are exempted.

Figure 15 shows this kind of regulation where cars under 16 years old are exempted from restriction while those older can't drive at all. The solution is very similar as the one implemented with the optimal subsidy as both of them retire cars earlier. Welfare calculations in this case give a value of US$8071,2, reaching 84,63% of the gains from the first best.

*** INSERT FIGURE 15 HERE OR BELOW ***

In Table 8 there is a complete summary for all the interventions simulated for the model of one closed city.

*** INSERT TABLE 8 HERE OR BELOW ***

This model shows us that both driving restrictions and scrappage subsidies can get very close to the first best if well designed. Both of them don't work in the same way and have advantages and disadvantages. The main disadvantage of a scrappage subsidy is its cost. A subsidy of US$5000 per scrapped car is a big subsidy and could be hard to implement. Welfare calculation can be also lower if we include some shadow cost for fiscal expenditure. Driving restrictions, on the other hand, are free to implement in monetary terms, but they can have greater political costs.

It is also important no remember that this simulations were done in a model were only one city existed. If we think on a world were there are many cities with different value of h, driving restriction will have another advantage over scrappage subsidies since they will allow the regulator to have differentiated policy interventions in each city.

5.4 Car fleet in a model of two cities

Another interesting dynamic that our model allows one to capture are policy responses under a framework of two different cities perfectly integrated in the used car market, but where damage functions are different. That will be the case of Chile, for example, where air pollution was highly problematic in Santiago but not in the rest of the country. We modeled two cities with the same cdf $F(\theta)$. City 1, analogue to Santiago, has big marginal damage from emissions so that $h = 0.012$. For city 2, h will be assumed to be zero.

Figure 16 shows the steady state in the world with no intervention. As the two cities has the same distribution of types θ, both the car fleet from city 1 and the car fleet from city 2 are equivalent. Welfare calculation of each city, however, are different because of differential negative externalities.

*** INSERT FIGURE 16 HERE OR BELOW ***

Figure 16 (a), (b) and (c) shows the car fleet in steady state from city 1, city 2 and the whole country respectively. Figure 16 (d) shows the difference between city one and national average. This will be important when analyzing different policies. Calculations of welfare gives a total surplus of US$7696,9 per household. We will set this value to 0 again in order to compare policies easier.

The first best allocation in this framework consist in a Pigouvian taxation where drivers from city 1 are charged for driving. Since city 2 has no negative externalities, drivers in city 2 would be able to drive without paying any taxes. Figure 17 shows the results from the steady state. Transitions to steady state are not reported to save space.

*** INSERT FIGURE 17 HERE OR BELOW ***

From Figure 17 we can learn several things. Lets first notice that in the first best, car fleet from city 1 is cleaner than that from city 2. New cars are mostly located in city 1 until they get old enough and the tax that one has to pay to use them gets too high. In that case cars older than 16 years are displaced to city 2, where they can be used without polluting the air. The welfare under the first best taxation is US$9027,6. We will set it to 100 as we did before.

5.5 Subsidies and restrictions in a two-city model

One of the main disadvantage of using scrappage subsidy programs in a framework were different cities have different marginal damage functions is that it doesn't allow the regulator to put different incentives in every city. As used car markets are well arbitraged, offering a scrappage subsidy in city 1 will allow car dealers to take used cars from city 2 and scrapped them in city one to receive the subsidy. When analyzing scrappage subsidy problems then we will soon notice that the two cities model behave in the same way as the one city model.

Driving restrictions on the other hand are more flexible in that way since they can ban the use of some cars during some days in a particular city. We start modelling the case of a driving restriction applied to all cars from city 1 using the estimated value of $R = 0,94$. Figure 18 shows that, contrary to what the regulator would want, newer cars are displaced from city 1 to city 2. Since every car is exposed to driving restriction, drivers from city 1 are not willing to pay high rental prices for a car they can't use every day of the week. Therefore, more expensive cars are moved to city two.

*** INSERT FIGURE 18 HERE OR BELOW ***

This shows the perverse incentive of the policy that can result in an even dirtier fleet in the city with highest air quality problems. The welfare in this scenario is US$7420,9, equivalent to -20,74% of the gains that were obtained in the first best.

A way to avoid the exodus of new cars is exempting them from the restriction. We simulated again a driving restriction program where cars with less than 12 year were exempted from restriction. Those older were exposed to it, but only in city 1. Figure 19 shows the steady state obtained from this implementation. This exercise is particularly important as we found many results analogous to the empirical part. First of all notice that the newest and oldest cars are located similarly in city 1 and 2. Cars just bellow 12 years old, however, are concentrated in city 1, while cars with an age just above from 12 years old are mainly concentrated in city 2. The differences between city 1 and national fleet can be seen in Figure 19 (d). This figure shows us the empirical result found in Figure 8, where cars from vintage 1992 and bellow were displaced from Santiago to other regions of the country, supporting the idea of a vertical differentiation market of used cars.

*** INSERT FIGURE 19 HERE OR BELOW ***

Under this situation social welfare is US$7865,7 and represents a 12,68% of the gains from the first best.

5.6 Optimal interventions in a two-city model

When optimizing scrappage subsidy programs we find that the optimal subsidy amounts to US$2980. This value is lower than the one obtained in the one-city model, because the regulator doesn't want to scrap vehicles that are not old enough and can still have value in city 2 where pollution is less of a problem. As the regulator can't induce drivers from city 1 to use newer cars and drivers from city 2 to use older ones he must induce a middle solution in which used cars are not too old, nor too new. Figure 20 shows the main results of this simulation. Welfare estimations are US$8609,7 which represents 68,59% from the gains of the first best.

*** INSERT FIGURE 20 HERE OR BELOW ***

When optimizing driving restrictions we get to better results. The best driving restriction that can be implemented consists in an aggressive restriction where older that 16 years old cars are forbidden to drive in city 1 ($R = 0$). As it can be seen in Figure 21, newer cars and all cars driven in city 2 are exempt from this restriction. In equilibrium what happens is that new cars get highly concentrated in city 1, while older ones go to city 2, where they can still generate some surplus in drivers and there are not negative externalities. Under this scheme of driving restriction welfare calculations give a value of US$8897,7, reaching 90,24% of the gains from the first best.

*** INSERT FIGURE 21 HERE OR BELOW ***

This implementation is much better than the best possible scrappage subsidy as it has the advantage mentioned above of changing incentives in city 1 and 2 in different manners. It is also surprising that using well design driving restrictions one can get very close to the first best. Table 9 summarizes the main results of the simulations in the two-city model.

*** INSERT TABLE 9 HERE OR BELOW ***

Contrary to what we found in the one-city model, where driving restrictions and scrappage subsidies lead to similar outcomes, in the two-city model there are significant differences between the two policy interventions. While a subsidy can at best aim at 70% of the gains from first-best implementation, a well design driving restriction can go further to 90%.

This model allows one also to analyze other kind of interventions such as a subsidy to new cars production (lowering the cost c of new cars) or a subsidy to public transport (by increasing the option value u_0).

6 Conclusions

As the experience in Latin America shows, driving restriction policies are becoming an increasingly popular instrument to fight vehicle pollution and congestion. While it is well document that restriction programs can produce undesirable results, the evidence from Santiago's program shows that they can be quite effective in accelerating the fleet turnover towards cleaner vehicles. Since the reality is that authorities will continue relying on these policies, it is important to understand how they work in their different formats and to find ways to improve them. Using a simple model of car ownership and use we illustrate that well-designed restrictions can perform quite well. This can be particularly important for the design of climate change policies aimed at curbing CO2 emissions from the transportation sector. We believe that driving restrictions can be relatively easier and more effective to implement than alternative policies such as scrappage subsidies and subsidies to the purchase of low-emission vehicles. We leave for future work the analysis of driving restrictions for carbon mitigation.

