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

Abstract

At the beginning of 2008 was introduced in France a feebate on the purchase of new cars called the "Bonus/Malus". Since January 2008, less polluting cars benefit from a price reduction of up to 1,000 euros, while the most polluting ones are 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. These emissions depend on the market shares and the average emissions per kilometer of each car, but also on their manufacturing, car fleet size and the average number of kilometers travelled by their owners. We first develop a simple tractable model that relates car choice and mileage. We then estimate this model, using both the exhaustive dataset of car registrations and a recent transportation survey which provides information on individual journeys. We show that if the shift towards classes benefiting from rebates is spectacular, the environmental impact of the policy is negative. The reform has notably increased sales, leading to an important increase in manufacturing and travelling emissions. We thus stress that such policies may be efficient tool for reducing CO_2 emissions since consumers do react to such financial incentives, but should be designed with care to achieve their primary goal.

Keywords: environmental taxation, automobiles, carbon dioxide emissions, policy evaluation

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L'impact du bonus/malus écologique sur les émissions de CO_2

Résumé

La politique du « Bonus/Malus écologique » a été introduite en France début 2008. Depuis janvier 2008, les voitures les moins polluantes bénéficient d'une réduction à l'achat qui peut aller jusqu'à 1 000 euros, alors que les plus polluantes sont soumises à une taxe de 2 600 euros. Nous estimons l'impact de cette politique sur les émissions de dioxyde de carbone à court et long terme. Ces émissions dépendent des parts de marchés et des émissions moyennes au kilomètre des voitures, mais également de leur fabrication, de la taille du parc et du nombre moyen de kilomètres parcourus. Nous développons un modèle simple et tractable qui relie le choix de la voiture et le kilométrage. Nous estimons ce modèle en utilisant la base exhaustive d'immatriculations des véhicules neufs et la dernière enquête Transport qui fournit des informations sur les déplacements individuels. Nous montrons que si le report vers les véhicules bénéficiant d'un bonus a été spectaculaire, l'impact environnemental de la politique a été négatif. Cette réforme a nettement augmenté les ventes, se traduisant par une augmentation importante des émissions liées à la production et à la circulation de ces nouvelles voitures. Nous soulignons ainsi qu'un tel dispositif peut être efficace puisque les consommateurs réagissent fortement aux incitations financières correspondantes, mais qu'il est nécessaire de les calibrer avec attention.

Mots-clés : taxation environnementale, automobiles, émissions de CO_2, évaluation de politiques publiques

Classification JEL : C25, L53, Q53

1 Introduction

Public awareness on environmental issues has raised in the past decade and global warming is now a growing concern for rich and emerging nations. Policy initiatives are launched in many countries to reduce the human contribution to greenhouse gas emissions, especially carbon dioxide (CO_2). Cutting automobile emissions is a crucial objective, as the transportation sector accounts for a large share of the CO_2 emissions (one third in France in 2008, 28% in the US in 2004),[1] and this share keeps on growing.

To reduce emissions stemming from transportation, a first solution, adopted by European northern countries, is to implement Pigovian taxes.[2] Such taxes have however proved very unpopular, as the recent attempt by the French government to implement a carbon tax attests.[3] A second solution, implemented recently in California, British Columbia and the European Union, is to impose low carbon fuel standards. Such norms, however, are in general inefficient. Holland et al. (2009) show they may even lead to an increase of net carbon emissions, by stimulating the production of low carbon fuel. Finally, feebates have recently received attention as an alternative way of internalizing pollution externalities. Their principle is to provide a rebate (resp. a fee) for purchasers of low-emitting (resp. high-emitting) new cars. Up to now, feebates have been implemented in Austria, France and Wallonia (a Belgium region), and are debated in other European countries (see Adamou et al., 2010).[4] In France, this feebate, called the "Bonus/Malus écologique", emerged as one of the main propositions of an environmental roundtable which took place by the end of 2007. It was implemented quickly after, at the beginning of 2008.

