The Environmental Effect of Green Taxation: The Case of the French "Bonus/Malus"*

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Abstract

A feebate on the purchase of new cars, the "Bonus/Malus", was introduced in France in 2008. The less polluting cars benefited from a price reduction of up to 1,000 euros, while the most polluting ones were subject to a taxation of 2,600 euros. We estimate the impact of this policy on carbon dioxide emissions in the short and long run. If the shift towards the classes benefiting from rebates is considerable, we estimate the environmental impact of the policy to be negative. While feebates may be efficient tools for reducing CO_2 emissions, they should thus be designed carefully to achieve their primary goal.

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In the attempt to mitigate global warming, many policies have been launched that aim at cutting vehicle carbon dioxide (CO_2) emissions. The transportation sector does indeed

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account for a third of the total CO_2 emissions in developed countries. While fuel taxes and standards such as the Corporate Average Fuel Economy in the US are the most commonly used instruments for reducing CO_2 emissions, feebates have recently received attention. A feebate is an original policy instrument that gives individuals an incentive to internalize the pollution externalities of specific goods, typically automobiles, by providing a rebate for purchasers of low-emitting cars and imposing a fee on those who prefer high-emitting vehicles.[1] Such feebates have several advantages over usual instruments (see Fullerton and West, 2002 for a discussion of alternative instruments). The rebate makes this policy easier to implement than fuel taxes, which are optimal in theory but also very unpopular.[2] Besides, empirical evidence suggests that consumers undervalue future fuel costs when they choose a new vehicle (see, e.g., Allcott and Wozny, 2011), selecting automobiles with poorer fuel economy than they should optimally do. Feebates may thus be a useful complement to fuel taxes.

Yet the effect of feebates on CO_2 emissions is ambiguous. Like other policies based on fuel economy performance, they do not act on the intensive margin. With vehicles that are more fuel efficient, drivers are likely to travel more. This "rebound effect" offsets the reduction of CO_2 emissions. If badly designed, feebate systems may also have the opposite effect to that intended, by increasing automobile sales and, as a result, overall CO_2 emissions. Moreover, an appropriate design may be difficult to achieve. It depends greatly on price elasticities, which may not be known accurately by policy makers (for a discussion of the optimal design of a feebate system, see for instance Greene *et al.*, 2005, or Peters *et al.*, 2008). It is therefore important to assess empirically the true effect of such policies.

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[1] Up to now, feebates have been implemented in Austria, France and Wallonia (a Belgium region), and are debated in other European countries. Most of the other European countries have implemented a taxation that is more or less related to the average CO_2 emissions of the vehicles (for more details, see for instance the ACEA site). California also proposed in 2007 a feebate system called the "Clean Car Discount" program on new cars, but the Bill failed to pass.

[2] In France, for instance, the government attempted to implement a carbon tax of 17 euros per ton of CO_2 in 2009. This tax was adopted by the Parliament but rejected by the Constitutional Court. Because of its unpopularity both in the opinion and in the governing party, the government finally decided to withdraw its proposal.

This paper estimates the impact on CO_2 emissions of the introduction in France of a feebate, the "Bonus/Malus écologique", in January 2008. We compute in particular the counterfactual emissions that would have prevailed in the absence of the feebate. For that purpose, we develop a simple demand model that combines car and annual mileage choices. This model accounts for consumers' heterogeneity in preferences, the differentiation of the automobile market, and the existence of rebound effects, while remaining very tractable. We estimate this model on an exhaustive monthly dataset of new car registrations. This dataset provides detailed information on vehicles but also on drivers. We can thus accurately take into account heterogeneity in taste due to observable characteristics of consumers. We also use a transportation survey conducted in 2007 that records in particular annual mileage for a large sample of French households. Our model and these two datasets allow us to recover choices both with and without the feebate system, and average emissions related to car use for a particular choice of car. An original aspect of our method is that we do not rely on list prices, but rather on a reduced form that combines the demand model and a simple price model. The reason for this is that list prices are typically modified once a year only, and are thus likely not to reflect the changes in transaction prices that occurred quickly after the introduction of the feebate.

A substantial shift towards the classes of automobile benefiting from a rebate occurred after the introduction of the policy. Nevertheless, we estimate the environmental short-run impact of the feebate to be, in fact, negative. This disappointing result is mainly explained by overly generous rebates. As a result, the policy appears to enhance the total sales of new cars by around 13%, despite the slowing down of the economy observed at this period. This large scale effect translates into extra CO_2 emissions through the increase in mileage and the manufacturing process of these new vehicles. Reactions of French consumers actually exceeded the forecasts of the French government. Planned to be neutral for the State budget, the measure turned out to cost 285 million euros in 2008 because of its overwhelming success in favoring the choice of cars with low CO_2 emissions. This suggests that automobile consumers may be very reactive to modest changes in prices (as also recently observed by Busse *et al.*, 2010). Even though consumers reacted massively to the policy, this reaction did not translate into a large decrease in the average

CO_2 emissions of new cars. Buyers shifted their purchase option to cars benefiting from rebates but with hardly lower emissions. This strategic response was previously observed by Sallee and Slemrod (2012) for automakers in Canada.

As the reform was announced only around the end of October 2007, manufacturers were unable to modify their vehicles' characteristics immediately. The short-run impact is thus purely a consequence of the demand-side reaction to the policy. One should interpret this impact with caution, however. In the short run, the demand shift due to the feebate corresponds to a very small part of the whole automobile fleet. The long run effect, when the whole fleet has been replaced, may be different. To compute such a long-run effect, the impact of the policy on the replacement rates of vehicles must be taken into account. Adda and Cooper (2000) and Li *et al.* (2009) show, in related settings, that changes in replacement rates may have large consequences. To estimate the effect of the policy on replacement rates, still ignoring supply-side reactions, we consider a simple dynamic model with competitive prices in the secondary market for cars. This model relates the change in replacement rates to changes in initial prices, following Engers *et al.* (2009). Ultimately, the scale effect of the policy still dominates in the long run, implying once more an increase in CO_2 emissions.

Due to data availability, our analysis is restricted to the demand reaction to the feebate. In the long run, however, automakers' reactions are likely to enhance the environmental effect of the policy. Klier and Linn (2010) for instance observe firms' responses over the medium term to high fuel prices (see also Knittel, 2011). To check the robustness of our results to such reactions, we perform a sensitivity analysis by simulating a 5% increase in the fuel economy of all new vehicles. This does not modify the overall assessment of the policy. On the other hand, we show that a modest decrease in the rebate amounts would slightly decrease overall CO_2 emissions, highlighting once more the importance of designing feebates appropriately.

The paper is organized as follows. The next section presents the reform and some initial evidence on its effects. The second section presents the parameters of interest. The third section describes the data, while the fourth presents our identification strategy. Our results are set forth and commented in Section 5. Finally, Section 6 concludes.

1 Overview of the Policy

1.1 The Feebate System

The feebate system on sales of new cars was introduced by the French government for all cars registered after the 1st of January 2008. The purchasers of new cars emitting less than 130g of CO_2 per kilometer benefited from a direct price cut on their invoice. The amount of the rebate varied, depending on the class of the vehicle (see Table 1), up to a maximum of 1,000 euros. The rebate actually rose to 5,000 euros for electric cars, but they represented a negligible share of the market at that time. Conversely, purchasers of cars emitting more than 160g of CO_2 per kilometer had to pay a tax of up to 2,600 euros. The system was neutral for cars emitting between 130 and 160 g per kilometer. The chosen classification corresponds to the one defined by the European Union for energy labeling on cars, except that the government split the A, C and E classes into two subclasses.

In practice, rebates apply to new cars ordered on or after the 5th of December 2007, while fees apply to vehicles first registered in France on or after the 1st of January 2008. At the same moment, the government introduced a scrapping subsidy of 300 euros called the "super bonus" for automobiles more than 15 years old, provided that the purchaser bought a new vehicle emitting less than 160g of CO_2. In 2008, this super bonus concerned only 5.4% of vehicle purchases benefiting from a rebate (see Friez, 2009), and we ignore it hereafter. This scrapping subsidy was raised to 1,000 euros and extended to 10 to 14 year-old cars in 2009, in order to dampen the economic impact of the crisis on the automobile industry. We shall not be concerned further with it here, as we focus on 2008 only. The feebate concerns all new car registrations, whether the purchaser is an individual or a firm. There is thus no incentive for companies to have their business cars (falsely) registered as the individual property of their employees.

The feebate policy was decided upon and then implemented at an unusually fast pace. It resulted from a national environmental roundtable organized in Autumn 2007 by the newly elected president, the aim of which was to define the key points of government

Table 1: Amount of the Feebate as a Function of CO_2 Emissions

Class	CO_2 Emissions (g/km)	Rebate	Average Price (2007)	Market shares (2007)
A+	≤60	5,000	-	-
A-	61-100	1,000	12.500	0.0%
B	101-120	700	15.500	18.4%
C+	121-130	200	19.000	10.2%
C-	131-140	0	19.000	18.8%
D	141-160	0	23.000	26.6%
E+	161-165	-200	23.500	3.2%
E-	166-200	-750	29.000	15.9%
F	201-250	-1,600	40.000	5.0%
G	≥251	-2,600	60.500	1.9%

Sources (for prices and market shares): dataset on the registration of new cars (CCFA).

Notes: we observe no sales for class A+ in 2007. Average prices are computed using list prices.

policy on ecological and sustainable development issues for the coming five years.[3] The policy measures, including the feebate system, were presented on the 25th of October 2007, for application almost immediately. This roundtable and the feebate policy came as quite a surprise, as they had not been mentioned during the electoral campaign, and the right-wing government party was not thought to give high priority to environmental issues.

In magnitude and scope, this "green" taxation scheme for the purchase of new cars by private owners has no precedent in France. Some measures had already been taken to increase the population's awareness of the environmental costs of motor vehicles. But for private users, they either focused on very specific segments of the market, or were wide in scope but marginal in magnitude. Examples include an income tax reduction for the purchasers of hybrid vehicles, or a very small tax on the most polluting vehicles (around 100 euros for cars costing on average 35,000 euros). In contrast, the feebate introduced at the end of 2007 applied to all cars, the rebate representing up to 8.8% of the list price, and the penalty rising to as much as 14.1% of the list price.

[3] This roundtable was called the “Grenelle de l'Environnement" as an evocation of the “Accords de Grenelle" concluded in May 1968; see http://www.legrenelle-environnement.fr/spip.php?rubrique112.

The objective of the feebate system was twofold. First, it aimed to shift consumer demand towards low CO_2-emitting cars. Second, it aimed at encouraging manufacturers to develop greener vehicles. To better achieve this second purpose, it was stated from the outset that the thresholds of the classes were to be gradually lowered in future, at a pace allowing manufacturers to adapt their products (5g of CO_2/km every two years).

1.2 Descriptive Evidence on the Impact of the Policy

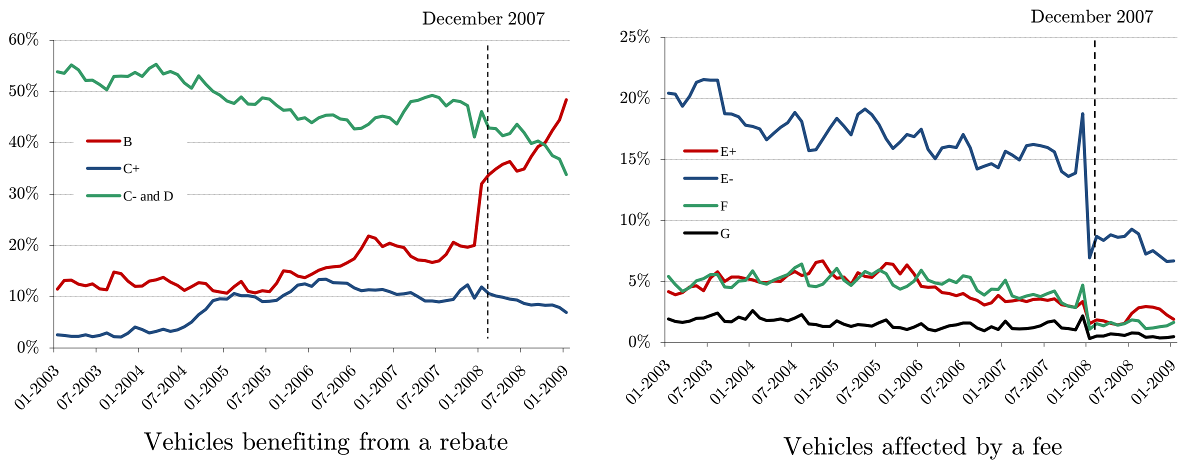
French consumers have reacted strongly to the feebate system.[4] This reaction has led to a replacement of polluting cars by the less polluting ones targeted by the tax rebates, but also, more surprisingly, to a net increase in the total sales of new cars. These impacts do not appear to be due to seasonal effects or changes in the macroeconomic situation. By contrast, we do not observe, in the very short run, any clear evidence of a sharp break in CO_2 emissions of cars supplied.