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Figures and Tables

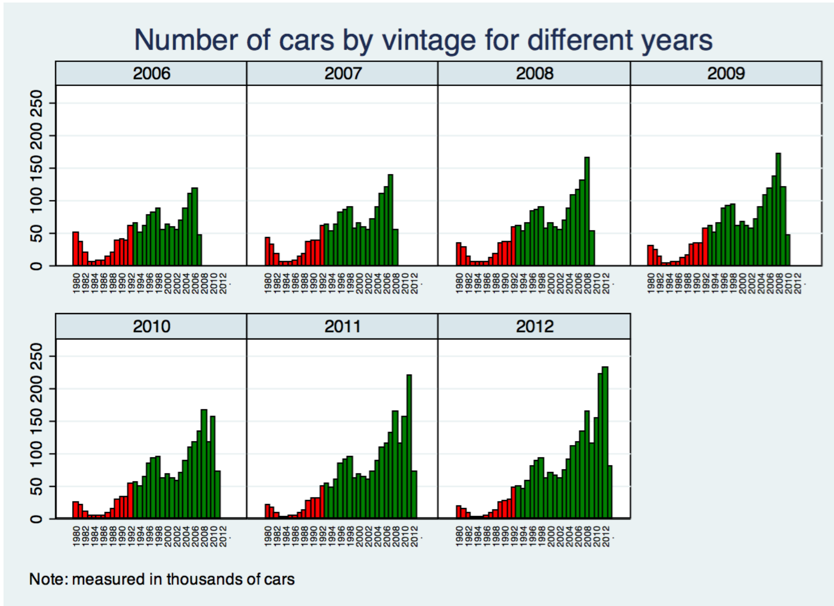
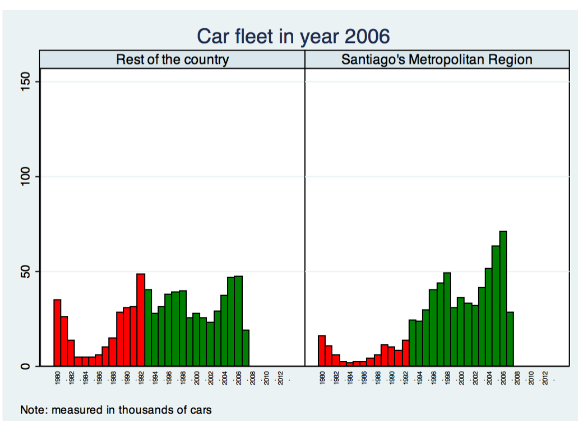
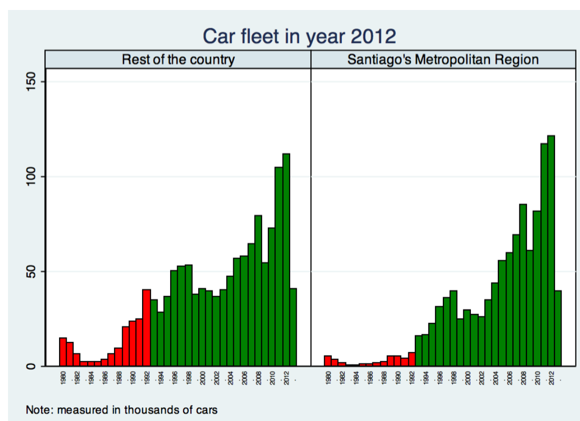


Figure 1: Evolution of the car fleet at the country level



(a) Fleet in 2006



(b) Fleet in 2012

Figure 2: Car fleet by region

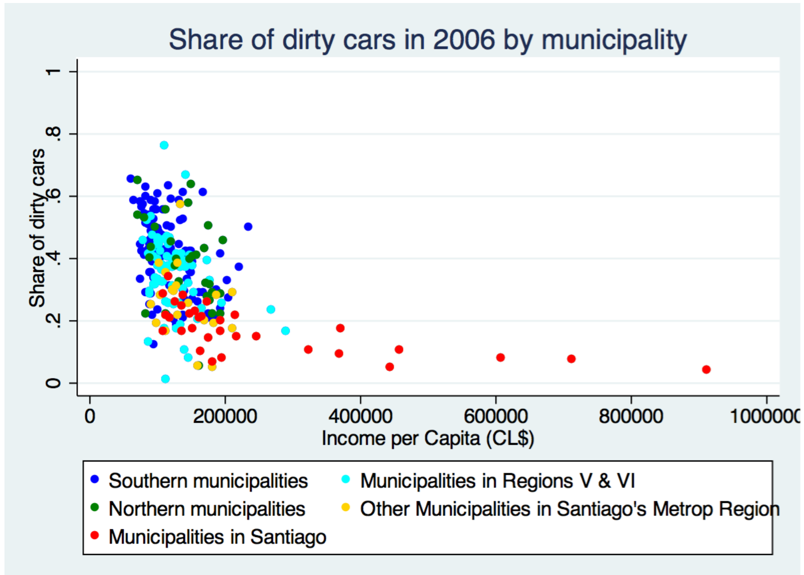


Figure 3: Share of dirty cars as function of income in 2006

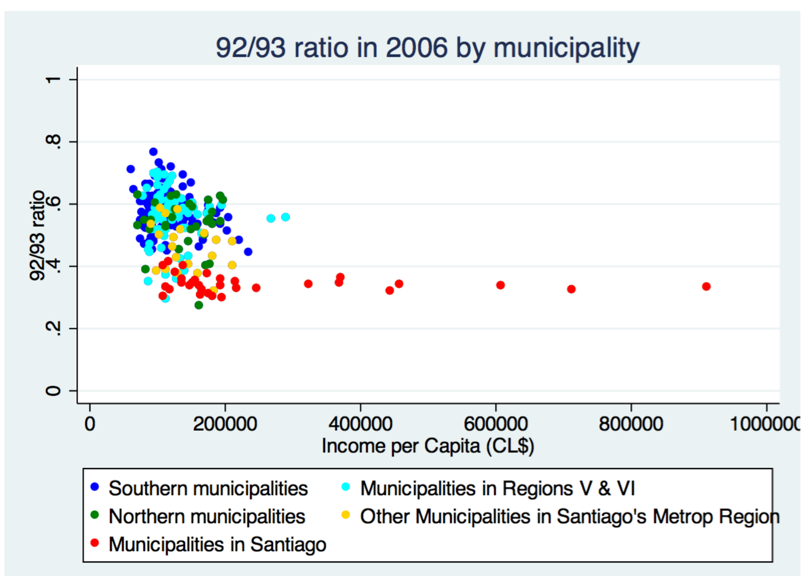
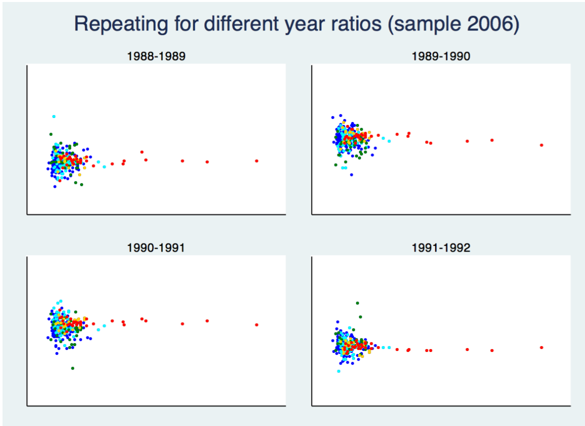
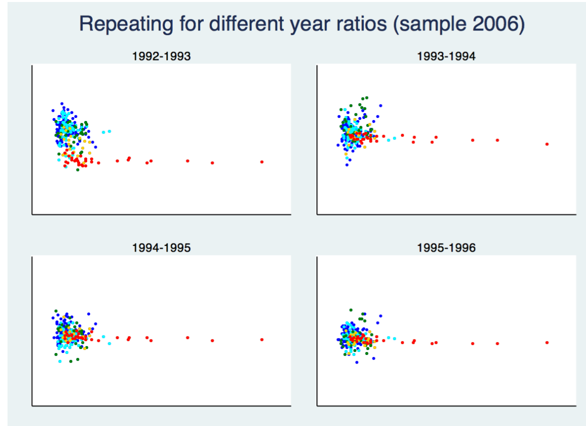