The main objective of such policies is to modify consumers' preferences in favor of greener cars. In the French case, this objective seems to have been achieved in a short period of time, as the share of cars whose emissions are below 120g of CO_2 per kilometer doubled within a few months. In the long run, feebates may also induce manufacturers to foster

[1] For France, see the report: http://www.citepa.org/emissions/nationale/Ges/Emissions_FRmt_GES.pdf. For the US, see the report of the U.S. Environmental Protection Agency (2006).

[2] For a comprehensive survey of environmental taxation, see for instance Fullerton & West (2002) or Fullerton et al. (2008).

[3] A tax of 17 euros per ton of CO_2 was adopted by the French Parliament in December 2009 but rejected by the Constitutional Court. Because of its unpopularity (including in the French governing party), the French government finally decided not to replace it by another device.

[4] Even if feebates have not been adopted yet in other European countries, most of them (17 in April 2010) have implemented a taxation which 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 it was suppressed in 2008.

innovation in favor of less emitting cars. It is worth emphasizing, however, that several adverse effects can hamper the impact of the changes in the demand induced by the feebate policy on CO_2 emissions. As an indirect taxation of CO_2 emissions, feebates are subject to the well-known "rebound effect", namely that with more more fuel efficient vehicles, drivers would travel more, thus mitigating the initial reduction of emissions. Another related issue is that the rebates were so important in the French case that the system increased notably total sales.[5] This scale effect translates into extra CO_2 emissions by an increase in mileages and the manufacturing of these new vehicles.[6] Hence, at the end, the effect of the policy on CO_2 emissions is not necessarily positive.[7]

In this paper, we estimate the impact of the French feebate on CO_2 emissions stemming from individuals, taking most of these effects into account.[8] In order to recover the counterfactual emissions that would have prevailed in the absence of the feebate, we propose a simple demand model that combines car and annual mileage choices. This model has the advantage of accounting for consumers' heterogeneity, the differentiation of the automobile market and the existence of rebound effects, while remaining very simple to estimate. Besides, it allows us to estimate separately mileage and vehicle choice parameters. This is convenient since our empirical analysis is based on two datasets that cannot be merged. The first is the exhaustive monthly dataset of car registration in France, which provides detailed information on both new vehicles and car owners. The second is a transportation survey conducted in 2007 which records in particular annual mileages on a large sample of French households. These two datasets allow us to recover both choices with and without the feebate system, and average emissions related to car use for a particular choice of car.

[5]A crucial parameter of a feebate system is the "pivot point" that divides vehicles charging fees from those receiving 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, these parameters were calibrated in order to make the system neutral for the State budget. But ex post the measure turned out to cost 285 millions euros in 2008.

[6]The manufacturing of a new car generates 5.5 tons of CO_2 per ton of new vehicle (see ADEME, 2010). The emissions stemming from scrapping of old vehicles may also be important. We do not include them in our analysis because of data unavailability.

[7]For a discussion of the optimal design of a feebate system, see for instance Greene et al. (2005) or Peters et al. (2008).

[8]We restrict ourselves to private owners, as we do not have information on the mileage of company cars. These vehicles were already subject to a specific tax in favor of the less polluting cars and have probably less reacted to the introduction of the feebate. We do not analyze either the effect of the policy on manufacturers due to a lack of accurate data. We do not have data on automobile industry, and observe sales until January 2009, i.e. only 13 months after the introduction of the feebate. This appears too short for estimating supply-side effects that are more likely to arise in the long run. We perform however a sensitivity analysis on the effect of such reactions on our final results.

As a result, we can recover the total CO_2 emissions under the feebate policy and without it. Another option, chosen e.g. by Feng et al. (2005), relies on the model of Dubin & McFadden (1984) that mixes choices between several discrete options (the vehicle model) and a continuous variable (the mileage). However it would require to observe in one single dataset cars choices and mileages, whereas the transportation survey only records mileages for the year 2007, not precise car choices.