To start with, the changes in the market shares of the energy classes after the reform came into effect were impressive. While class B only represented 20% of sales at the end of 2007, its market share reached nearly 50% at the beginning of 2009 (see Figure 1). Over the same period, the market share of class E- fell from nearly 15% to 5%. These changes induced a significant impact on average emissions (see Figure 2). However, this effect is much smaller than the one observed on market shares. Compared to what we would expect, given the trend between November 2005 and November 2007, the average decrease in emissions over the period from March 2008 to January 2009 only reaches 5%. This results mainly from threshold effects (see Figure A.1 in Appendix A1). Many buyers have only marginally modified their purchasing decisions, choosing for instance a car emitting 120 g/km and thus falling into class B, rather than a car emitting 121 or 122g/km and thus falling into class C+.

As the implementation of the measure was almost immediate, neither consumers nor manufacturers could anticipate the reform before November 2007. On the other hand,

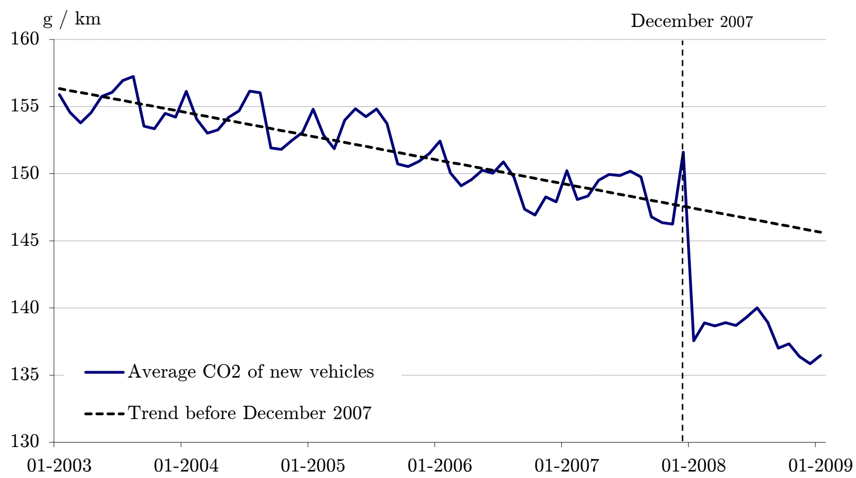
[4] Here and throughout we focus on personal cars only. Our data suggest that companies also react to the feebate, but to a somewhat smaller extent. Company cars had already been taxed on the basis of energy classes since 2006.

Figure 1 shows that anticipation on the part of consumers spiked in December 2007, especially for the most polluting cars, for which the fee would only apply in January 2008. Not surprisingly, this large increase for the most polluting classes was followed by an "undershoot" in January and, to a lesser extent, in February. We do not observe any noticeable change in November, even though the reform had already been announced then. This is probably due to the delivery time of new cars, as well as the waiting time between the purchase and the registration of a new car.



Sources: dataset on the registration of new cars (CCFA).
Note: market shares of the different classes sum to one.

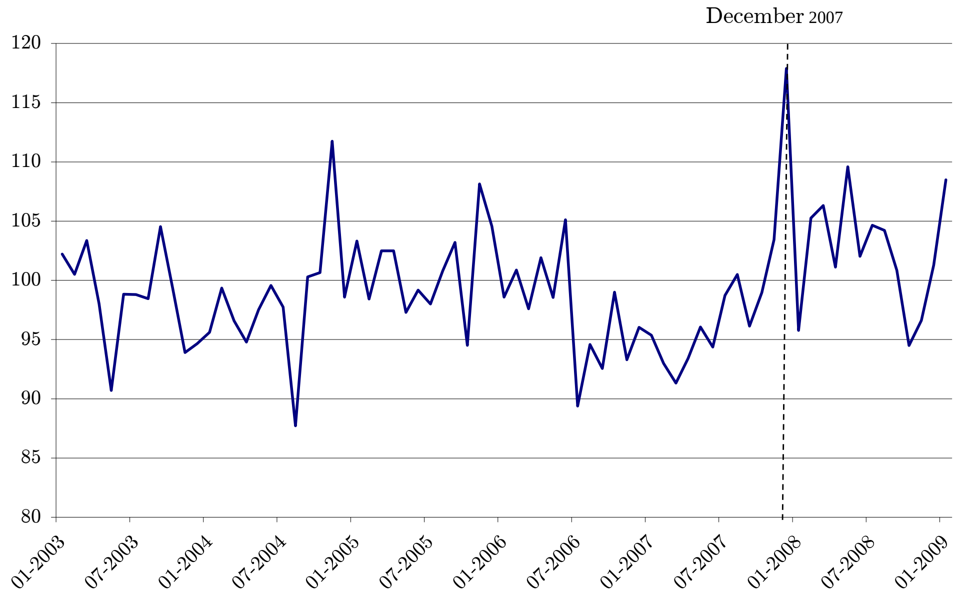
Fig. 1: *Evolution of the Market Shares of the Different Classes of CO_2 Emissions*



Sources : dataset on the registration of new cars (CCFA).

Fig. 2: *Evolution of the Average CO_2 Emissions of New Cars*

Market share variations are quite striking, given that the feebate only represents a modest fraction of list prices, around 4.7% for class B and 2.6% for class E-. Reactions of French consumers actually exceeded the forecasts of the French government. While the measure was designed to be neutral for the State budget, it finally cost 285 millions euros in 2008. Part of this unexpected result is due to a sharp increase in the total sales of new cars. A simple comparison of the trimesters just before the reform took place (from September to November 2007) and just after (from March to May 2008), shows that total sales increased by around 13.4%. This increase far outstrips usual seasonal variations in this market and cannot be explained by such effects. If we use the trimester from March to May 2007 instead of the one from September to November 2007, we still observe in our data an increase in sales of 13.8%. The seasonally-adjusted index of the purchase of new cars by individual consumers produced by the national statistical institute (Insee) also indicates a sharp increase in 2008 compared to 2007, after the anticipation effect in December 2007 (see Figure 3). This increase in total sales is all the more impressive in that there was a sharp drop in economic activity and an important fuel price increase during that period (see Figures 4 and 5). These two factors are expected to depress, not to boost, the total sales of new cars.



Source : INSEE

Fig. 3: *Seasonally-adjusted Index of the Sales of New Cars*

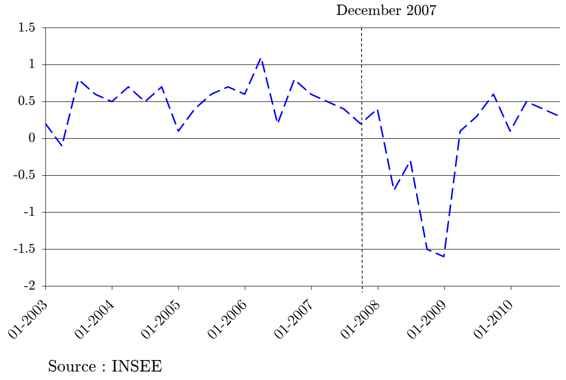


Fig. 4: Quarterly GDP Growth

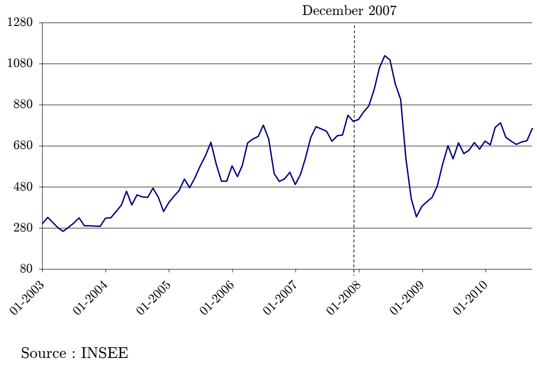


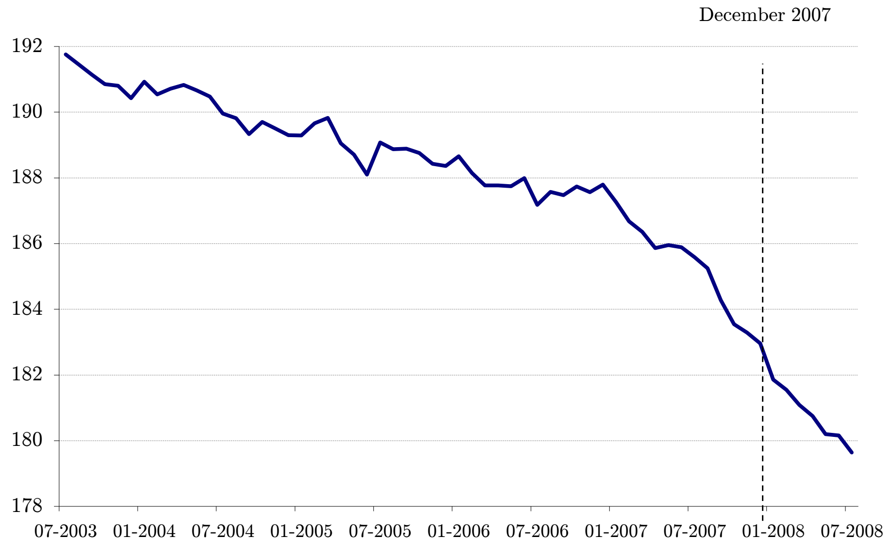
Fig. 5: Petrol Price Evolution (in Real Terms)

This sharp rise in sales could however be temporary and due to changes in decisions about vehicle replacement. Because of price changes, there may have been a decrease in the optimal lifetime of smaller cars and an increase in the optimal lifetime of bigger ones, so that many individuals with small cars found it optimal to replace them at the beginning of the period, while a large portion of individuals with bigger cars postponed their replacement. But if we focus on sales from March to May 2008, a large part of these adjustments should already have taken place. This is supported by the fact that we do not observe any rise in the average level of CO_2 emissions a few months after the introduction of the feebate (see Figure 2). Moreover, aggregate data suggest that the potential decrease in automobile lifetimes did not completely offset the increase in total sales. For instance, the estimated number of personal cars increased by 225,000 units between 2007 and 2008, and the share of French households owning at least one car also increased, from 82.4% to 82.7%.[5]

The exact extent of the supply-side reaction to the feebate is difficult to assess. Data on the supply of new cars are not available. Several clues indicate that in the first months of 2008 this reaction was small, however. As the policy was announced just before its implementation, manufacturers did not have time before January 2008 to adjust their production to the reform. Even if it is technically possible to modify horsepower (and thus CO_2 emissions) quickly, the vehicle with its new characteristics must be certified before being distributed. This process typically takes several months. More substantial

[5]See respectively `http://www.insee.fr/fr/themes/tableau.asp?reg_id=0&ref_id=NATTEF13629` and `http://www.insee.fr/fr/themes/tableau.asp?reg_id=0&ref_id=NATTEF05160`).

technological changes are likely to take even longer. A rough quantitative analysis of the number of patents in the corresponding domains (in the innovation patent classification, F02B, F02D et F02M for fuel engines and B60L for electric ones) does not show any particular acceleration during this period. This result is also consistent with the one of Pakes *et al.* (1993), who observed a two-year gap between the increase in the fuel price following the first oil crisis and the corresponding technical innovations. We also analyze the evolution of average emissions of cars that are sold each month, without weighting each product by its sales, so as to eliminate demand-side effects. Figure 6 shows an acceleration of technical changes around the beginning of 2007. This may be due to the fact that European Union energy labels became compulsory in May 2006. On the other hand, we do not observe any shock in 2008. Of course, this apparent absence of reaction on the part of manufacturers is plausible only in the short run.



Sources: dataset on the registration of new cars (CCFA).
Note: we suppose that a model is available for sale at a given month if we observe at least one sale at or before the given month and one sale at or after the given month. To avoid boundary effects (at the beginning or at the end of the period, only vehicles with enough sales are included, and these vehicles tend to have lower CO_2 emissions), we drop the first and last six months.