Figure 4: 92/93 ratio for sample 2006

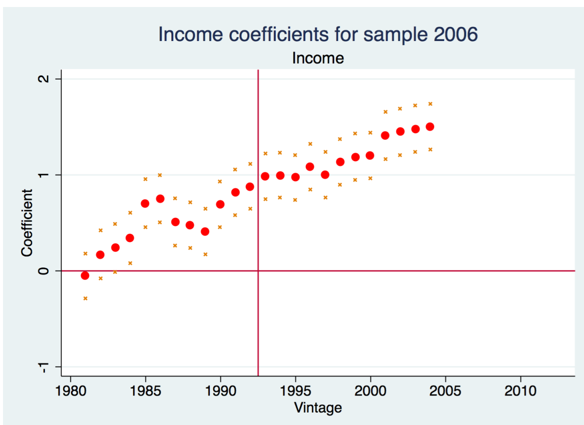


(a) Vintages 88 to 92

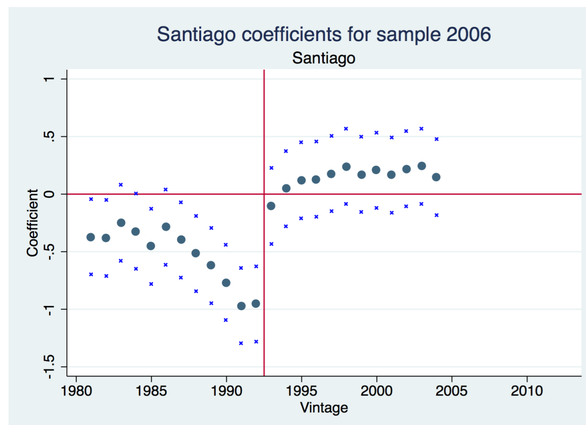


(b) Vintages 92 to 96

Figure 5: Falsification excersice with different ratios

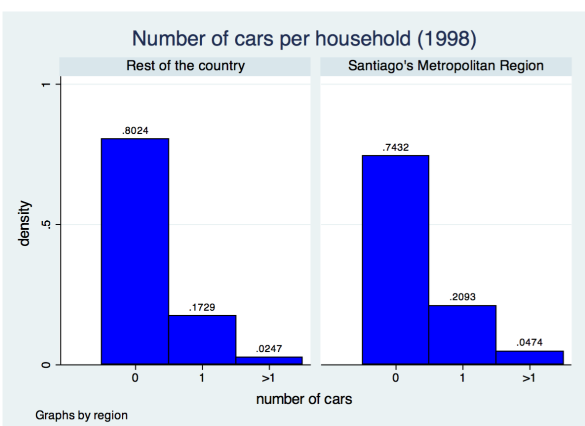


(a) *Income* coefficients

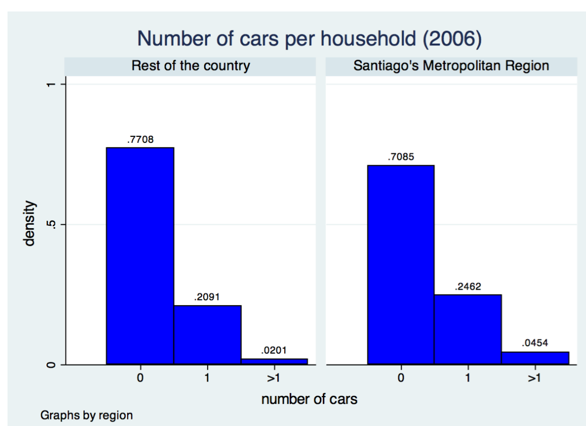


(b) *Santiago* coefficients

Figure 6: Coefficients by vintage



(a) sample 1998



(b) sample 2006

Figure 7: Histogram of numbers of cars per houshold

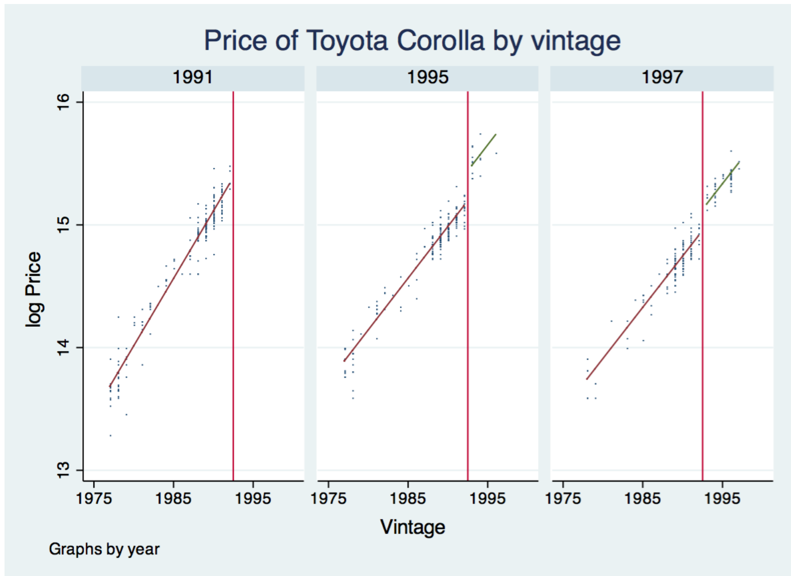


Figure 8: Price of used car Toyota Corolla by vintage

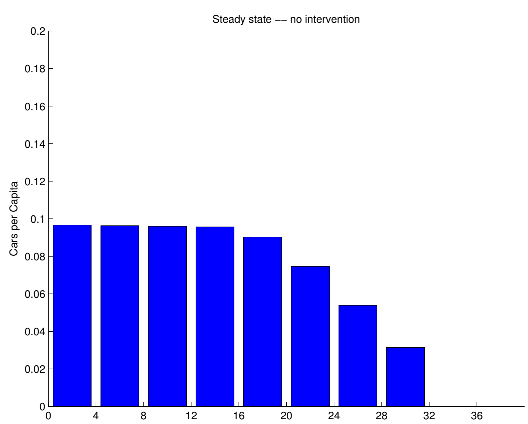
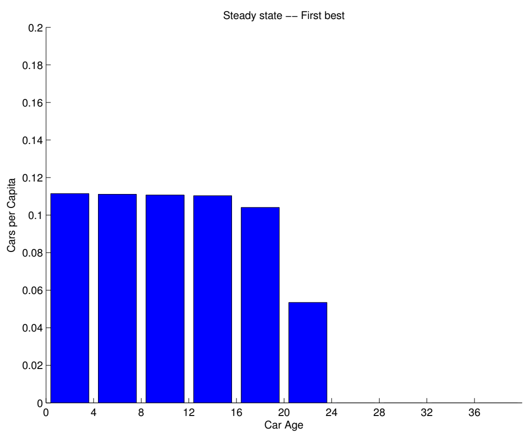


Figure 9: No intervention, steady state



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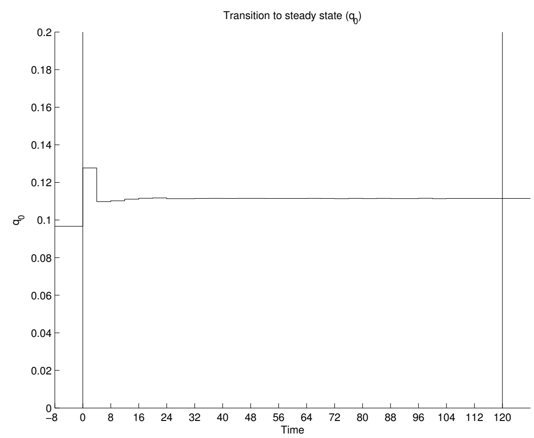
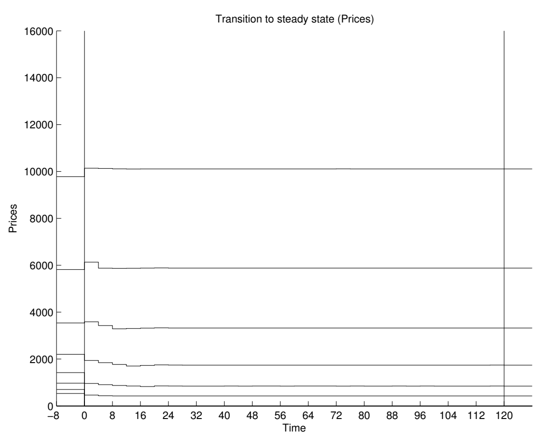
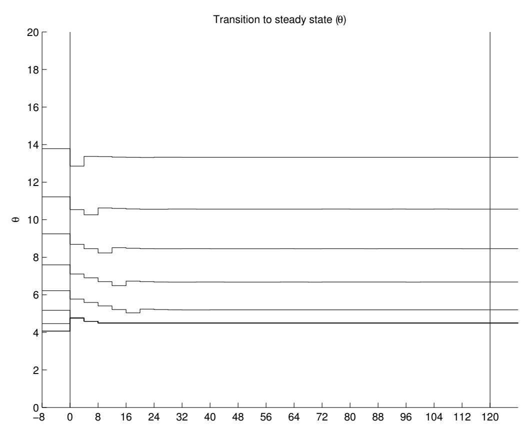