Thanks to our detailed monthly dataset, we estimate the model using sales just before and after the reform took place. As the reform was announced only by the end of October 2007, manufacturers were not able to modify immediately their vehicles characteristics, apart from prices. We estimate a reduced form that combines the demand model relating market shares with characteristics and a price model. An advantage of this approach over the traditional separate estimation of demand and supply is that we do not need to observe real transaction prices. The validity of price models hinges on a correct observation of real prices. However, as usually when studying the car industry, we observe list prices rather than transaction prices. Whereas it is likely that the policy has resulted in a quick adjustment of transaction prices, we do not observe such changes in the list prices. The difference between transaction prices and list prices is thus correlated with the feebate, making this measurement error problematic. Our approach does not suffer from this endogeneity limitation.

We show that if the magnitude of the shift towards the classes benefiting from a rebate is very important, the environmental short-run impact of the feebate is actually negative. This result can be explained by three main effects. First, the policy has significantly enhanced total sales, resulting in particular in an increase in manufacturing. This stresses the need for a careful design of the feebate policy, in order not to generate such negative effects from the demand side. The rebound effect also reduces part of the gain due to the shift in consumers' purchase towards less emitting vehicles. Finally, this disappointing result is also due to threshold effects. Buyers shift their purchase to cars benefiting from rebates but with hardly lower emissions. This overall negative assessment of the feebate policy is robust to various assumptions. In particular, it still holds if we neglect rebound effects.

We also perform an analysis of the long-run impact of the policy (still ignoring supply-side reactions). In the short run, the demand shift due to the feebate corresponds to a very small part of the whole fleet of cars. It is thus important to estimate what would happen with the replacement of the whole fleet. Computing such a long-run impact is however delicate. A crucial issue is the potential impact of the policy on the replacement rate of cars: as emphasized for instance by Adda & Cooper (2000), such replacement effects may be large. In the absence of accurate data on car replacement, we consider two scenarios. In the first, we neglect the impact of the policy on the replacement rate. In the second, we consider a simple dynamic model with competitive prices in the second-market, following Engers et al. (2009). In this case, the change in replacement rates is related to changes in initial prices. Both scenarios lead to a large negative impact of the policy. Once more, this mainly results from the fact that the feebate leads to an increase in automobile equipment, inducing more car use emissions. This effect widely overcomes the composition effect stemming from changes in car choices. As previously, and even if the long-run effects are more sensitive than the short-run ones to some assumptions, our overall conclusion is robust to several departures from our preferred model. It still holds without any rebound effects, and even if the policy had induced a large reduction by manufacturers of the average emissions of their vehicles.

The paper is organized as follows. The next section presents the reform and the datasets at our disposal. The third part presents the parameters of interest and our identification strategy. Finally, the fourth part displays our results.

2 First insights on the policy

2.1 The feebate system

The feebate system on new cars sales was introduced by the French government in December 2007. The purchasers of new cars emitting less than 130g of CO_2 per kilometer benefit from a direct price cut on their invoice. The amount of the rebate varied, depending on the class of the vehicle (see Table 1) with a maximum of 1,000 euros, and even 5,000 euros for electric cars, which still however represents a negligible share of the market. 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.[9] In practice, rebates applied to new cars ordered on or after 5 December 2007, while fees applied to vehicles first registered in France on or after 1 January 2008. At the same moment, the government introduced a scrapping subsidy of 300 euros (called the "super bonus") for more than 15 year-old automobiles, provided that the purchaser bought a new vehicle emitting less than 160g of CO_2. Given the age condition, this additional rebate

[9]The classification corresponds to the one defined by the European Union for the cars energy labels, except that the government split the A, C and E classes into two subclasses.

was however provided in only 5.4% of the purchases of vehicles benefiting from a rebate (see Friez, 2009).[10]

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%

Note: we observe no sales for class A+ in 2007.