Fig. 6: *Evolution of Average CO_2 Emissions of Available Models Before and After the Reform*

2 Decomposition of CO_2 Emissions

The overall amount of CO_2 emitted by vehicles depends not only on the composition of the fleet but also on mileage and on the production of the cars themselves. In what follows we take into account all these elements in the estimation of short-run and long-run effects of the measure on CO_2 emissions. The short-run effect corresponds to the difference between CO_2 emissions with and without the policy, between March and May 2008. We focus on this period because January and February are affected by the "undershooting" effect mentioned previously. The long-run effect corresponds to the variation in emissions per trimester in a long-run scenario defined below. This effect is probably the most relevant parameter, since in the short run the policy only affects new cars, which in each month represent less than 1% of the whole stock of cars. In the long run, with the progressive replacement of the whole stock, the policy is expected to yield larger effects. The identification of the long-run impact relies on stronger assumptions, however.

Let us first define the short-run effect of the policy. Let $d \in \{0, 1\}$ denote the policy status ($d = 1$ if the feebate is introduced, $d = 0$ otherwise) and let $Y(d) \in \{0, ..., J\}$ denote the new car chosen by an individual between March and May 2008 with policy status d. As is usual in the related literature, choice 0 is the outside option, which represents either the non-replacement of an old car by a new one (or its replacement by a second-hand car), or the resort to an alternative means of transportation. For $j \in \{1, ..., J\}$, let $A_j(d)$ denote the average CO_2 emissions of vehicle j per kilometer. When $j = 0$, average emissions $A_0(d)$ is random and depends on the vehicle the individual already owns. Because we do not have precise information on the pollution emitted by other means of transportation (such as buses or vehicles used but not owned by individuals) in the Transportation Survey, we will henceforth neglect average emissions for individuals who do not own a car.

CO_2 emissions depend on the emissions per kilometer of the cars chosen by consumers, but also on average mileage. We define $N_j(d)$ as the mileage of an individual with vehicle j between March and May 2008.

Finally, we take into account emissions caused by the process of manufacturing new cars, and let M_j denote the emissions caused by producing car j (so that by definition, $M_0 = 0$). The emissions of a household with policy status d satisfy

$$\text{CO}_2(d) = \mathbb{1}\{Y(d) = 0\}A_0(d)N_0(d) + \sum_{j=1}^{J} \mathbb{1}\{Y(d) = j\}(M_j + A_j(d)N_j(d)).$$

Then the short-run effect of the policy on total carbon dioxide emissions satisfies

$$\Delta^{SR} = nE\left[\text{CO}_2(1) - \text{CO}_2(0)\right],$$

where n is the number of potential buyers. To take into account heterogeneity among individuals in both the purchase of cars and mileage driven, we separate individuals according to some observable characteristics X, namely their labor market status, type of geographical area and income group (see Section 3). Letting $X \in \{1, ..., K\}$, we then have $\Delta^{SR} = \sum_{x=1}^{K} \Pr(X = x)\Delta_x^{SR}$, with

$$\begin{aligned}\Delta_x^{SR} &= n\Bigg[s_{x0}(1)\overline{E}_{x0}(1) - s_{x0}(0)\overline{E}_{x0}(0) + \sum_{j=1}^{J}(s_{xj}(1) - s_{xj}(0))M_j \\ &\quad + \sum_{j=1}^{J}(s_{xj}(1)A_j(1)\overline{N}_{xj}(1) - s_{xj}(0)A_j(0)\overline{N}_{xj}(0))\Bigg], \end{aligned} \tag{1}$$

where, for $d \in \{0, 1\}$, we let $s_{xj}(d) = P(Y(d) = j|X = x)$, $\overline{E}_{x0}(d) = E(A_0(d)N_0(d)|Y(d) = 0, X = x)$ and $\overline{N}_{xj}(d) = E(N_j(d)|Y(d) = j, X = x)$.

A decomposition of the overall impact into its several components helps to better understand the effects at stake. We denote by $\overline{A}(1)$, $\overline{N}_x(1)$ and $\overline{M}$ the average emission of new cars with the policy, the average mileage driven by individuals with characteristics x using new cars with the policy, and the average production emissions of these new cars, respectively. We let $\Delta s_{xj} = s_{xj}(1) - s_{xj}(0)$ denote the impact of the policy on the market share of j among individuals with characteristics x. From Equation (1), we obtain:

$$\begin{aligned}\Delta_x^{SR} &= n\Bigg[\underbrace{\sum_{j=1}^{J}\Delta s_{xj}((A_j(1) - \overline{A}(1))\overline{N}_{xj}(1) + M_j - \overline{M})}_{\text{Composition effect}} \\ &\quad \underbrace{+\overline{A}(1)\sum_{j=1}^{J}\Delta s_{xj}(\overline{N}_{xj}(1) - \overline{N}_x(1))}_{\text{Rebound effect}} + \underbrace{(\overline{A}(1)\,\overline{N}_x(1) - \overline{E}_{x0}(1))\sum_{j=1}^{J}\Delta s_{xj}}_{\text{Fleet size effect}} \\ &\quad + \underbrace{\overline{M}\sum_{j=1}^{J}\Delta s_{xj}}_{\text{Manufacturing scale effect}} \underbrace{+ s_{x0}(0)\Delta\overline{E}_{x0} + \sum_{j=1}^{J}s_{xj}(0)\Delta(A_j\overline{N}_{xj})}_{\text{Second-order effect}}\Bigg]. \end{aligned} \tag{2}$$

The first component (*composition effect*) corresponds to the change in the composition of new cars in favor of less CO_2-emitting cars. If the policy is well-designed, this component should be negative (thus contributing to a decrease in the overall level of CO_2 emissions). For instance, we expect the sales of the less polluting cars, i.e. those for which $A_j(1) - \overline{A}(1) < 0$, to increase, i.e. $\Delta s_{xj} > 0$. These less polluting cars are also smaller on average, so that the average emissions caused by the manufacturing of a new car should be smaller, $\Delta s_{xj}(M_j - \overline{M}) < 0$. However, three other effects may offset this positive composition effect. The feebate scheme is designed on (easily observed) emissions per kilometer $A_j(1)$, but the result also depends on how the cars are used ($\overline{N}_{xj}(1)$). Because of the rebound effect, individuals may increase their mileage as the cost per kilometer of their car decreases. It is thus likely that $\overline{N}_{xj}(1) - \overline{N}_x(1) > 0$ for the less polluting cars. Besides, the decomposition makes it clear that the policy impact depends on a scale effect. If total sales increase because of the policy (namely, if $\sum_{j=1}^{J} \Delta s_{xj} > 0$), the production of these new cars (*manufacturing scale effect*) and the travelling emissions corresponding to this larger fleet (*fleet size effect*) lead to a rise in CO_2 emissions. This is partly, but only partly, offset by the fact that these extra new cars are used instead of older ones (the term $-\overline{E}_{x0} \sum_{j=1}^{J} \Delta s_{xj}$ in the fleet size effect), and older cars are the higher-emitting ones. Finally, the fifth component in the decomposition corresponds to what we call second-order effects. The first term in it corresponds to the change in outside emissions due to the policy. This effect is small in the short run because the composition of the whole stock of cars is hardly affected by the reform after just a few months. The second term corresponds to changes in average emissions of an individual with car j due to the policy. Such a change may be due to a supply side effect ($\Delta A_j < 0$ if manufacturers react to the policy) and a selection effect (individuals who choose vehicle j differ with and without the feebate, so that $\Delta \overline{N}_{xj}$ may change). We expect the former to be negligible in the short run however, and the latter to be small once observed heterogeneity X is controlled for.

Let us now turn to long-run effects. In the main specification, we still abstract from supply side effects here. We assume that the automobiles supplied in the long run are those which were proposed at the beginning of 2008. We also assume that the sales of new cars and annual mileage remain constant each quarter after the beginning of 2008. Thus, we abstract from potential transitory effects in sales, assuming that sales between March and May 2008 already correspond to a steady state. As mentioned previously, it is likely indeed that most of the transitory effects due to vehicle replacement adjustments have already taken place. With these two assumptions in place, the only difference from the short-run scenario is that the whole fleet of cars has now been replaced.

Under these assumptions, long-run effects for group x on quarterly emissions satisfy

$$\Delta_x^{LR} = n \sum_{j=1}^{J} (s_{xj}(1) - s_{xj}(0)) M_j + (\widetilde{s}_{xj}(1) A_j(1) \overline{N}_{xj}(1) - \widetilde{s}_{xj}(0) A_j(0) \overline{N}_{xj}(0)), \quad (3)$$

where $\widetilde{s}_{xj}(d)$ denotes the share of individuals of type x equipped with model j with policy status d in this long-run scenario. As before, we neglect emissions corresponding to other means of transportation here. In a steady-state equilibrium, the share of car j in the whole fleet and its share in the flow of new cars are related by

$$\widetilde{s}_{xj}(d) = T_{xj}(d) s_{xj}(d), \quad (4)$$

where $T_{xj}(d)$ is the average lifetime of vehicle j when bought by individuals of type x under policy status d.

Using $\Delta \widetilde{s}_{xj} = \Delta T_{xj} s_{xj}(1) + T_{xj}(0) \Delta s_{xj}$, (3) and (4), we obtain, as previously, the decomposition

$$\begin{aligned}
\Delta_x^{LR} = n \Bigg[& \underbrace{\sum_{j=1}^{J} \Delta s_{xj} \left[T_{xj}(0)(A_j(1) - \overline{A}(1)) \overline{N}_{xj}(1) + M_j - \overline{M} \right]}_{\text{Composition effect}} \\
& + \underbrace{\overline{A}(1) \sum_{j=1}^{J} \Delta s_{xj} T_{xj}(0) \left[(\overline{N}_{xj}(1) - \overline{N}_x(1)) \right]}_{\text{Rebound effect}} + \underbrace{\overline{A}(1)\, \overline{N}_x(1) \sum_{j=1}^{J} \Delta s_{xj} T_{xj}(0)}_{\text{Fleet size effect}} \\
& + \underbrace{\overline{M} \sum_{j=1}^{J} \Delta s_{xj}}_{\text{Manufacturing scale effect}} + \underbrace{n \sum_{j=1}^{J} s_{xj}(1) \Delta T_{xj} A_j(1) \overline{N}_{xj}(1)}_{\text{Replacement rate effect}} \\
& + \underbrace{\sum_{j=1}^{J} s_{xj}(0) T_{xj}(0) \Delta(A_j \overline{N}_{xj})}_{\text{Second-order effect}} \Bigg]. \quad (5)
\end{aligned}$$

The change in emissions due to the production of new cars over a quarter is the same as in the short run, whereas the change in the composition effect is far larger, the first term inside brackets being multiplied by $T_{xj}(0)$ (around 80 quarters on average in our sample). This underlines the fact that the whole fleet is replaced in the long run. The rebound effect is also increased by the same scale factor, while the fleet scale effect is multiplied by an even larger one, as it is not offset anymore by the fact that in the short run, new cars replace older, more polluting ones. The replacement rate effect corresponds to potential changes in renewal choices. We expect that vehicles burdened with a fee are kept for a longer period than those benefiting from a rebate, so that their share in the whole fleet is larger than their share in total sales, partially offsetting the impact of the policy (since $\Delta s_{xj} \Delta T_{xj} < 0$). On the other hand, longer average lifetimes means that the increase in total sales due to the policy does not increase the share of individuals owning a car that much, countering the fleet size effects. This replacement rate effect is thus potentially ambiguous.

3 Data

The market shares of new automobiles are computed using the exhaustive dataset on the registration of new cars from January 2003 to January 2009, which was provided by the Association of French Automobile Manufacturers (CCFA, *Comité des Constructeurs Français d'Automobiles*). It includes all the information necessary for the registration of a new car, primarily its characteristics (brand, model, CO_2 emissions, list prices, type of fuel, number of doors, type of car body, horsepower, weight and cylinder capacity). This array of information allows us to define products at a detailed level. As usual, we define a product by a set of characteristics, here the brand, the model, the type of fuel, the type of car body (urban, station wagon, convertible, etc), the number of doors and its class of CO_2 emissions (see the Appendix for a discussion). With this definition in hand, we observe 950 different products for the period between September and November 2007 (see Table 2).

Table 2: Number of Products and Sales Between September and November 2007

	Models	Number of sales
Overall	950	239,606
By number of doors		
3	182	42,704
5	499	168,949
Others	269	27,953
By type of car-body		
Station wagon	234	28,446
Convertible	83	6,611
Urban	626	204,538
Disabled	7	11
By type of fuel		
Petrol	453	80,390
Diesel	497	159,216

Sources: dataset on the registration of new cars (CCFA).