(b) Dynamics of q_0

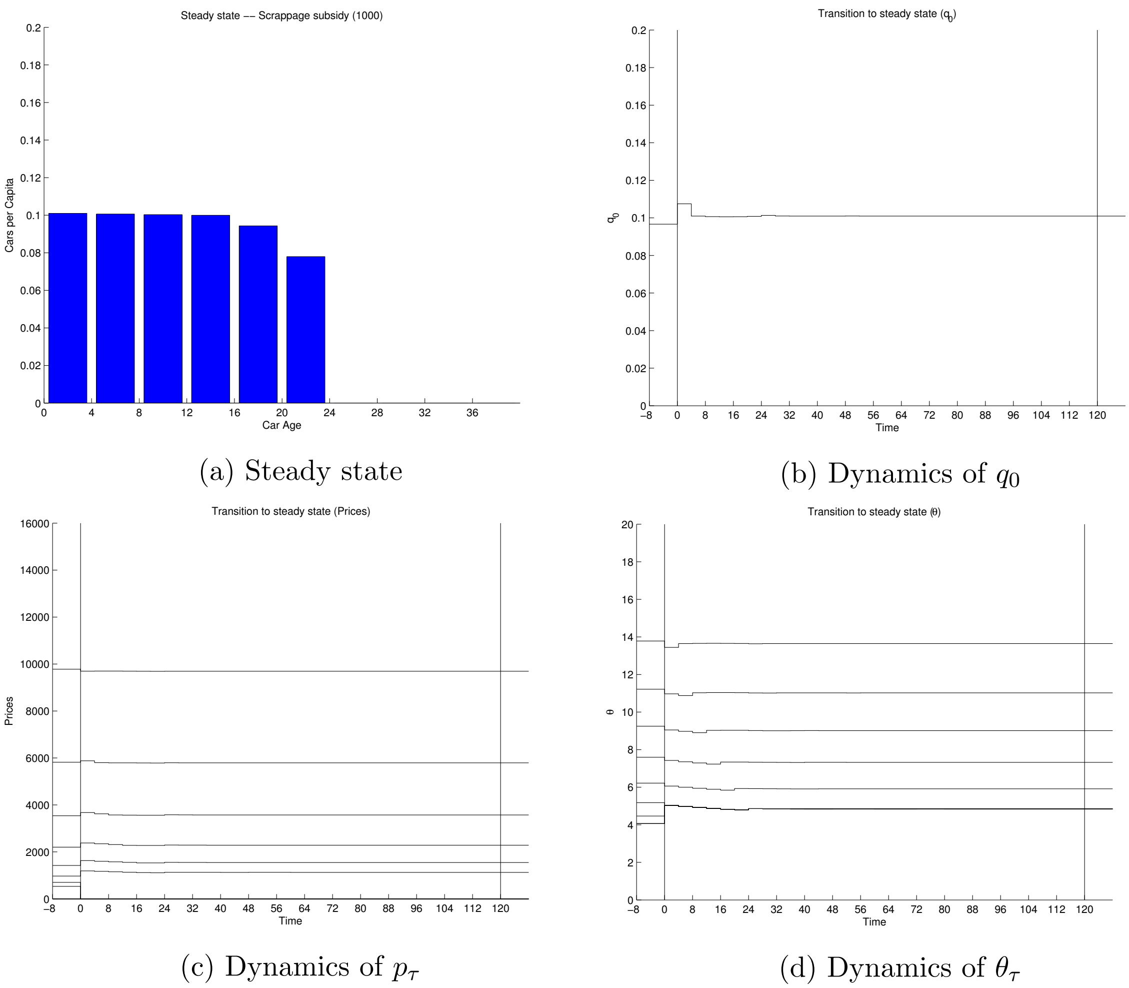


(c) Dynamics of p_τ



(d) Dynamics of θ_τ

Figure 10: First best



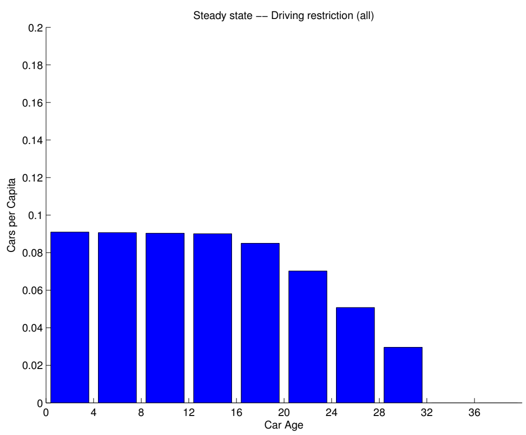
(a) Steady state

(b) Dynamics of q_0

(c) Dynamics of p_τ

(d) Dynamics of θ_τ

Figure 11: Scrappage subsidy (US$1000)



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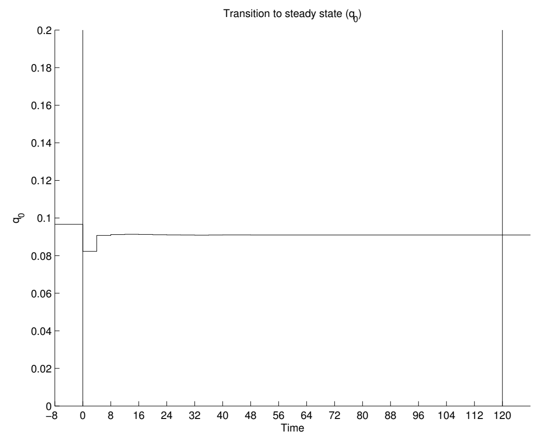

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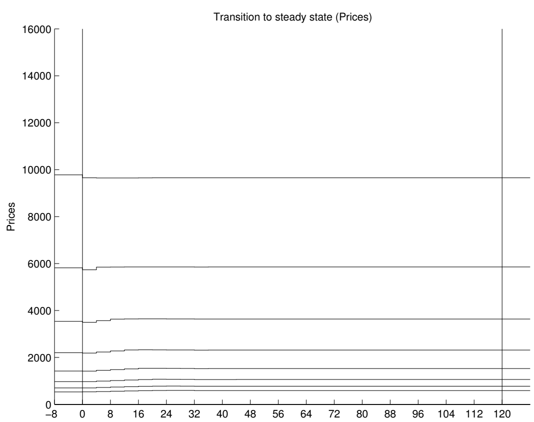

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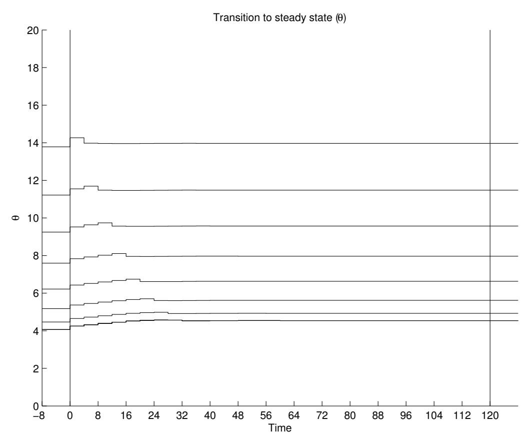
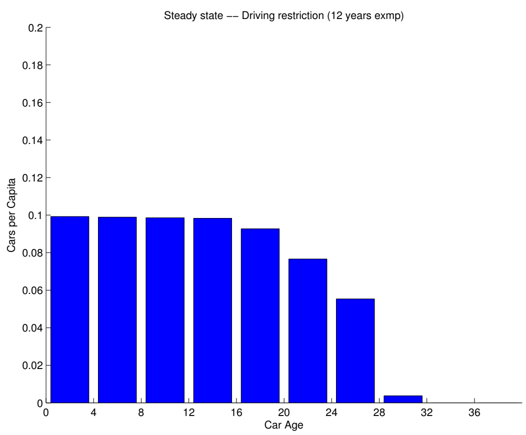


(d) Dynamics of θ_τ

Figure 12: Driving restriction (all cars)



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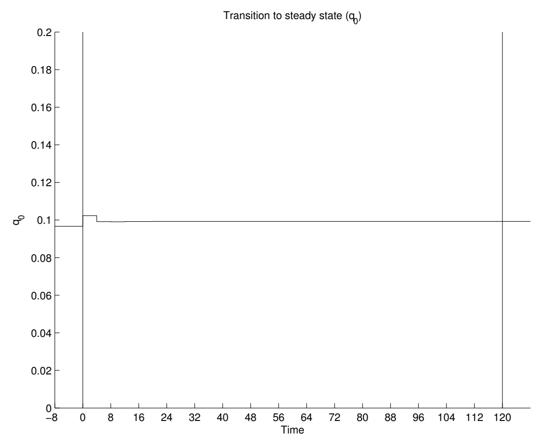