It is worth emphasizing that the feebate policy was decided and then implemented with unusual speed. It resulted from a national environmental roundtable organized in Autumn 2007 by the newly elected president, whose aim was to define the key points of government policy on ecological and sustainable development issues for the coming five years.[11] The concrete measures, including the feebate system, were presented on 25 October 2007, for an almost immediate application. This roundtable and the feebate policy came as quite a surprise as they were not mentioned during the electoral campaign and the right-wing government party was considered not to be preoccupied with environmental issues.

This green taxation for the purchase of new cars by private owners has no precedent in France in magnitude and scope. Some measures already intended 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 only, or were larger in scope but marginal in magnitude. Examples include an income tax reduction to the purchasers of hybrid vehicles, or a very slight taxation of the most polluting vehicles (around 100 euros for cars costing on average 35,000 euros). In contrast, the feebate introduced at the

[10]This scrapping subsidy was extended to 1,000 euros and to cars between 10 and 14 years in 2009, in order to dampen the economic consequences of the 2009 crisis on car industry. We shall not be concerned with this here as we focus on 2008 only.

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

end of 2007 applied to all cars, the rebate representing up to 8.8% of the list price of the corresponding cars, while the penalty could be as large as 14.1% of this price.

The objective of the feebate system was twofold. First, it intended to shift consumers' demand towards low CO_2-emitting cars. Secondly, it aimed at encouraging manufacturers to develop greener vehicles. To better achieve this second purpose, it was mentioned from the beginning of the reform that the thresholds of eligibility for the rebates and imposition of the fees were to be lowered, at a pace allowing manufacturers to adapt their production (5g of CO_2/km every two years). As a result, the thresholds were decreased in January 2010. Less expectedly, the amount of the rebates were also moved at the same date (from 1,000, 700 and 200 euros to 700, 500 and 100 euros, respectively), in order to make the feebate system cost-neutral. Although the initial values of the rebates and fees were already decided according to this criterion, the system turned out to cost around 285 million euros to the state in 2008 because of its overwhelming success in favor of low CO_2-emitting cars.

2.2 Demand reaction

We use the exhaustive dataset on the registration of new cars from January 2003 to January 2009 provided by the Association of French Automobile Manufacturers (CCFA, *Comité des Constructeurs Français d'Automobiles*). It includes all the information that is necessary for the registration of a new car, i.e. some characteristics of the car (brand, model, CO_2 emissions, list prices, type of fuel, number of doors, type of car-body, horsepower, weight and cylinder capacity) as well as a few information on the owner (professional activity, age and the city he lives in). These informations allow us to define the products at a rather detailed level (see the appendix for more details), and take into account consumers' heterogeneity.

As the implementation of the measure was almost immediate, neither consumers nor manufacturers could anticipate the reform before November 2007. On the other hand, Figure 1 shows that anticipation was spectacular on consumers' side in December 2007, especially for the most polluting cars for which the fee only applied in January 2008. Not surprisingly, this large increase for the last classes was followed by an "undershooting" in January and, to a lesser extent, in February. As we do not seek to measure anticipations or undershooting effects, we exclude subsequently December 2007 as well as January and February 2008 from our analysis. We do not observe any noticeable change in November even though the reform was already announced then. This is probably due to the delivery time of new cars, as well as the shift between the purchase and registration of a new car. Similarly, we observe a jump in the sales of the less polluting cars in January only, even though the measure was already in force for vehicles ordered after the 5th of December. This stems from the fact that owners of cars bought in December had to register it after the 1st of January 2008 to receive the rebate.