Though our data include the list prices provided by manufacturers, we do not make use of them in what follows. In the French automobile market, almost all dealers negotiate prices individually with customers. List prices are thus not reliable proxies for transaction prices, as the measurement error can be correlated with individual heterogeneity. Besides, list prices are typically modified once a year only. It is thus likely that many list prices were not yet adjusted to the reform at the beginning of 2008. This hypothesis is supported in our dataset, where no clear pattern in the evolution of list prices emerges (see Table A.2 in Appendix A.1). We do not observe systematic differences between classes of emissions in the evolution of list prices over the period of the reform, though the feebate policy should lead to an increase in list prices (excluding the feebate) for cars benefiting from rebates and a decrease for those with fees.

The new cars registration dataset not only provides information on the car, but also on its owner. This allows us to take into account in a simple way the heterogeneity in taste of customers for differentiated products. We observe in particular the labor market status, the age, and the city in which the owner resides. Based on this information, we define 20 groups of customers according to their participation in the labor market, the type of area in which they live (urban or rural) and their income group (5 groups). This last information comes from the French income tax data, which provide the distribution of income by age class at the city level. We impute to each purchaser the median income of his age class in his city, using fiscal data.[6]

For each of these 20 groups, we compute the market shares of each product on the two trimesters of interest (namely, September to November 2007 and March to May 2008). This amounts to considering the 20 groups of consumers as different markets. Usually, the purpose of defining different markets, by geographical boundaries for instance, is to provide exogenous variation in the model. Here, we do this rather to account for observable heterogeneity in the car choice model (see Subsection 5.2). Table A.3 in Appendix A.2 displays the average characteristics of new car purchasers in terms of age, income, participation rate and type of location, computed using the Transportation Survey. Not surprisingly, these individuals are on average older, belong to wealthier households and work more often than the rest of the population. This underlines the importance of accounting for consumers' heterogeneity. There is a price to pay for our approach, though. Since the markets we define are small (5% of the French adult population over a trimester), some observed market shares can be zero and cannot be used in the estimation, which could result in a selection bias. This is why we restrict ourselves to 20 groups of consumers and do not include all vehicle characteristics in the definition of our products (see Appendix A.1 for a discussion).

Finally, mileage is measured using the Transportation Survey conducted by the French national institute of statistics (INSEE) from March 2007 to April 2008. This survey provides detailed information about the travel of individuals (in particular the annual mileage they put on their cars), and some characteristics of their vehicles, such as their type of fuel, weight or average CO_2 emissions. Table 3 displays the average mileage of cars depending on their characteristics and those of the owners. Results confirm the importance of taking heterogeneity in the yearly mileage of individuals into account.

[6]The median income is available only for cities with more than 50 households. It is decomposed by age for cities with more than 10,000 inhabitants. If the buyer lives in a city with less than 10,000 inhabitants, or if his/her age is unknown, we impute the median income of the city. Sales to individuals living in cities of less than 50 households, which correspond to 5% of the data, were dropped.

Drivers who choose a heavy (and thus large) car, or those who choose one with a diesel engine, cover many more kilometers per year than others. High-income people, who work or who live in rural areas, also use their car more intensively.

Table 3: Average Yearly Mileage (in Kilometers)

Variable	Yearly mileage (kms)
Weight (in kilograms)	
Less than 900	11,073
Between 900 and 1,100	12,156
Between 1,100 and 1,300	15,228
More than 1,300	17,747
Type of fuel	
Petrol	10,114
Diesel	17,193
Household income	
First quintile	11,585
Second quintile	12,368
Third quintile	13,720
Fourth quintile	15,138
Fifth quintile	15,428
Type of Area	
Rural and suburban	15,108
Urban	13,024
Activity	
working	15,886
non working	10,584

Sources: Transportation Survey 2007 (INSEE).

4 The Identification Strategy

As the decomposition (2) makes clear, the identification of short-run effects requires the econometrician to recover the market shares, average mileage and outside emissions that would have prevailed in the absence of the policy. For that purpose, we rely on a simple model that relates mileage, cost of travelling and choice of car. We also impose a nested logit specification for modeling market shares. Identification is then achieved, basically, by using shifts in the market shares following the introduction of the feebate. We assume that, apart from their price, cars' characteristics were not affected by the policy in the short run. The identification of long-run effects also requires computing vehicle lifetimes with and without the policy. We adjust car lifetimes using a simple model of replacement rate.

4.1 A Model of Car Choice and Mileage

To model rebound effects but also the effect of the policy on market shares, we consider a discrete-continuous choice model of car choice and mileage, following Dubin and McFadden (1984) and Goldberg (1998). Our identification strategy differs substantially from theirs, however, since we do not use the micro-level data of the Transportation Survey to estimate the car choice model, but rather the market-level CCFA dataset. We do so for two reasons. First, the subsample in the Transportation Survey of individuals who bought a new car just after the reform is too small to yield accurate estimates. Second, many automobile characteristics, including purchase price, are not available in this survey. These issues would greatly complicate the estimation of car choice with these micro-level data.

We let $U_{it}(j, N)$ denote the indirect utility of individual i with characteristics $X_i = x$ when choosing at quarter t the vehicle j and anticipating that he will travel N kilometers during this quarter. We assume that

$$U_{it}(j, N) = N^{\frac{\gamma_x}{\gamma_x - 1}} \alpha_x + (y_{it} - p_{jt}) \beta_{1x} - c_{jt} N \beta_{2x} + e_{ijt}, \tag{6}$$

where y_{it} denotes the income of i, p_{jt} is the transaction price of vehicle j (including the feebate if there is one), c_{jt} is the average cost per kilometer of vehicle j and e_{ijt} represents the valuation by the individual of observable and unobservable characteristics of vehicle j. The indirect utility of not buying a new car (the outside option 0) writes similarly with $p_{0t} = 0$. We suppose that $0 < \gamma_x < 1$ and $\alpha_x < 0$, so that utilities are increasing, concave functions of N. The dependence on x of $(\beta_{1x}, \beta_{2x}, \gamma_x)$ reflects the heterogeneity in the way people value the corresponding characteristics of the car.

We assume that the average cost per kilometer corresponds to current costs, so that $c_{jt} \propto f_{jt} A_j$, where f_{jt} denotes the price of the type of fuel (namely petrol or diesel) of model j at t. The factor of proportionality $c_{jt}/f_{jt}A_j$ only varies with the type of fuel: the combustion of a liter of diesel emits 2.6kg of CO_2, versus 2.3kg for petrol. Using such costs per kilometer in the choice model amounts to assuming that when purchasing a vehicle, agents make a no-change forecast on the future price of petrol. Such a pattern was observed for instance by Anderson *et al.* (2011) on US data. This assumption, and the fact that consumers do not anticipate that the set of new vehicles will change over time, makes our model essentially static. The latter assumption about anticipations seems a reasonable approximation, given that cars' characteristics do not evolve rapidly.[7] Because the feebate policy may foster innovation however, consumers may rationally anticipate that the set of vehicles will evolve with time. We come back to this issue later.

4.2 Average Mileage

Individuals are assumed to maximize their utility both in N and j. Focusing on the choice of N first, the optimal anticipated mileage N^*_{ijt} for a given model j satisfies

$$N^*_{ijt} = \left(\frac{\beta_{2x}(\gamma_x - 1)c_{jt}}{\alpha_x \gamma_x} \right)^{\gamma_x - 1}. \tag{7}$$

This relationship highlights rebound effects. As soon as $\gamma_x < 1$, individuals will increase the mileage they drive following a reduction of the cost per kilometer of their car. We assume that individuals are rational, so that actual mileage satisfies the same equation as (7), but includes an additional idiosyncratic term unexpected by individuals at the time of their decision. Henceforth we let $Y_{it}(d)$ denote the car chosen by i at t under policy status d.

Assumption 4.1 *(Link between anticipated and actual mileage) There exists a function $\widetilde{\tau}(.)$ such that the actual mileage for i at date t, N_{it}, satisfies*

$$\ln N_{it} = \ln N^*_{iY_{it}(d)t} + \widetilde{\tau}(X_i) + \nu_{it},$$

where ν_{it} is independent of the choice $Y_{it}(d)$ conditional on X_i, $E(\nu_{it}|X_i) = 0$ and the distribution of ν_{it} does not depend on t.

[7] This contrasts with, e.g., the camcorder industry studied by Gowrisankaran and Rysman (2012). They propose a dynamic model for consumers choice of durable goods that are subject to quick evolutions.

The important restrictions in Assumption 4.1 are that the distribution of the error term does not depend on t, and that it is independent of the choice of car. These restrictions and Equation (7) yield

$$\ln N_{it} = \tau(X_{it}) + (\gamma_{X_{it}} - 1)\ln c_{it} + \nu_{it}, \text{ with } E(\nu_{it}|X_{it}, c_{it}) = 0, \tag{8}$$

where

$$\tau(x) = \widetilde{\tau}(x) + (\gamma_x - 1)\ln\left(\frac{\beta_{2x}(\gamma_x - 1)c_{jt}}{\alpha_x \gamma_x}\right).$$

We can therefore identify $\gamma_{X_{it}}$ by a simple regression, using the Transportation Survey. The cost per kilometer is estimated using the fuel economy of the car and the average fuel prices (diesel or petrol) at the county level (French départements) over the three month period before the interview.[8] Identification is thus achieved through the regional and temporal variation of fuel prices (the date of the interview for each household is exogenously distributed over the collection period), but also through individual variation in fuel economy. This latter source of variation is not endogenous here because we have ruled out any unobserved heterogeneity in the choice model, in particular on the individual valuation of mileage. This assumption is restrictive however. Even conditional on their observable characteristics, individuals who travel more are likely to choose a higher fuel economy vehicle. Our cross-sectional estimation may thus overestimate the rebound effect. As a robustness check, we investigate in Subsection 5.3 to what extent our basic results would be affected if we ruled out any rebound effect, by fixing γ_x to 1.

Once identified, the parameters of Equation 8 can be used to measure the average mileage by individuals of type x using vehicle j at quarter t, $\overline{N}_{xjt}$. One can show indeed (see Appendix A.4) that

$$\overline{N}_{xjt} = E\left(\exp(\nu_{it})|X_{it} = x\right)\exp(\tau(x))c_{jt}^{(\gamma_x - 1)} \tag{9}$$

where $E\left(\exp(\nu_{it})|X_{it} = x\right)$ does not depend on t by assumption and is therefore identified using the Transportation Survey.

[8]This information comes from a database that gives day-to-day fuel prices for each petrol station since 2007 (see Gautier and Le Saout, 2012, for more details).

4.3 Market Shares

Plugging N^*_{ijt} into (6) and letting $\mu_x = \frac{\alpha_x}{\gamma_x - 1}\left(\frac{\beta_{2x}(\gamma_x-1)}{\gamma_x\alpha_x}\right)^{\gamma_x}$, the utility for i of choosing j at date t is equal to

$$U_{it}(j) = (y_{it} - p_{jt})\,\beta_{1x} - c_{jt}^{\gamma_x}\mu_x + e_{ijt}.$$

Let us write $e_{ijt} = \xi_{xjt} + \eta_{ijt}$, where ξ_{xjt} denotes the average valuation of observable and unobservable characteristics of the car by group x and η_{ijt} is an individual-specific taste for j. To obtain realistic substitution patterns, while keeping the model simple to estimate, we rely on a nested logit assumption on the $(\eta_{ijt})_{j=1...J}$. The first nest is the set of all new cars, while the second corresponds to the outside option. The underlying idea is that consumers first choose to buy a new car or not, and then if they do so choose, select a model (see for instance Gowrisankaran and Rysman, 2012, for a similar sequential choice for a durable good). An advantage of this model is that it can be estimated very simply. A standard alternative is random coefficient models (see Berry *et al.*, 1995), which is popular since it allows for heterogeneity of purchasers even when no information on these purchasers is available. Here, we have already captured heterogeneity in consumers' preferences since our data allow us to estimate different models for each kind of consumer. Besides, even if we consider a basic segmentation of the automobile market, our model fits accurately the observed market shares, as shown in Subsection 5.1.

The nested logit specification leads to this simple market-level relationship between equilibrium vehicle prices, market shares and cost per kilometer at period t:

$$\ln(s_{xjt}) = \frac{1}{1-\sigma_x}\left[\ln(s_{x0t}) - \sigma_x \ln(1 - s_{x0t}) - p_{jt}\beta_{1x} - c_{jt}^{\gamma_x}\mu_x + \xi_{xjt}\right]. \qquad (10)$$

Estimating this equation by OLS is problematic for at least two reasons. First, it is likely that ξ_{xjt} is correlated with prices even once controlled for observable characteristics, since ξ_{xjt} includes for instance unobservable car quality. To get rid of fixed effects, we time-differentiate the log market shares of the trimesters September-November 2007 (denoted by t_0) and March-May 2008 (t_1).[9] These two spells correspond to periods just before and

[9] December 2007 as well as January and February 2008 are excluded from estimation to avoid capturing the anticipation or undershooting effects described in Subsection 1.2

right after the introduction of the policy. As mentioned already, it is unlikely that the manufacturers could have adjusted their supply so quickly. Thus, most of the observed change can be attributed to price changes following the feebate, or specific effects of the feebate itself through consumers' valuation of CO_2 emissions for instance. Formally, we make the following assumption. Hereafter, Z_j denotes the fee of vehicle j under the feebate policy (so that $Z_j < 0$ if j actually benefits from a rebate).