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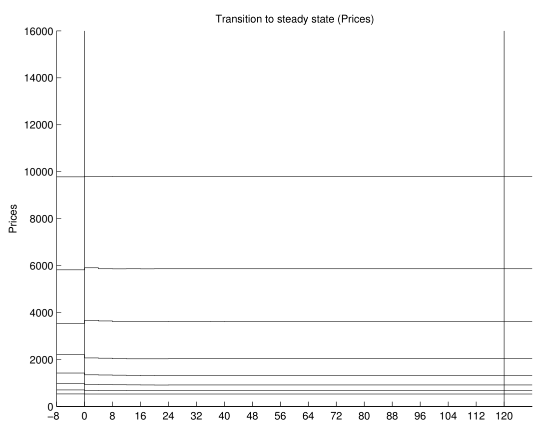

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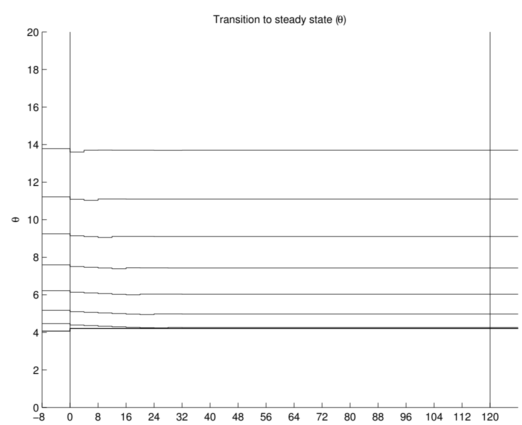
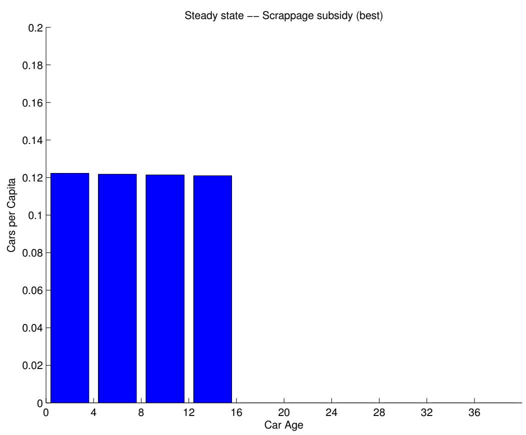


(d) Dynamics of θ_τ

Figure 13: Driving restriction (12 years exemption)



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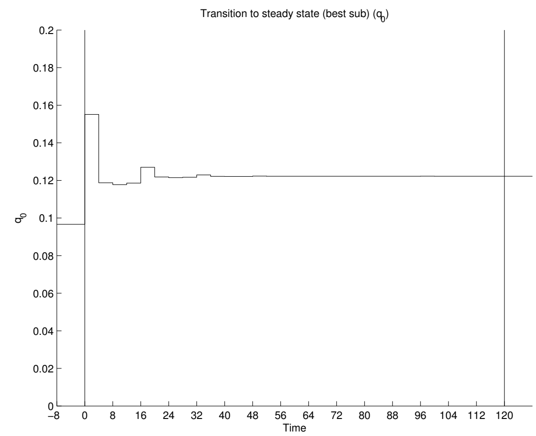

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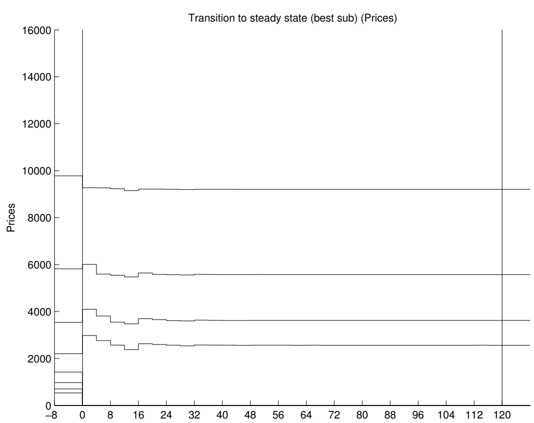

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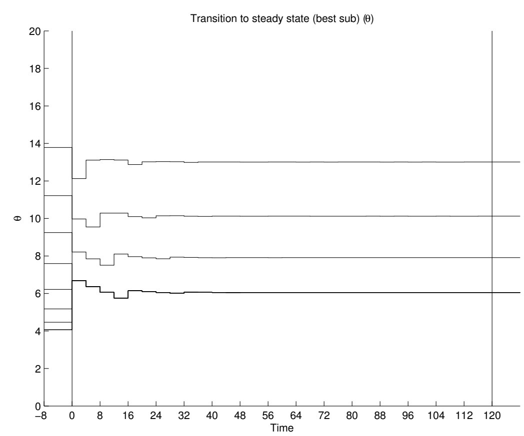
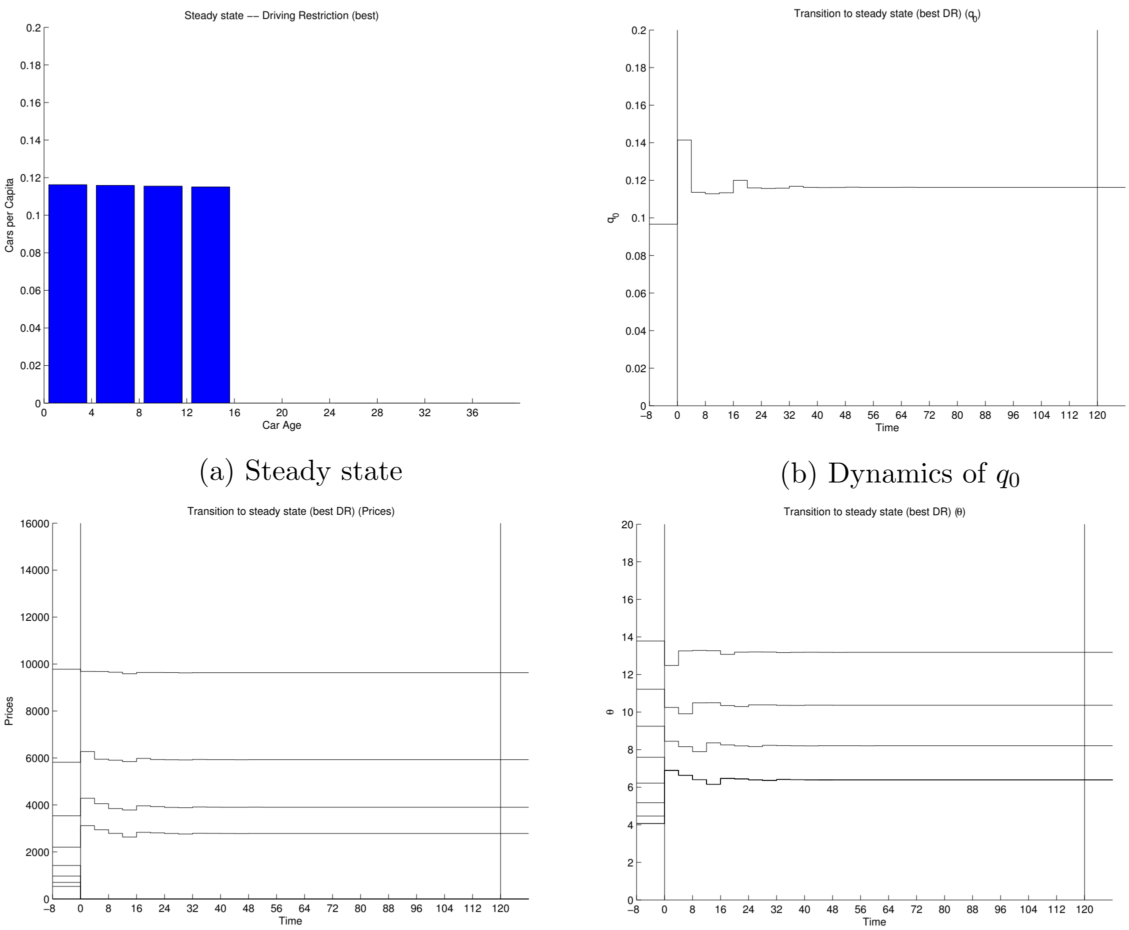