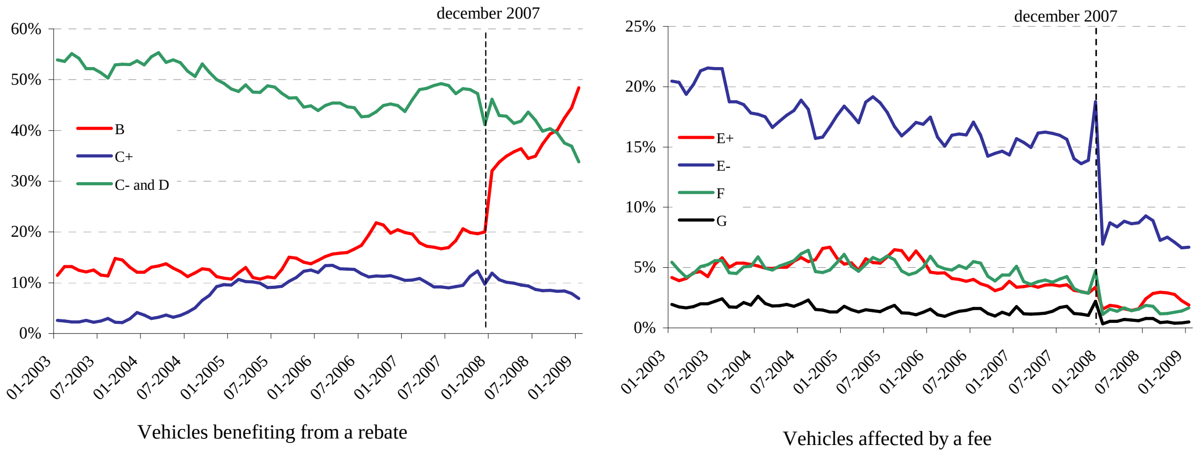

Figure 1: Evolution of the market shares of the different classes of CO_2 emissions.

Figure 1 also highlights the importance of the changes in the market shares of the classes of energy after the reform took place. While class B only represented 20% of sales at the end of 2007, its market share reached nearly 50% at the beginning of 2009. In the same time, the market share of class E- fell from nearly 15% to 5%. These variations are all the more striking that the feebate only represents a modest fraction of list prices, around 4.7% for class B and 2.6% for class E-. It thus seems difficult to rationalize these changes by pure price effects only.[12]

These changes induce a significant impact on average emissions (see Figure 2). This effect is however much smaller than the one observed on market shares. Compared to the trend between November 2005 and November 2007, the average decrease between March 2008 and January 2009 only reaches 5%.[13] This mainly results from threshold effects: many buyers have probably only marginally modified their purchasing decisions, choosing for instance a car emitting 120 g/km (thus belonging to class B) instead of one emitting 121 or 122g/km (belonging to class C+). This fact is confirmed by the density of average

[12] D'Haultfœuille et al. (2010) provide evidence that the feeebate has shifted the individual preferences towards lower CO_2-emitting vehicles.

[13] We restrict ourselves to the period after November 2005 as the CO_2 emissions label became compulsory at this date. There is an acceleration in the decrease of average CO_2 emissions after this period (see D'Haultfœuille et al., 2010).

emissions of new cars bought just before and just after the reform (see Figure 3). 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 to display the European Union energy labels indicating the energy class of their new cars, so that these classes were known by the consumers in 2007. It may also stem from the pre-existing taxation of company cars, already based on these classes since 2006. Car manufacturers thus already had the possibility to adapt their products to this classification.

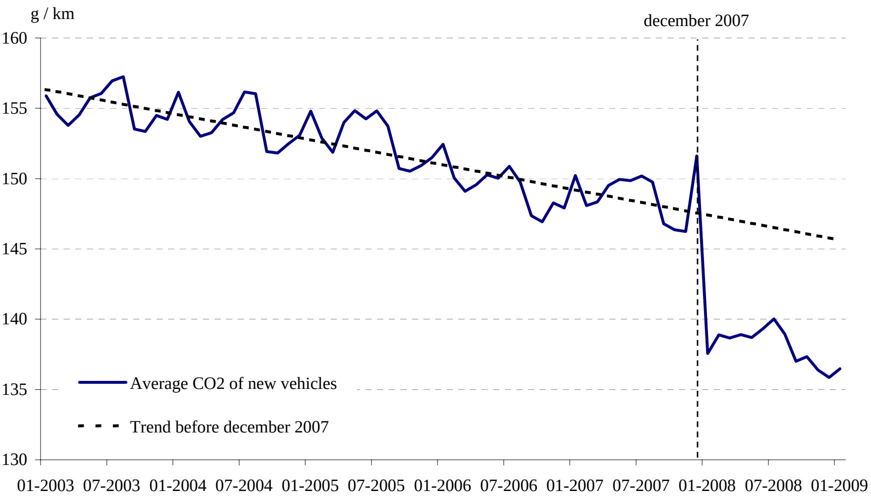

Figure 2: evolution of the average CO_2 emissions of new cars.