Assumption 4.2 *(No short-run effect of the feebate on the characteristics of cars apart from price) For all j, A_j and c_{jt_1} are not affected by the feebate policy. Moreover, $\xi_{xjt_1}(1) - \xi_{xjt_1}(0)$ only depends on Z_j,*

The condition on ξ_{xjt_1} allows for possible changes in individuals' valuation of the CO_2 emissions of the vehicle. There is indeed evidence that the reform has had an impact on the environmental awareness of consumers, apart from price effects (see D'Haultfœuille *et al.*, 2013). On the other hand, Assumption 4.2 rules out changes in preferences for other attributes such as horsepower.

The second issue when trying to estimate (10) is that we do not observe transaction prices but list prices, which, as indicated before, appear to lack reliability. Moreover, measurement errors are likely to be nonclassical, as they may be correlated with feebates. Thus, usual instruments such as the sum of characteristics of the other products may fail in this context. To solve this issue, we posit the following flexible model on transaction prices. Hereafter, we let Z_j^S denote the sum of the fees applying to vehicles produced by the firm that produces j.

Assumption 4.3 *(Dependence of transaction prices on the feebate scheme)*

$$p_j(1) = p_j(0) + f_1(Z_j) + f_2(Z_j^S), \tag{11}$$

where $f_1(0) = f_2(0) = 0$.

Equation (11) captures the fact that when fixing the price of j so as to maximize its profit, the firm should take into account its effect on the profit flowing from j but also from the other cars it produces. This can be seen as a linearization of the price equation resulting from an oligopolistic model with product differentiation and multiproduct firms (see details in Appendix A.4.2).

To estimate the demand model, the idea is to replace transaction prices by their expression in (11). This strategy is convenient as it is both very easy to estimate and does not require any instrument, provided that the following condition holds.

Assumption 4.4 *(Exogenous residuals in market shares and no systematic trend in the short run)* $E(\varepsilon_{xj}|Z_j, Z_j^S, c_{jt_1}, c_{jt_0}) = 0$, *where* $\varepsilon_{xj} = \xi_{xjt_1} - \xi_{xjt_0} + (p_{jt_1}(0) - p_{jt_0}(0))\beta_{1x}$.

The residual ε_{xj} can be interpreted as the evolution, for a constant fuel price, of the valuation of vehicle j if the feebate had not been introduced. Assumption 4.4 states that this evolution is unrelated to the vehicle's feebate and its cost per kilometer. It also rules out potential seasonal effects. We provide a robustness check of this assumption in Subsection 5.3.

Finally, we show in Appendix A.4 that under a linear specification, the change in the log market shares just before and after the feebate can be approximated by

$$\ln(s_{xjt_1}/s_{xjt_0}) = \ln\left(\frac{1 - s_{x0t_0}}{1 - s_{x0t_1}}\right) x'\lambda + \sum_{l=1}^{7} \mathbb{1}\{Z_j = z_l\}\theta_l + Z_j^S\theta^S - \left(c_{jt_1}^{\gamma_x} - c_{jt_0}^{\gamma_x}\right)\widetilde{\mu}_x + \varepsilon_{xj}, \quad (12)$$

where $(z_l)_{l=1\ldots7}$ denote the different nonzero possible values of the feebate. By Assumption 4.4 and because the parameter γ_x is already estimated by the mileage equation (8), we can identify by simple OLS these parameters. In turn, these coefficients allow us to recover the counterfactual market shares at period t_1, $s_{xjt_1}(0)$, viz. the market shares that would have prevailed without the feebate policy (see Equation (A.3) in Appendix A.4).

4.4 Outside Emissions

The short-run effect depends in part on the emissions of individuals who decide not to buy a new car. As the decomposition (2) makes clear, we have to recover the counterfactual average emissions $\overline{E}_{x0}(0)$, but also the actual ones $\overline{E}_{x0}(1)$, since we do not observe the true outside emissions that prevail at the beginning of 2008. The idea for that purpose is to use the outside emissions at the end of 2007 and the fact that in the short run, the stock of existing vehicles is only very marginally affected by the policy. This is the substance of Assumption 4.5 below. Henceforth we let $F_{0t}(d)$ denote the type of fuel of the car owned by an individual when choosing the outside option ($F_{0t}(d) = 2$ for a petrol car, 1 for a diesel one and 0 if the individual does not have a car).

Assumption 4.5 *(No short-run effect of the policy on the stock of existing cars) For all i, the distribution of $(A_{0t}(d), F_{0t}(d))$ conditional on $Y_{0t}(d) = 0$ does not depend on d and t.*

Under Assumption 4.5, we get (see Appendix A.4)

$$\overline{E}_{x0t_1}(0) = \overline{E}_{x0t_1}(1) = I_1^{\gamma_x - 1} P(F_{0t_0}(0) = 1)\overline{E}_{x0t_0,1}(0) + I_2^{\gamma_x - 1} P(F_{0t_0}(0) = 2)\overline{E}_{x0t_0,2}, \qquad (13)$$

where I_f is the ratio between fuel price of type $f \in \{1, 2\}$ at period t_1 and at period t_0, and $\overline{E}_{x0t_0,f}(0)$ are the average outside emissions for individuals such that $F_{0t_0}(0) = f$:

$$\overline{E}_{x0t_0,f}(0) = E(A_{0t_0}(0)N_{0t_0}|Y_{t_0}(0) = 0, X_{t_0} = x, F_{0t_0}(0) = f).$$

As Equation (13) makes clear, Assumption 4.5 implies that the feebate does not affect outside emissions in the short run. Also, compared to the end of 2007, outside emissions at the beginning of 2008 are only modified because of fuel price changes. Individuals reduce their mileage to counter the effect of the fuel price increase, lowering the outside emissions.

4.5 Long-run Effects

The identification of the long-run effects of the policy requires stronger restrictions. As explained above, it depends on the long-run shares of individuals equipped with model j with policy status $d \in \{0, 1\}$, namely $\widetilde{s}_{xjt_1}(d)$. This depends in turn on the average lifetime of vehicle j when bought by individuals of type x.

Unfortunately, as far as we know, no French data provide recent information on cars' lifetimes at a micro level. As a result, we have to make quite restrictive assumptions. The first is that we posit a constant average lifetime across vehicles before the introduction of the feebate, $T_{xjt_0} = \overline{T}_{t_0}$. In this case $\widetilde{s}_{xjt_0} = \overline{T}_{t_0} s_{xjt_0}$ for all $j \geq 0$, so that by summing over j, we have

$$\overline{T}_{t_0} = \frac{1 - \widetilde{s}_{0t_0}}{1 - s_{0t_0}},$$

and we can recover $\overline{T}_{t_0}$ using the Transportation Survey. Our computation gives us an average value of around 80 quarters, consistent with official statistics. The monthly flow of new cars indeed represents 0.5% of the stock of cars that are less than 15 years old, corresponding to an estimated lifetime of 67 quarters. Because official statistics are available only for cars less than 15 years old, and are not restricted to cars owned by households, this figure probably underestimates the true average lifetime we are interested in here.

We assume that average lifetimes at t_1 without the policy would have remained the same as in t_0, so that $T_{xjt_1}(0) = \overline{T}_{t_0}$. To compute lifetimes with the policy $T_{xjt_1}(1)$, we consider a model derived from Engers *et al.* (2009). If the purchase of a car occurs at quarter t, let us assume that at quarter $t+k$, the car can either be sold on the secondary market at a price $\widetilde{p}_{jt+k}$ or kept, generating a current net surplus of v_{jt+k}. The value W_{jt+k} of a car j of age k then satisfies the simple relation:

$$W_{jt+k} = \max\{v_{jt+k} + \rho W_{jt+k+1}, \widetilde{p}_{jt+k}\},$$

where ρ denotes the quarterly discount factor. Assuming that prices perfectly adjust at equilibrium, we get

$$\widetilde{p}_{jt+k} = \max\{\widetilde{p}_{jt+k+1}, W_j^s\},$$

where W_j^s represents the scrapping value of car j. As shown by Engers *et al.* (2009), the consumer keeps the car while its price remains above the scrapping value. Let us denote by T_{jt} the lifetime of the car. We assume that the current net surplus decreases at a constant rate r over time, so that $v_{jt+k} = v_j r^k$. We then get the following system:

$$\widetilde{p}_{jt+k} = \begin{cases} v_j r^k + \rho \widetilde{p}_{jt+k+1} & \text{if } 0 \leq k < T_{jt}, \\ W_j^s & \text{if } k = T_{jt}. \end{cases}$$

After a little algebra,

$$p_{jt} = v_j \frac{1-(\rho r)^{T_{jt}}}{1-\rho r} + r^{T_{jt}} W_j^s. \tag{14}$$

For standard values of W_j^s (i.e., between 0 and 200 euros), the second term in the right-hand side is negligible. Writing Equation (14) with and without the policy, we obtain

$T_{jt_1}(1)$ as a function of $T_{jt_1}(0)$:

$$T_{jt_1}(1) = \frac{\ln\left[1 - \left(1 - (\rho r)^{T_{jt_1}(0)}\right)\frac{p_{jt_1}(1)}{p_{jt_1}(0)}\right]}{\ln(\rho r)}.$$

This equation shows that individuals who choose vehicles benefiting from a rebate (so that $p_{jt_1}(1) < p_{jt_1}(0)$) tend to replace their vehicle more often ($T_{jt_1}(1) < T_{jt_1}(0)$). Basically, this is because the value of the vehicle reaches its scrappage level more quickly, as the vehicle is initially cheaper. In the right-hand side, we approximate the car price without the policy by the observed price minus the malus, $p_{jt_1}(0) \simeq p_{jt_1}(1) - Z_j$. The importance of the adjustment also depends on the quarterly discount factor r of individuals (supposed to be independent of x here), the (quarterly) depreciation rate in the utility flow corresponding to the usage of a vehicle, r, and sale prices $p_{jt_1}(d)$. In practice, we set $r = \rho = 0.987$, corresponding to an annual interest rate (or depreciation rate) of 5%.

5 The results

5.1 Estimation of the Mileage and Market Share Equations

This subsection presents details on the estimates of the mileage and market shares equations. We first present results from the estimation of Equation (8), which relates the annual mileage to the cost per kilometer, controlling by observable characteristics of households X (see Table 4). As we did not find any evidence of heterogeneity in x of γ_x, we estimate a model with constant γ. The estimated γ is then plugged into the market shares equation (12). The estimates from Equation (8) are also used to compute average mileage through Equation (9) and average outside emissions, using Equation (13).

Table 4: Estimates of the Mileage Model (Log)

Variables	Estimate
Intercept	10.46^{***} (0.191)
Non working	-0.364^{***} (0.015)
Rural and suburban area	-0.012 (0.014)
Income in 2nd quintile	0.076^{***} (0.027)
Income in 3rd quintile	0.14^{***} (0.025)
Income in 4th quintile	0.21^{***} (0.024)
Income in 5th quintile	0.246^{***} (0.024)
Cost per kilometer	-0.53^{***} (0.027)

Sources: Transportation Survey 2007 (INSEE).
Notes: OLS Estimates of Equation (8). The cost per kilometer is estimated for each car using the corresponding fuel price (unleaded petrol or diesel) at the county level during the three months preceding the date of the interview. Significance levels: *** 1%, ** 5%, * 10%.

We thus obtain $\widehat{\gamma}-1 \simeq -0.53$. As discussed in Subsection 4.2, this estimate may however be biased. Recall that the cost per kilometer $c_{Y_{it}t}$ is proportional to $f_{jt}A_{Y_{it}t}$, where f_{jt} is the fuel price for vehicle j three months before the date of the interview. Identification through Equation (8) relies on regional and temporal variation in fuel prices (as we use local fuel prices and there is variation in the date of the interview), which can be considered exogenous, but also on the selection of the car through the CO_2 emissions per kilometer $A_{Y_{it}t}$. It may thus depend on unobserved characteristics of the drivers.