(d) Dynamics of θ_τ

Figure 14: Optimal subsidy (US$5050)



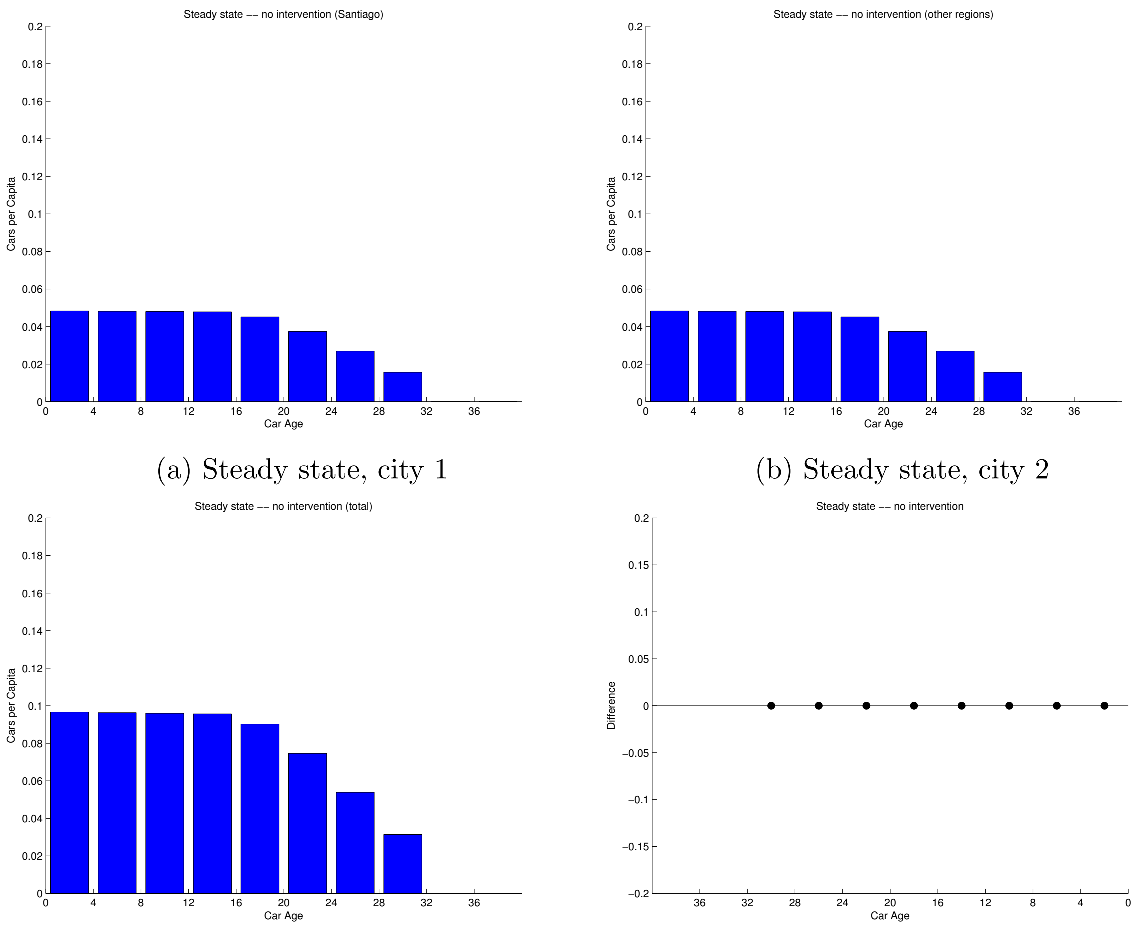
(a) Steady state

(b) Dynamics of q_0

(c) Dynamics of P_τ

(d) Dynamics of θ_τ

Figure 15: Optimal driving restriction



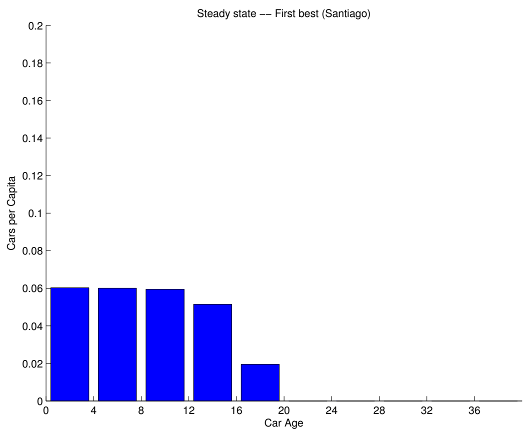
(a) Steady state, city 1

(b) Steady state, city 2

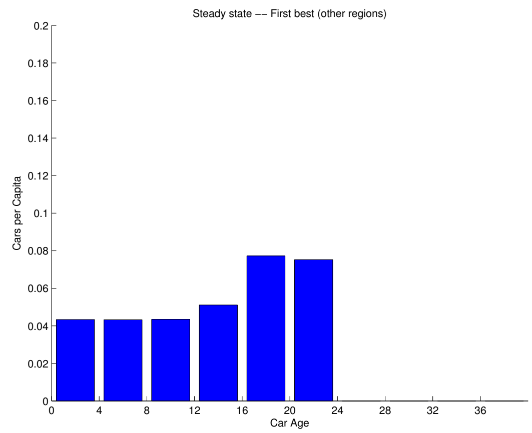
(c) Steady state, national level

(d) Difference between both cities

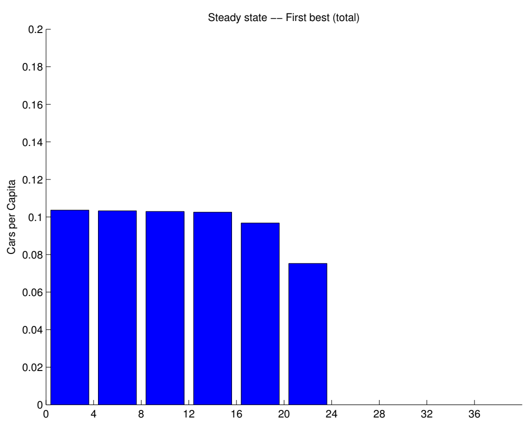
Figure 16: No intervention



(a) Steady state, city 1



(b) Steady state, city 2



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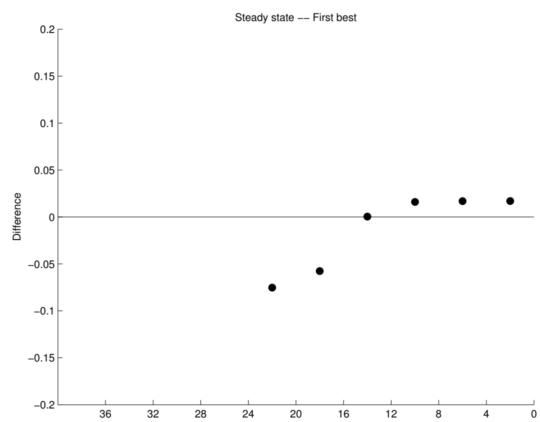
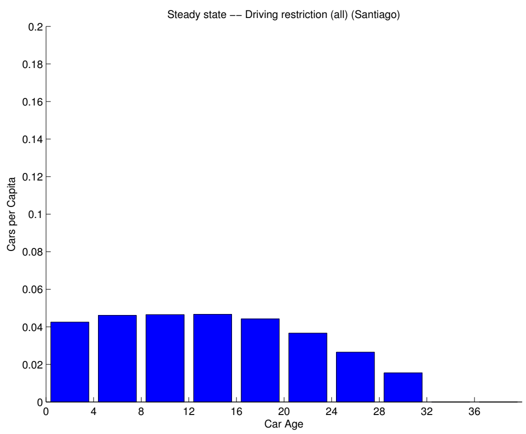