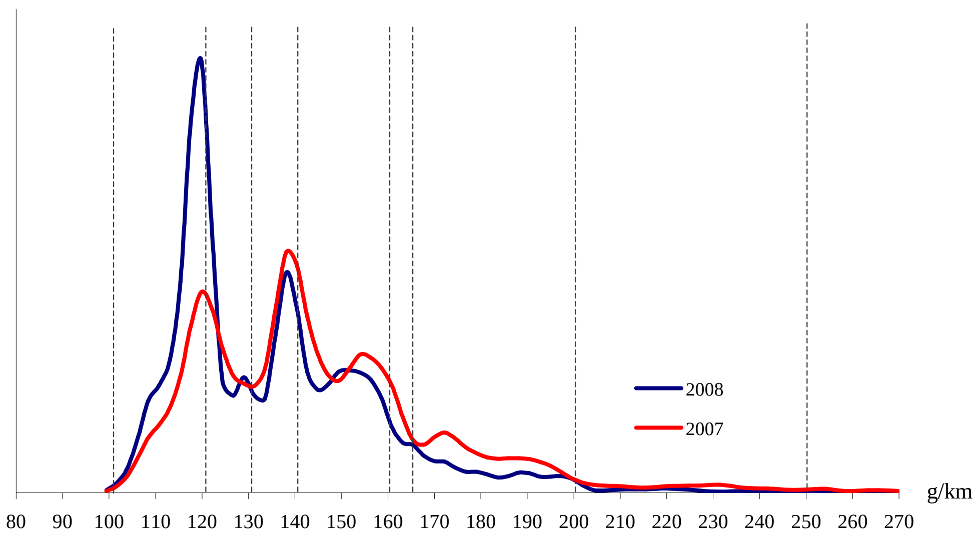

Figure 3: Density of average CO_2 emissions of new cars sold in 2007 and 2008.

The gains in the average emissions of new cars is an interesting insight on the effect of the policy, but does not translate directly into gains in total CO_2 emissions. A first reason is that it does not incorporate the emissions due to the production of new cars. A second reason is the large heterogeneity in the yearly mileage of drivers, which is also related to the characteristics of the car. This heterogeneity is likely to affect the final impact of the policy. In the following, we take this dependence into account using the Transportation Survey conducted by the French national institute of statistics (INSEE) in 2007. This survey provides detailed information about individuals traveling (in particular the annual mileage of their car) and on the characteristics of their vehicles, such as their type of fuel, weight or average CO_2 emissions. Table 2 summarizes the average number of kilometers covered by the cars depending on their characteristics and those of the owners. Results confirm the importance of taking the heterogeneity in the yearly mileage into account. Drivers who choose a heavy (and thus large) car, or those who choose a diesel one, make much more kilometers per year than the others. People with high income as well as these who work and who live in rural areas also use their car more intensively.

Table 2: Average yearly mileage (in kilometers) as a function of the characteristics of the owner or of the car.

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	
Gasoline	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

The introduction of the feebate seems also to have had a positive effect on total sales. A simple comparison of the quarters that we use subsequently, namely the one from September to November 2007 and the one from March to May 2008, shows that total sales increase by around 13.4%.[14] This increase is spectacular as this period also corresponds to an important increase of fuel price, which was likely to reduce the total sales of new vehicles.