An overview of the related results in the literature helps to assess the plausibility of our estimated value of $\gamma - 1$. The literature has mostly focused on how fuel prices affect fuel consumption. A change in fuel prices has a direct impact on the cost per kilometer $c_{Y_{it}t}$ but also potentially on $A_{Y_{it}t}$, as individuals may decide to change their cars according to fuel price fluctuations. Thus, denoting by ζ_N (resp. ζ_A) the elasticity of mileage (resp. of average emissions per kilometer) to fuel price, the long-run price elasticity of fuel consumption is equal to $\zeta_N + \zeta_A$. By Equation (8), we get

$$\gamma - 1 = \frac{\zeta_N}{1 + \zeta_A}.$$

We thus expect $\gamma - 1$ to be smaller than the short-run price elasticity of fuel consumption, but larger than the long-run elasticity (if $\zeta_N + \zeta_A > -1$). Our results are consistent with this prediction. The usual estimates of the short and long-run elasticities lie between -0.3 and -0.2 and between -0.8 and -0.6, respectively (see, e.g., Graham and Glaister, 2002, for a survey). While the evidence is rather scarce for France, two recent studies based on micro data (Clerc and Marcus, 2009, and Calvet and Marical, 2011) obtain similar results. Our estimate therefore seems broadly consistent with the literature. As we rely on this parameter to calibrate the rebound effect later on, it is nonetheless important to assess the sensitivity of our final estimation to this estimation. We consider below, as a robustness check, an extreme scenario where drivers do not respond at all to the change in the cost per kilometer, by setting $\gamma = 1$.

In a second step, we estimate the reduced form of our nested logit model, using Equation (12). Results are displayed in Table 5. As expected, market shares of vehicles benefiting from a bonus increase at the expense of those incurring a penalty. The penalty effect is actually more pronounced for classes E+ and E- than for classes F and G, which may seem surprising. It suggests that these coefficients not only reflect price effects, but also environmental concerns on the part of consumers. Classes F and G only correspond to very large cars, for which consumers were probably already aware of their environmental effect, whereas the introduction of the feebate may have acted as a negative environmental signal for cars in class E. Finally, and as expected, the estimated coefficient of the cost per kilometer is significant and negative (-3.67).

Table 5: Impact of the Feebate on Market Shares

Parameter	Estimate
Substitutability terms (λ)	
Intercept	2.032^{***} (0.258)
Non working	0.001 (0.133)
Rural and suburban area	0.315^{**} (0.13)
Income in 2nd quintile	0.092 (0.215)
Income in 3rd quintile	-0.138 (0.207)
Income in 4th quintile	-0.042 (0.209)
Income in 5th quintile	0.406^{*} (0.212)
Other terms	
Cost per kilometer	-3.665^{***} (0.138)
Rebate $= 1,000$ €	0.383^{*} (0.209)
Rebate $= 700$ €	0.698^{***} (0.029)
Rebate $= 200$ €	0.011 (0.029)
Fee $= 200$ €	-0.257^{***} (0.037)
Fee $= 750$ €	-0.280^{***} (0.022)
Fee $= 1,600$ €	-0.147^{***} (0.033)
Fee $= 2,600$ €	-0.144^{***} (0.049)
Sum of fees of the firm	0.003^{***} (0.0004)

Sources: dataset on the registration of new cars (CCFA). Notes: OLS Estimates of Equation (12). The standard errors are computed by bootstrap (with 1,000 simulations) and take into account the fact that γ is estimated in Equation (12). Significance levels: *** 1%, ** 5%, * 10%.

In order to check whether our model accurately predicts market shares, we compare those observed in 2007 with the counterfactual ones, as predicted by the model. Relying on our model, we can derive the counterfactual market shares without the policy $s_j(0)$ from the market shares observed in March-May 2008 $s_j(1)$ and the parameters estimated by Equation (10). More specifically, relying on the nested logit specification, it can be shown (calculations are provided in Appendix A.4.1) that

$$s_{xj}(0) = \frac{s_{xj}(1)\exp(-B_j)}{\frac{s_{x0}(1)}{(1-s_{x0}(1))^{\sigma_x}}\left[\sum_{k=1}^{J} s_{xk}(1)\exp(-B_k)\right]^{\sigma_x} + \left[\sum_{k=1}^{J} s_{xk}(1)\exp(-B_k)\right]} \tag{15}$$

where $B_j = \sum_{l=1}^{7} \mathbb{1}\{Z_j = z_l\}\hat{\theta}_l - Z_j^S \hat{\theta}^S \ s_j(1)$. In order to make these counterfactual market shares more comparable with the observed ones in September-November 2007, thus before the introduction of the feebate, we add to B_j the term $c_{j2007}^{\gamma_x} - c_{j2008}^{\gamma_x}$ that corrects for the evolution of fuel prices from the end of 2007 to the beginning of 2008. These counterfactual market shares may still differ from the observed markets shares in 2007, as they neglect the change in the prices of cars that would have been observed between these two quarters, absent the feebate policy. This estimation would have required measuring the price elasticity β_{2x} that we do not estimate. Still, the differences between observed market shares at the end of 2007 and the predicted one using the model, absent the feebate and with the same fuel prices as observed at the end of 2007, are small and not significant (see Table 6). The biggest gap is observed for the share of classes C+ and D, but corresponds to only 1.5 percentage points. Overall, the average gain in terms of CO_2 emissions of new vehicles is equal to 4.0%, which perfectly matches the observed gain on our subsample. Another important indicator to look at is the prediction of the model on global sales. According to our estimates, the policy has increased sales by 13.2%. This effect is substantial, but consistent with the empirical evidence that shows an increase in sales of 13.4% between September-November 2007 and March-May 2008 (see Subsection 1.2). It will prove to have large consequences on the effect of the policy on total emissions.

Table 6: Observed Market Shares Before the Introduction of the Feebate and Counterfactual Market Shares Without Feebate (%)

Class	Observed	Counterfactual
A	0.02	0.02 (0.02)
B	21.56	21.00 (4.5)
C-	11.39	11.49 (2.89)
C+ and D	48.84	50.35 (5.61)
E-	2.61	2.06 (0.63)
E+	12.87	12.63 (2.08)
F	1.98	1.81 (0.39)
G	0.72	0.65 (0.17)
Total	*100.00*	*100.00*

Sources: dataset on the registration of new cars (CCFA) and authors' computations.

Notes: market shares sum to 100% because we do not include the outside option. The observed market shares correspond to September-November 2007. The counterfactual market shares are obtained from the observed market shares in March-May 2008 and parameters estimated by Equation (10), setting the feebate to zero and using the average fuel prices in September-November 2007. Standard errors computed by bootstrap (with 1,000 simulations).

5.2 Effect on CO_2 Emissions and Decomposition

The overall effects of the policy, both in the short and long run, are displayed in Table 7, while the decomposition of these effects is presented in Table 8. Emissions stemming from the manufacturing of new cars were computed by assuming that the production of a new car generates 5.5 tons of CO_2 per ton of new vehicle, following the carbon assessment of the French agency for the environment (*Agence De l'Environnement et de la Maîtrise de l'Energie*, see ADEME, 2010).

In the short run, the composition effect of the change in the composition of sales of new cars reaches approximately -80.5 kilotons of quarterly CO_2 emissions, well above (in absolute value) the rebound and fleet size effects. Hence, the measure would have been positive without the manufacturing effect. However, this latter effect dominates in the short run, representing around 232 kilotons of quarterly CO_2 emissions. As a result, we obtain a significant increase in the short run of around 168.8 kilotons per quarter. With the cost of a ton of CO_2 fixed at 32 euros (consistent with the meta-analysis of Yohe *et al.*, 2007), the overall environmental short-run cost of the measure would reach 5.4 million euros per quarter.

Table 7: Short and Long-run Effects of the Feebate Policy

Parameter	Kilotons	Million of euros	% of total emissions
Short-run effect Δ^{SR}	168.8^{***} (49.3)	5.4^{***} (1.6)	$1.2\%^{***}$ (0.3%)
Long-run effect Δ^{LR}	$1,048.5^{***}$ (352.9)	33.6^{***} (11.3)	$9.2\%^{***}$ (3.3%)

Sources: Transportation Survey 2007 (INSEE) and dataset on the registration of new cars (CCFA).

Notes: we consider a price of 32 euros for a ton of CO_2. Standard errors were computed by bootstrap (with 1,000 simulations). Significance levels: *** 1%, ** 5%, * 10%.

As expected, we obtain far larger effects in the long run, even when taking into account the potential impact of the feebate on cars' lifetimes. With our calibration, we obtain substantial lifetime changes. The average lifetime of class B vehicles decreases by 14% while that of class G cars increases by 24%. For instance, starting from a lifetime of 20 years without the reform, we obtain a lifetime of around 17 years for a class B vehicle with an initial price of $12,000$ euros, and of 30 years for a class G vehicle with an initial price of $30,000$ euros. However, these effects are not large enough to offset the increase in sales. Overall we estimate the whole stock to rise by 8.9%. Note that if the lifetime adjustments of cars were not taken into account, the increase would be as high as 14%. While in the short run, the main component of the negative impact is the emissions of the manufacturing process, travelling emissions due to the increase in the size of the fleet predominate in the long run. As a result, we estimate that the introduction of the feebate accounts for an increase of 1,048.5 Kilotons of CO_2 per quarter, corresponding to an increase by 9.2% in total automobile emissions.

Table 8: Decomposition of the Short and Long-run Effects

Parameter	Estimate (kilotons) short run	long run
Composition effect	-80.5^{***} (16.4)	-911.0^{***} (191.3)
Rebound effect	6.1^{***} (1.5)	499.4^{***} (122.3)
Fleet size effect	10.9^{***} (2.9)	$1,734.0^{***}$ (456.2)
Manufacturing scale effect	232.0^{***} (60.8)	232.0^{***} (60.8)
Replacement rate effect		-506.0^{***} (133.0)

Sources: Transportation Survey 2007 (INSEE) and dataset on the registration of new cars (CCFA).

Notes: we consider a price of 32 euros for a ton of CO_2. Standard errors were computed by bootstrap (with 1,000 simulations). Significance levels: *** 1%, ** 5%, * 10%.

Our model allows us to identify the effect of feebate schemes that differ from the one implemented in 2008. Recall however that to be as flexible as possible, we specify in the market shares model the effect of the feebate as a sum of indicators. Thus, we cannot identify the effect of counterfactual feebate schemes with values of fees that do not exist in 2008, viz. values outside the set $\{-1,000, -700, -200, 0, 200, 750, 1,600, 2,600\}$. But we can shift these values to different classes of emissions. We compute in Table 9 below the effect of a feebate scheme where all rebates are shifted compared to the 2008 ones (700 € instead of 1,000€ for class A-, 200€ instead of 700€ for class B and 0€ instead of 200€ for class C+). This scheme may be seen as intermediate between those implemented in 2010 and 2011. Such a scheme would have led to a reduction in average CO_2 emissions in the long run when taking into account renewal effects. This is mainly due to the fact that total sales do not increase much in this scenario. As a result, the fleet size effect is sharply reduced. As with most of the parameter estimates, the estimate of Δ^{LR} is not significantly different from zero, however.

Table 9: Long-run Effects of an Alternative Feebate Scheme

Parameter	Estimate (kilotons)
Composition effect	-158.0 (109.0)
Rebound effect	76.5 (59.0)
Fleet size effect	215.1 (280.8)
Manufacturing scale effect	28.8 (37.5)
Replacement rate effect	-206.0^{**} (87.6)
Long-run effect Δ^{LR}	-43.3 (259.8)

Sources: Transportation Survey 2007 (INSEE) and dataset on the registration of new cars (CCFA).

Notes: standard errors were computed by bootstrap (with 1,000 simulations). Significance levels: *** 1%, ** 5%, * 10%.

5.3 Robustness Checks

Our results suggest that the feebate policy actually increases CO_2 emissions. These results are provocative, so it behooves us to check their sensitivity to our underlying assumptions. First, and as stated before, we restrict the estimation periods to months around the introduction of the feebate policy in order to avoid changes in the supply induced by the policy and dramatic modifications of the macroeconomic situation. As a result, however, we may capture seasonal effects. Sales in the automobile market are cyclical, and if these cyclical effects vary with the type of car, the dummies measuring the emission classes Z_j in Equation (A.2) will capture part of these seasonal effects. To assess the importance of these effects, we perform a falsification test using the 2006-2007 period instead of 2007-2008. More specifically, we imagine that the measure had been adopted in 2007 instead of 2008, falsely attributing the corresponding feebates to cars in 2007. Without seasonal effects, the coefficients corresponding to the emissions classes should be equal to zero. Table 10 shows that the estimates of these coefficients are far smaller than those obtained for 2007-2008, even if several remain significant.[10] For instance the parameter corresponding to class B is more than 7 times smaller than when comparing 2007 to 2008. Next, computing the short and long-run placebo estimates (Table 11), we obtain estimates not significantly different from zero. The point estimates are respectively -12.5 kilotons and -104.4 kilotons, namely around 10 times lower in magnitude than our estimates on 2007-2008. Hence, seasonal effects do not seem to be a major issue here.