(d) Difference between both cities

Figure 17: First best



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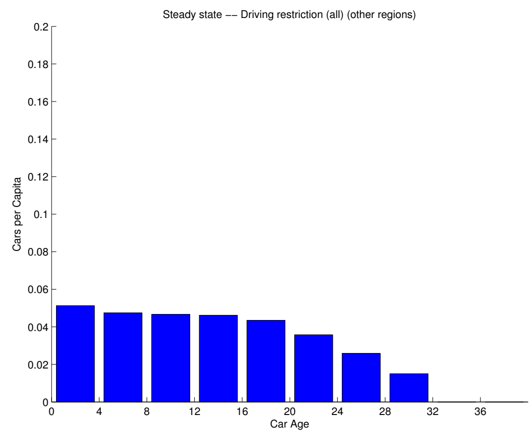
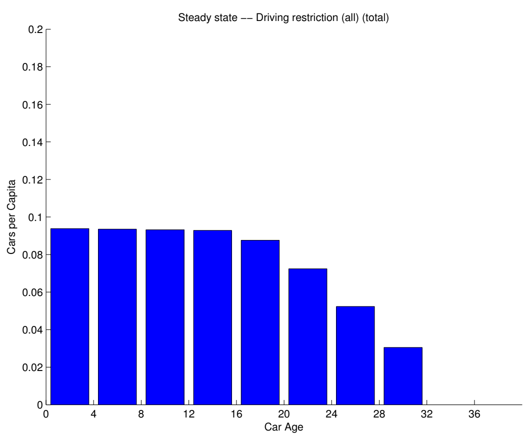


(b) Steady state, city 2



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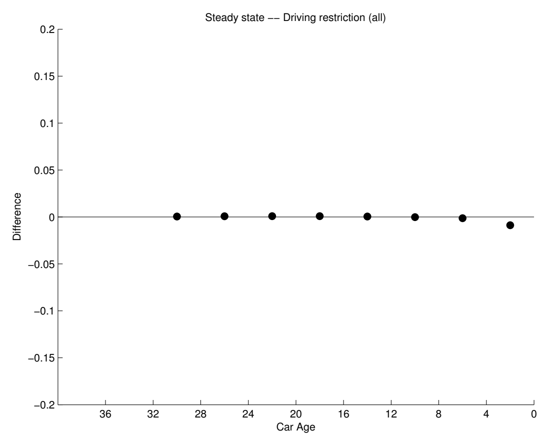
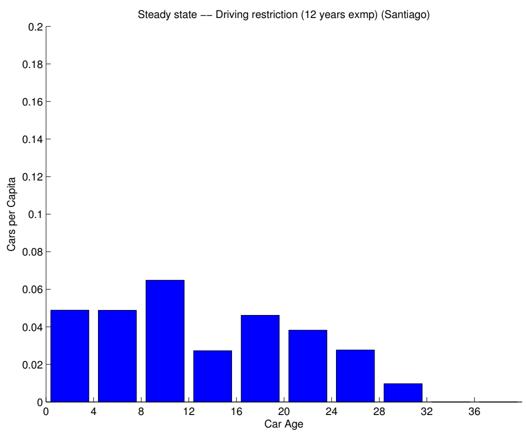


(d) Difference between both cities

Figure 18: Driving restriction (all cars)



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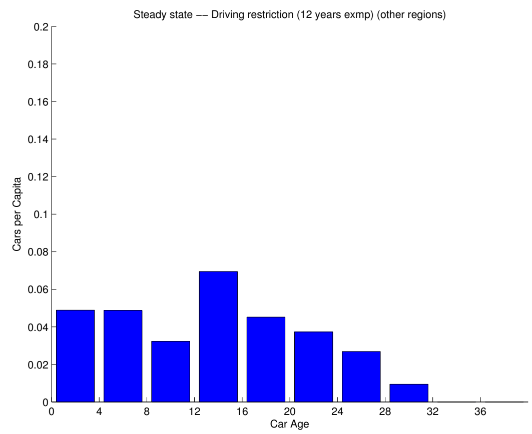

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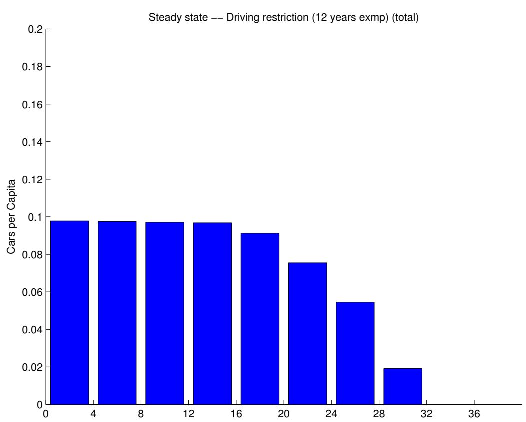

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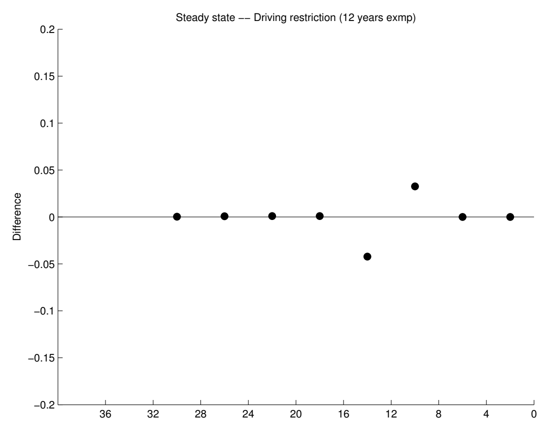

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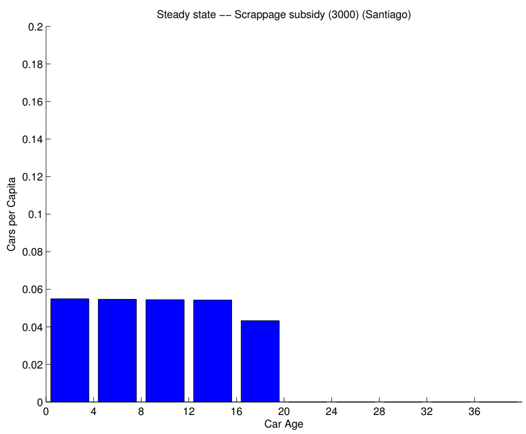
Figure 19: Driving restriction (12 years exemption)



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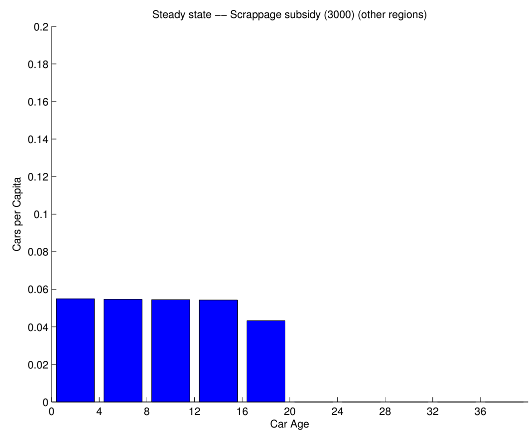

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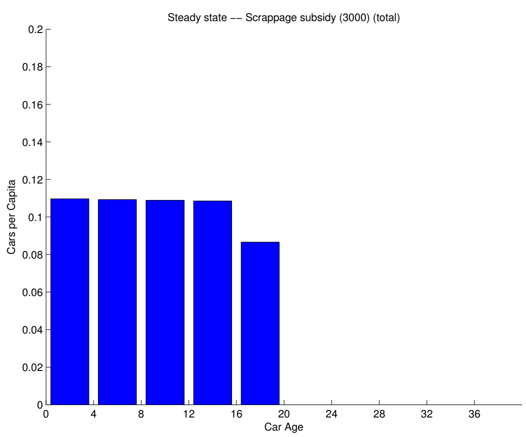

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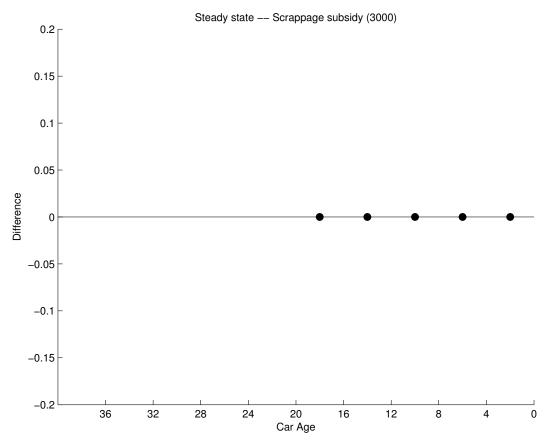
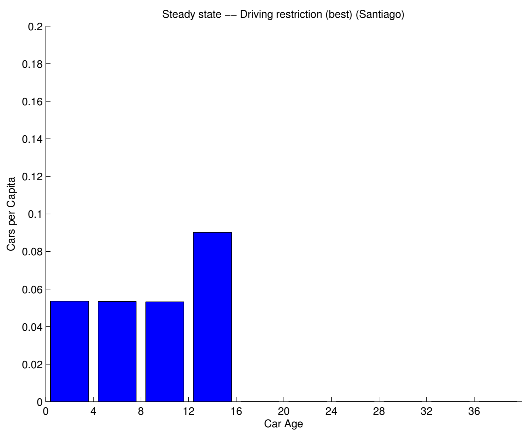