Table 10: *Estimates of the Demand Model on 2006-2007*

Parameter	Estimate
Rebate $= 1,000$ €	*not identifiable*
Rebate $= 700$ €	-0.084^{***} (0.027)
Rebate $= 200$ €	-0.149^{***} (0.025)
Fee $= 200$ €	0.09^{***} (0.031)
Fee $= 750$ €	0.079^{***} (0.019)
Fee $= 1,600$ €	0.039 (0.024)
Fee $= 2,600$ €	0.085^{**} (0.041)
Sum of fees of the firm	-1.58×10^{-6} (0.0003)

Sources: dataset on the registration of new cars (CCFA).
Notes: OLS estimates of the coefficients on Z_j and Z_j^S in Equation (12) on 2006-2007. Significance levels: *** 1%, ** 5%, * 10%.

Second, the assumption that over this short amount of time, manufacturers do not react to incentives created by the feebate may be challenged. We therefore simulate a situation where the policy would lead to a 5% reduction of all average emissions. This reduction is very large, as it corresponds to the average decrease in the average CO_2 emissions of new vehicles proposed by manufacturers between January 2003 and July 2008 (see Figure 6). Considering the decompositions (2) and (5), this reduction of course decreases the composition effect, but also increases the rebound, fleet size and manufacturing scale effects. At the end, and as expected, the first effect dominates the others, but our basic conclusion remains unchanged. We obtain an increase of 757 kilotons of CO_2 per

[10] Apart from seasonal effects, this may be due to long-run evolutions in preferences for low emitting cars among French consumers. See D'Haultfœuille *et al.* (2013) for a detailed analysis on this issue.

quarter instead of 1,030 in the long run. This computation fails however to account for possible dynamic effects in consumer demand. In reality, people are likely to modify their vehicle choice and replacement rate because they rationally expect an evolution of the fuel consumption of vehicles. As the feebate may modify the supply side in the long run, this dynamic aspect can also contribute to the long-run effect of the policy. It is however likely that the overall impact of this channel is small compared to the change in the supply of new cars.

Finally, our results are based on an estimate of the price elasticity of miles traveled where households' mileage is regressed on the annual operating cost of their vehicles. This estimate may be biased, for instance because we neglect unobserved heterogeneity in the valuation of mileage (α_x is only group-specific). Households expecting to drive more would probably purchase more efficient cars. To assess how much this bias might alter our final results, we use an alternative specification that neglects the rebound effect in the demand model (12), by setting the parameter γ to 1. Results, displayed in Table 11, show that the policy still leads to an increase of CO_2 emissions in the short and long run under this very favorable assumption.

Table 11: *Robustness Checks: Short and Long-run Effects Under Alternative Assumptions*

Alternative Assumptions	Estimate (in kilotons) Δ^{SR}	Δ^{LR}
Baseline	168.8^{***} (49.3)	1048.5^{***} (352.9)
Placebo (2006-2007)	-12.5 (28.8)	-104.4 (297.3)
Manufacturers reaction	169.8^{***} (55.2)	767.5^{*} (407.2)
No rebound effect	160.5^{***} (48.9)	733.7^{**} (285)

Sources: Transportation Survey 2007 (INSEE) and dataset on the registration of new cars (CCFA).

Notes: Standard errors were computed by bootstrap with 1,000 simulations. Significance levels: *** 1%, ** 5%, * 10%.

6 Conclusion

Overall, the impact of the policy is very disappointing. Yet this result does not invalidate feebate systems as efficient tools for environmental policy. French consumers have reacted strongly to financial incentives created by the policy. The problem arises rather from the design of this feebate. A crucial parameter of a feebate system is the "pivot point" that divides vehicles incurring fees from those attracting rebates, and the rate that specifies the fee or rebate as a function of distance from the pivot point (see Greene *et al.*, 2005). In the French case, it looks as though this pivot point was set too high in terms of average CO_2 emissions. The rebates were also too generous. As our policy exercise shows, an adjustment in these rebates might easily lead to a decrease in overall CO_2 emissions. As the first-order terms in the policy effects are manufacturing or fleet size effects, the most important focus in order to ensure a reduction of CO_2 emissions would be to calibrate the policy in order to decrease, or keep constant, total sales.

One limitation of our study, due to a lack of appropriate data, is that we do not include manufacturers' reactions. Even if, as mentioned above, these reactions are unlikely to modify our conclusions, to stimulate innovation in favor of less polluting cars was another objective of the measure. Besides, consumers may modify their vehicle choice and replacement rate because they rationally expect technology, especially as regards fuel consumption, to evolve. Developing a dynamic model of supply and demand for new cars incorporating these technical changes remains a real challenge, one that we leave for future research.

A Appendix

A.1 Definition of Products

As usually in this literature, a product is defined by a set of characteristics. An important issue, then, is to choose which characteristics one ought to retain in this definition. On the one hand, if products are defined by a narrow array of characteristics, very different items are mixed together, possibly leading to strong aggregation biases if the underlying model of demand is not linear, which is the case here. On the other hand, retaining too wide an array of characteristics leads to small market shares for each product, or even null markets shares, as exactly similar cars are often not sold in every month. The theoretical model presented above links the logarithm of the market shares with the observed characteristics. Thus, null sales are not used, which leads to a selection bias.[11] As a compromise, we select the brand, the model, the type of fuel, the type of car-body (urban, station wagon, convertible, etc.), the number of doors and its class of CO_2 emissions. Thus, we adopt a slightly more restrictive definition of a product than Berry *et al.* (1995). Even so, the dispersion of the remaining characteristics (such as price) within each product is not that small compared to the overall dispersion (see Table A.1). A more restrictive definition of products (by including, e.g., horsepower) would reduce this dispersion, but at the cost of increasing the proportion of null sales. Our definition allows us to keep this proportion of null sales relatively small on the whole population of buyers (15% of the models with positive sales between September and November 2007 were not sold between March and May 2008).

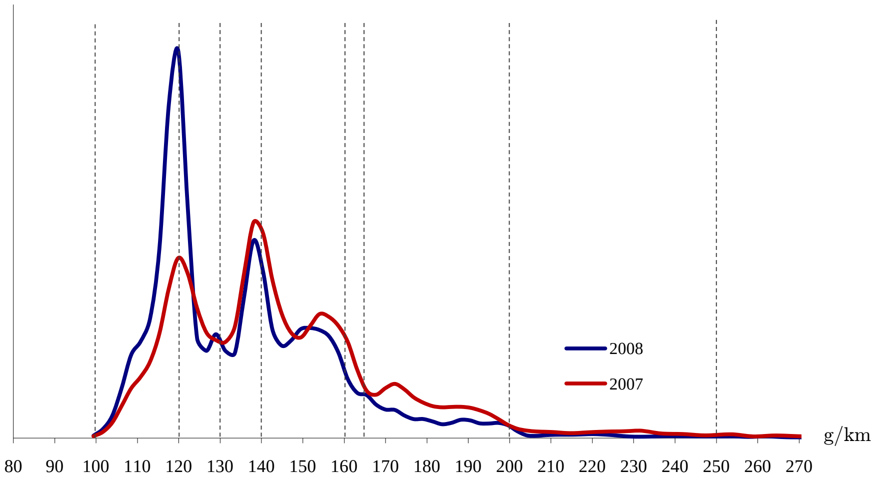
[11] The existence of null sales is a consequence of the finiteness of the French population, and does not invalidate the model. If the market share of a product is 10^{-9}, it is very unlikely that it is sold during a given quarter in France.

Table A.1: *Dispersion of Some Characteristics of New Cars Registered Between September and November 2007*

Variable	Overall dispersion	Dispersion within products
Price (euros)	9,107	1,169
CO_2 (g/km)	27.8	2.4
Taxable horsepower	2.4	0.5

Sources: dataset on the registration of new cars (CCFA).

Figure A.1 presents the density of average emissions of new cars bought just before and just after the reform. The shifts have mainly been towards the most polluting models of the lower classes. We also see that these threshold effects already existed before the introduction of the feebate. This may be due to the fact that consumers value energy classes *per se*. Since May 2006, manufacturers have had to display the European Union energy labels indicating the energy class of their new cars, so that these classes were familiar to consumers in 2007. It may also stem from the pre-existing taxation of company cars, which had been based on these classes since 2006, so that car manufacturers had been able to adapt their products to this classification already.



Sources: dataset on the registration of new cars (CCFA)
Note: Dashed lines correspond to the thresholds in emision classes

Fig. A.1: *Density of Average CO_2 Emissions of New Cars Sold in 2007 and 2008*

Table A.2: *Evolution of Average Prices (in %) Before and After the Reform*

Class of CO_2	2003	2004	2005	2006	2007	2008
B	0.32	-1.16	1.92	1.03	-0.22	1.60
C+	-1.36	2.01	2.79	-0.28	0.71	1.81
C- and D	0.76	0.88	1.78	1.39	-0.01	0.77
E+	0.55	0.16	0.37	0.44	0.74	0.54
E-	0.75	0.99	0.04	0.49	0.75	0.98
F	0.62	-0.14	0.48	-0.71	0.85	1.36
G	0.51	-0.82	0.69	-0.66	0.61	0.07

Sources: dataset on the registration of new cars (CCFA).

Notes: For year $t = 2003$ to 2007, changes in prices are computed between September to November of year t and March to May of year $t+1$. For year 2008, changes in prices are computed between March to May 2008 and September to November 2008. Results for class A are not reported due to the small number of sales until 2007.

A.2 Characteristics of the Buyers of New Cars and the Overall French Adult Population

Table A.3: *Buyers of New Cars Versus the Overall French Adult Population*

Variable	Buyers of new cars	Overall
Activity rate (%)	60.1	58.4
Age (years)	52.3	48.7
Rural and suburban area (%)	41.7	41.1
Median income of the household (%)		
First Quintile	10.6	41.1
Second Quintile	15.7	20.1
Third Quintile	24.1	21.7
Fourth Quintile	38.0	24.5
Fifth Quintile	52.3	48.7

Sources: Transportation Survey (INSEE).

To compute market shares, we also need to define potential markets. We assume here that they correspond, for the subpopulation with characteristics x, to the number of individuals with a driver's license at quarter t. We thus assume that individuals cannot purchase more than two cars during a quarter.

A.3 Computation of The Mileage N_{T_0}

Average emissions of CO_2 vary from one vehicle to another but also according to the use of the vehicle. In particular, emissions differ in urban areas and on highways. Let us denote respectively by A_j^1 and A_j^2 the corresponding average emissions for vehicle j. The total CO_2 emissions of an individual at t_0 is $N_{t_0}^1 A_{Y_{t_0}}^1 + N_{t_0}^2 A_{Y_{t_0}}^2$, where $N_{t_0}^1$ (or $N_{t_0}^2$) corresponds to the mileage in urban area (or on high roads) in 2007. In the CCFA dataset, we observe only the average emissions $A_j = (A_j^1 + A_j^2)/2$ corresponding to a 50% - 50% mixed use, which does not necessarily coincide with the real use of the vehicle. To obtain correct total emissions, we compute $N_{t_0}^*$, defined by

$$N_{t_0}^* \frac{A_{Y_{t_0}}^1 + A_{Y_{t_0}}^2}{2} = N_{t_0}^1 A_{Y_{t_0}}^1 + N_{t_0}^2 A_{Y_{t_0}}^2.$$

$N_{t_0}^*$ simply corresponds to a weighted average of the two mileages:

$$N_{t_0}^* = pN_{t_0}^1 + (1-p)N_{t_0}^2, \text{ where } p = \frac{2A_{Y_{t_0}}^1}{A_{Y_{t_0}}^1 + A_{Y_{t_0}}^2}.$$

Quantities A_j^1 and A_j^2 have been obtained on the ADEME website. Note that we do not observe directly $N_{t_0}^1$ and $N_{t_0}^2$ in the Transportation Survey. To compute them, we consider that 80% of “regular” trips (all trips except those made for professional purposes other than commuting, or for vacation) are made in urban areas for people living in an urban area, and on highways for people living in a rural or suburban area. We consider that other trips consist of 90 % highway travel and 10 % urban area travel. These assumptions allow us to compute $N_{t_0}^1$ and $N_{t_0}^2$ from the total mileage $N_{t_0}^1 + N_{t_0}^2$.

A.4 Proofs of Section 4

A.4.1 Estimation of market shares

According to the model defined in Section 4, in particular Equation (6), we can decompose the utility of j for individual i as

$$U_i(j) = \delta_j + \widetilde{\eta}_{ij}$$

with $\delta_j = (y_x - p_j)\,\beta_{1x} - c_j^{\gamma_x}\mu_x + \xi_{xj}$ for all new car $j = 1...J$, $\delta_0 = y_x\beta_{1x}$, $\widetilde{\eta}_{i0} = \eta_{i0} - c_0^{\gamma_x}\mu_x$ and $\widetilde{\eta}_{ij} = \eta_{ij}$ for $j = 1..J$. While we observe $c_j^{\gamma_x}$ for each new car, this is not the case for the outside option, and thus $-c_0^{\gamma_x}$ is a random term integrated in the residual. The term ξ_{xj} represents the common valuation of individuals of type x for unobservable characteristics of product j. Here we make the normalization $\xi_{x0} = 0$.

As stated below, we use a nested-logit distributional assumption on the residuals $(\widetilde{\eta}_{ij})$. We assume two nests: one constituted by the outside option 0, and the other by all new cars. $\widetilde{\eta}_{i0}$ is independent of $(\widetilde{\eta}_{ij})_{j=1...J}$, while these latter are correlated through a common factor $\widetilde{\upsilon}_i$:

$$\widetilde{\eta}_{ij} = \sigma_x\widetilde{\upsilon}_i + (1 - \sigma_x)\upsilon_{ij}.$$

The $(\upsilon_{ij})_{j=1...J}$ are independent, follow a Gompertz distribution, and are independent of $\widetilde{\upsilon}_i$. The $(\widetilde{\eta}_{ij})_{j=0...J}$ also follow a Gompertz distribution. The distribution of $\widetilde{\upsilon}_i$ is implicitly defined by those of $\widetilde{\eta}_{ij}$ and υ_{ij} and this independence restriction. Cardell (1997, Theorem 2.1) shows that there exists a unique distribution satisfying these conditions, for each value of $\sigma_x \in [0, 1]$.

Considering each type of consumer x as separate markets, the market shares s_{xj} of product j satisfies (see, e.g., Berkovec and Rust, 1985) :

$$s_{xj} = \frac{\exp(\delta_j/(1 - \sigma_x))}{D_{g(j)}^{\sigma_x}\sum_{g=1}^{G} D_g^{1-\sigma_x}}$$

where $g(j)$ denotes the group of product j and $D_g = \sum_{k\in g}\exp\left(\delta_k/(1 - \sigma_x)\right)$ for any group g. This yields

$$\ln\left(\frac{s_{xj}}{s_{x0}}\right) = \frac{\delta_j - \delta_0}{1 - \sigma_x} - \sigma_x \ln\left(\frac{D_g(j)}{D_0}\right) \tag{A.1}$$

As $\sum_{j=1}^{J} s_{xj} = 1 - s_{x0}$, we have $\ln(D_g(j)/D_0) = 1/(1 - \sigma_x)\ln((1 - s_{x0})/s_{x0})$. Under these conditions and using the definition of the utility given by (6), we get

$$\ln(s_{xj}) = \frac{1}{1 - \sigma_x}\left[\ln(s_{x0}) - \sigma_x \ln(1 - s_{x0}) - p_j\beta_{1x} - c_j^{\gamma_x}\mu + \xi_{xj} - \xi_{x0}\right] \tag{A.2}$$

As $\ln(s_{x0})$ is very small in absolute value compared to $\ln(1 - s_{x0})$ (around -0.006 on average, compared to -5.1), we neglect it in A.2.

This definition holds at each period of time. We differentiate it between t_1 (after the introduction of the feebate policy) and t_0 (prior to its introduction) and use the linear price model states by (4.3). Moreover, we assume for simplicity (although not needed for identification) a linear specification for $\sigma_x/(1-\sigma_x)(=x'\lambda)$, $-f_1(z)\beta_{1x}/(1-\sigma_x)$ $(=\sum_{l=1}^{7}\mathbb{1}\{z=z_l\}\theta_l)$ and $-f_2(\tilde{z})\beta_{1x}/(1-\sigma_x)$ $(=\tilde{z}\theta^S)$. We finally obtained (12), where the residual ε_{xj} corresponds to $\xi_{xjt_1}-\xi_{xjt_0}+(p_{t1}(0)-p_{t0}(0))\beta_{1x}$. $p_{t0}(0)$ is the actual price at period t_0 and $p_{t1}(0)$ is the counterfactual price that would have prevailed absent the feebate policy.

We can recover the counterfactual market shares $s_{xj}(0)$ using our estimates and the observed market shares $(s_{xj}(1))_{j=0\dots J}$ (we omit t here for simplicity). To see this, note that

$$s_{xj}(d)=\frac{\exp(\widetilde{\delta}_j(d))}{\left[\sum_{k=1}^{J}\exp(\widetilde{\delta}_k(d))\right]^{\sigma_x}+\left[\sum_{k=1}^{J}\exp(\widetilde{\delta}_k(d))\right]},$$

where $\widetilde{\delta}_j(d)=(\delta_j-\delta_0(d))/(1-\sigma_x)$ for $d=0,1$. Moreover, by Assumption 4.2, the valuation ξ_{xj} and the cost per kilometer c_j are not affected by the feebate policy. Thus, $\widetilde{\delta}_j(0)=\widetilde{\delta}_j(1)-\beta(1-\sigma_x)\left(f_1(Z_j)+f_2(Z_j^S)\right)$ and we obtain

$$s_{xj}(0)=\frac{s_{xj}(1)\exp(-B_j)}{\frac{s_{x0}(1)}{(1-s_{x0}(1))^{\sigma_x}}\left[\sum_{k=1}^{J}s_{xk}(1)\exp(-B_k)\right]^{\sigma_x}+\left[\sum_{k=1}^{J}s_{xk}(1)\exp(-B_k)\right]}\tag{A.3}$$

with $B_j=\sum_{l=1}^{7}\mathbb{1}\{Z_j=z_l\}\theta_l-Z_j^S\theta^S$.

A.4.2 Derivation of Assumption 4.3 from an oligopoly model

We show here that the price equation we posit in Assumption 4.3 is close to being satisfied if we linearize the standard Bertrand-Nash equilibrium of the oligopoly model. First consider the situation without feebate. Letting $\mathcal{J}_f$ denote the set of products sold by firm f, the profit of f when the vector of all final prices is $\widetilde{\mathbf{p}}=(\widetilde{p}_1,\dots,\widetilde{p}_J)$ satisfies

$$\pi_f=\sum_{j\in\mathcal{J}_f}s_j(\widetilde{\mathbf{p}})\times(\widetilde{p}_j-mc_j).$$

$s_j(\widetilde{\mathbf{p}})$ is the market share of product j when the vector of prices is equal to $\widetilde{\mathbf{p}}$, while mc_j is the marginal cost for producing j. The first-order condition for the profit maximization yields

$$\mathbf{\Omega}_0\mathbf{p}(0)=\mathbf{\Omega}_0\mathbf{mc}(0)-\mathbf{s}(\mathbf{p}(0)),\tag{A.4}$$

where $\mathbf{p}(0)$ is the vector of the equilibrium prices without feebates, $\mathbf{mc}(0)$ is the vector of marginal costs without feebates, $\mathbf{s}(.)$ is the function that maps a vector of price to the vector of market shares, and $\mathbf{\Omega}_0$ denotes the matrix whose (j, j') entry is $\partial s_{j'}/\partial p_j(\mathbf{p}(0))$ when j and j' are made by the same firm, 0 otherwise.

After the introduction of the feebate, a similar equation is generated, but now the firm receives $(\widetilde{p}_j - Z_j - mc_j)$ instead of $\widetilde{p}_j - mc_j$ for each sale of j (recall that $\widetilde{p}_j$ denotes the final price and Z_j denotes the fee, with $Z_j < 0$ in case of rebates). Thus,

$$\mathbf{\Omega}_1\mathbf{p}(1) = \mathbf{\Omega}_1(\mathbf{Z} + \mathbf{mc}(1)) - \mathbf{s}(\mathbf{p}(1)), \tag{A.5}$$

where $\mathbf{Z}$ denotes the vector of fees and $\mathbf{\Omega}_1$ is the same as $\mathbf{\Omega}_0$, but derivatives are taken at $\mathbf{p}(1)$ instead of $\mathbf{p}(0)$. Supposing that marginal costs remain constant, neglecting the difference between $\mathbf{\Omega}_0$ and $\mathbf{\Omega}_1$ and using a first-order Taylor expansion of $\mathbf{s}(\mathbf{p}(0)) - \mathbf{s}(\mathbf{p}(1))$, we obtain

$$(\widetilde{\mathbf{\Omega}} + \mathbf{\Omega}_0)\Delta\mathbf{p} \simeq \mathbf{\Omega}_0\mathbf{Z}, \tag{A.6}$$

where $\widetilde{\mathbf{\Omega}}$ denotes the matrix whose (j, j') entry is $\partial s_{j'}/\partial p_j(\mathbf{p}(0))$. Under our nested logit model, and neglecting heterogeneity according to X, we get

$$\frac{\partial s_{j'}}{\partial p_j} = \frac{\beta_1}{1-\sigma} s_j \left[s_{j'} \left(1 + \sigma \frac{s_0}{1-s_0} \right) - \mathbb{1}\{j = j'\} \right].$$

Using these expressions and developing the matrix products in (A.6), we obtain, for all $j \in \mathcal{J}_f$,

$$2\Delta p_j - b \sum_{j' \in \mathcal{J}_f} s_{j'} \Delta p_{j'} - b \sum_{j'=1}^{J} s_{j'} \Delta p_{j'} = Z_j - b \sum_{j' \in \mathcal{J}_f} s_{j'} Z_{j'},$$

with $b = 1 + \sigma s_0/(1 - s_0)$. This shows that $\Delta p_j = Z_j/2 + C_f$, with

$$2C_f - \frac{b}{2} \sum_{j' \in \mathcal{J}_f} s_{j'} Z_{j'} - b s_f C_f - \frac{b}{2} \sum_{j'=1}^{J} s_{j'} Z_{j'} - b \sum_{f'} s_{f'} C_{f'} = -b \sum_{j' \in \mathcal{J}_f} s_{j'} Z_{j'},$$

where $s_f = \sum_{j' \in \mathcal{J}_f} s_{j'}$. Hence, for a given $\mathbf{Z}$ there exists a constant C (with $C = 0$ when $\mathbf{Z} = \mathbf{0}$) such that

$$C_f = \frac{C - \frac{b}{2} \sum_{j' \in \mathcal{J}_f} s_{j'} Z_{j'}}{2 - b s_f}.$$

As market shares are defined on a trimester basis, the total market share of firm f s_f is expected to be close to zero. At the first order, the price change of model j, Δp_j, thus depends linearly on the fee incurred by model j, Z_j, and on a weighted sum of the fees incurred by models produced by the same firm. Provided that the market shares $s_{j'}$ of these models does not vary too much within the same firm, the change in price can be approximated by the price model in (11). Note that weighting each fee $Z_{j'}$ by the corresponding market shares $s_{j'}$ would make the equation endogenous, so we consider an equal weighting scheme here.

A.4.3 Equations (9) and (13)

Using notations of the model described in Section 4, let

$$g_x = E\left(\exp(\nu_{it})|X_{it} = x\right).$$

Note that by Assumption 4.1, g_x does not depend on t. Moreover, it is identified using the residuals of Equation (8). We then have

$$\begin{aligned}
\overline{N}_{jt_1} &= E\left[N_{it_1}|Y_{it_1} = j, X_{it_1} = x\right] \\
&= \exp(\tau(x))c_{jt_1}^{\gamma_x - 1}E\left(\exp(\nu_{it_1})|Y_{it_1} = j, X_{it_1} = x\right) \\
&= g_x \exp(\tau(x))c_{jt_1}^{\gamma_x - 1},
\end{aligned}$$

where the third equality stems from Assumption 4.1. Equation (9) follows.

First, by the law of iterated expectations,

$$\overline{E}_{x0t_1}(0) = P(F_{i0t_0}(0) = 1)\overline{E}_{x0t_1,1}(0) + P(F_{i0t_0}(0) = 2)\overline{E}_{x0t_1,2}(0). \tag{A.7}$$

Second, by Equation (8) and Assumption 4.2, we have, for $f \in \{1, 2\}$,

$$\overline{E}_{x0t_1,f}(0) = I_f^{\gamma_x - 1}\overline{E}_{x0t_0,f}(0). \tag{A.8}$$

Third, by Assumptions 4.2 and 4.5, $E_{x0t_1}(0) = E_{x0t_1}(1)$. This, together with (A.7) and (A.8), proves Equation (13).

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