(d) Difference between both cities

Figure 20: Optimal subsidy (US$2980)



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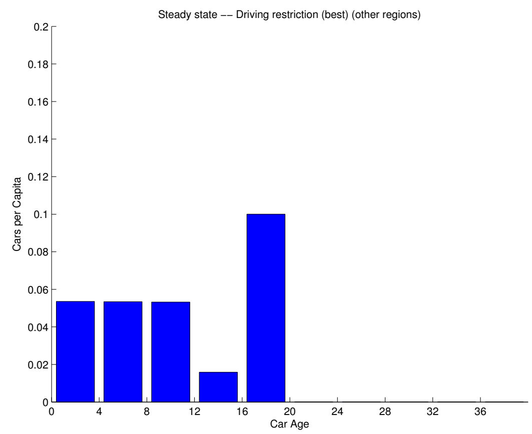

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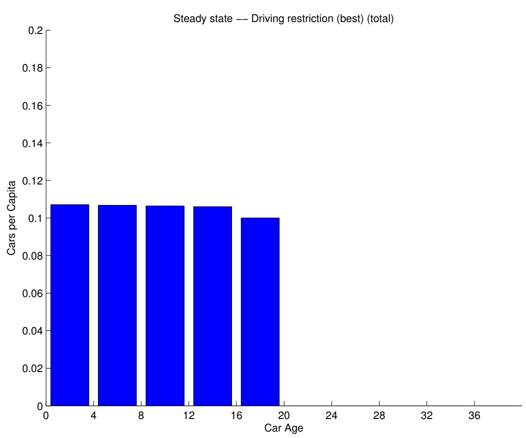

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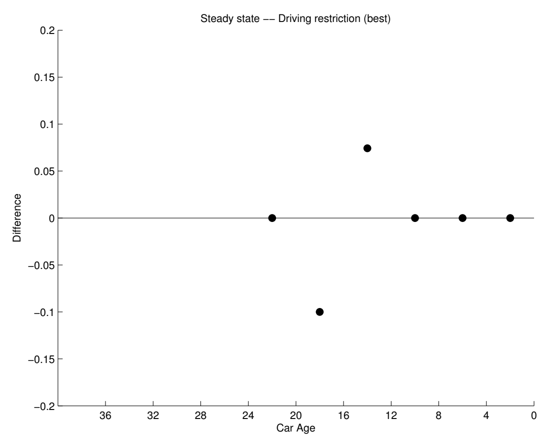

(d) Difference between both cities

Figure 21: Optimal driving restriction

Table 1: OLS results for different contiguous-year ratios

	(1) 88-89	(2) 91-92	(3) 92-93	(4) 93-94	(5) 95-96
Santiago	0.0166	0.00166	-0.171***	-0.0183	-0.00646
	(0.014)	(0.013)	(0.018)	(0.015)	(0.012)
Population	-0.000208	0.00235	-0.00743	-0.00174	0.000280
	(0.005)	(0.004)	(0.006)	(0.005)	(0.004)
Income per capita	-0.00145	-0.00522	-0.00655	-0.00655	-0.0100*
	(0.005)	(0.005)	(0.006)	(0.005)	(0.004)
Distance to Santiago	-0.0626*	-0.0138	0.141***	0.0184	0.00601
	(0.026)	(0.024)	(0.033)	(0.027)	(0.022)
(Distance to Santiago)^2	0.0285	0.0200	-0.0906***	0.00330	0.00805
	(0.020)	(0.018)	(0.025)	(0.020)	(0.017)
Far away regions	0.0974**	-0.0451	0.00516	0.135***	0.0760**
	(0.034)	(0.031)	(0.043)	(0.035)	(0.029)
Income dispersion	0.00262	-0.000899	0.00143	-0.00741	0.00369
	(0.006)	(0.005)	(0.007)	(0.006)	(0.005)
North	0.0240*	0.0398***	-0.0277	0.0346**	-0.0250*
	(0.012)	(0.011)	(0.015)	(0.012)	(0.010)
Urbanization	-0.0485**	-0.0288	-0.00372	-0.00707	0.0108
	(0.017)	(0.015)	(0.021)	(0.017)	(0.014)
Constant	0.372***	0.413***	0.542***	0.559***	0.444***
	(0.014)	(0.013)	(0.018)	(0.015)	(0.012)
Observations	266	266	266	266	266
R^2	0.165	0.085	0.520	0.336	0.189

Standard errors in parentheses

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

Income per capita in hundreds of thousends of pesos.

Population in hundreds of thousends of persons.

Distance to Santiago in hundreds of kilometers.

Table 2: Effect of living in Santiago on having more than one car

	(1998)			(2006)		
Panel A: marginal effects on probability of having two cars conditional on having at least one						
OLS	0.0018			0.00999		
	(0.006)			(0.0144)		
probit	-0.00076			0.0031		
	(0.001)			(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***	-0.0258***	-0.0021***	0.0206*	-0.0192*	-0.0014*
	(0.01)	(0.009)	(0.0007)	(0.011)	(0.0104)	(0.0007)
ordered probit	0.0318***	-0.0299***	-0.002***	0.0212*	-0.01998*	-0.00126*
	(0.01)	(.0103)	(0.0007)	(0.012)	(0.0112)	(0.00067)
Panel C: marginal effects on having an extra car using count data models						
poisson	-0.0185***			-0.0181***		
	(0.0058)			(0.0065)		
hurdle poisson-logit	0.062			-0.01216		
	(0.081)			(0.0968)		

Standard errors in parentheses

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

Table 3: Effect of driving restriction on Toyota Corolla prices

	(1991)	(1995)	(1997)
Panel A: Linear control			
Vintage	-0.110***	-0.0843***	-0.0834***
	(0.002)	(0.002)	(0.002)
Post 1992		0.243***	0.175***
		(0.028)	(0.022)
Observations	259	222	194
R^2	0.953	0.947	0.944
Panel B: RD			
Post 1992		0.331***	0.251***
		(0.074)	(0.067)

Standard errors in parentheses

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

Table 4: Effect of driving restriction on Honda Accord prices

	(1991)	(1992)	(1993)	(1994)
Catalytic	0.223***	0.189***	0.0206	-0.00487
	(0.059)	(0.040)	(0.036)	(0.026)
Constant	15.60***	15.68***	15.96***	16.40***
	(0.031)	(0.026)	(0.023)	(0.009)
Observations	47	53	58	49
R^2	0.245	0.309	0.006	0.001

Standard errors in parentheses

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

Table 5: Relation between fleet percent share and emissions contribution in Mexico (Molina and Molina, 2002)

Car vintage	Fleet Percent Share	Emissions Contribution
1993-2001	60%	15%
1985-1992	28%	30%
1980-1985	7%	25%
1979 & older	5%	30%

Table 6: Fleet percent share in Chile

Car vintage	Fleet Percent Share
1993-2001	63.3%
1985-1992	24.1%
1980-1985	9.3%
1979 & older	3.3%

Table 7: Average externalities produced by a car in Santiago and other regions in one year

Car vintage	Santiago	Other regions
1993-2001	US$180	US$21
1985-1992	US$771	US$90
1980-1985	US$2571	US$300
1979 & older	US$4320	US$504

Table 8: Welfare calculations in a one city model

Contrafactual	Welfare (US$)	Transformed welfare
No intervention	5897,8	0
First best	8465,9	100
Subsidy US$1000	7451,5	60,50
Subsidy US$5050	8076,5	84,83
Driving restriction $R = 0.94$ $\forall \tau$	5066,9	-32,35
Driving restriction $R = 0.94$, $\tau > 3$	6492,6	23,16
Driving restriction $R = 0$, $\tau > 4$	8071,2	84,63

Table 9: Welfare calculations in a two cities model

Contrafactual	Welfare (US$)	Transformed welfare
No intervention	7696,9	0
First best	9027,6	100
Subsidy US$2980	8609,7	68,59
Driving restriction $R = 0.94$ $\forall \tau$	7420,9	-20,74
Driving restriction $R = 0.94$, $\tau > 3$	7865,7	12,68
Driving restriction $R = 0$, $\tau > 4$	8897,7	90,24