2.3 Supply reactions

Apart from the effects on the demand side, an explicit goal of the reform was also to stimulate the reduction of CO_2 in a second round, by triggering innovation by manufacturers to produce lower CO_2-emitting cars. It seems difficult to evaluate such effects with data only up to 13 months after the introduction of the feebate policy. Still, we can study manufacturers reaction in the short-run by looking at the evolution of average emissions of cars that are sold each month, without weighting each product by their sales to eliminate composition effects of aggregate demand.[15] Figure 4 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. As the policy was announced very lately, 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 technological changes are likely to take even more time. A rough quantitative analysis of the number of patents on the corresponding domains[16] 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 shift between the increase in the fuel price following the first oil crisis and the corresponding technical innovations.

[14]The conclusion is similar (13.8%) if we consider the quarter from March to May 2007 instead of the one from September to November 2007 to avoid possible seasonal effects.

[15]We suppose that a model is available for sale at a given month if we observe at least one sale before or at the given month and one sale after or at 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.

[16]According to the European Patent Offices, the patents corresponding to the domains for engine (in the innovation patent classification, F02B, F02D et F02M for fuel engine and B60L for electric ones) does not increase significantly on the considered period.

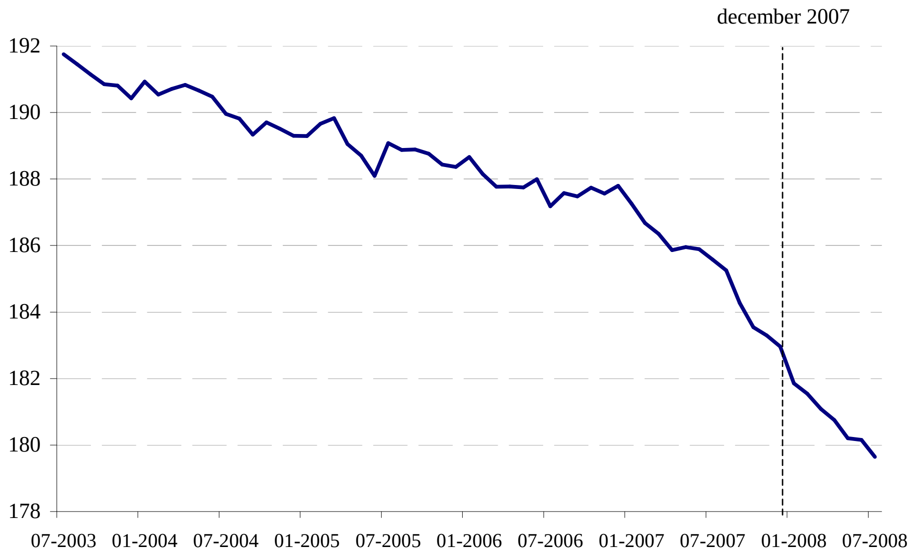

Figure 4: Evolution of average CO_2 emissions before and after the reform.

Apart from CO_2 emissions, we should expect manufacturers to compensate the effects of the measure by increasing prices of the cars benefiting from rebates while decreasing those with fees, to soften the shifts in demand resulting from the policy. However, we do not observe systematic differences between classes of emissions in the evolution of list prices at the period of the reform (see Table 3). A natural explanation is that list prices are typically modified only once a year, so that between March and May 2008, many list prices were not adjusted yet to the reform. To explore further this issue, we also computed the evolution during the year 2008. We observe a rise in prices of B and C+ classes vehicles, but no sharp decrease for high-emitting vehicles. Thus, it seems that either standard predictions of the theory are wrong or that list prices, as proxies of transaction prices, are unreliable (or both). This is the reason why we do not rely on list prices subsequently, and prefer to use a reduced form approach rather than modeling both the demand and supply.[17]

[17]It is possible to consistently estimate a demand model with measurement error in prices because prices are instrumented anyway. Yet, consistent estimation of the supply models requires to observe prices without errors.

Table 3: 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

Reading 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 few number of sales until 2007.

3 Methodology

3.1 Parameters of interest

Before presenting our identification strategy, we define the parameters of interest. We both consider the short-run and long-run effects of the measure on CO_2 emissions. The first corresponds to emissions between March and May 2008,[18] while the second corresponds to quarterly emissions in a long-run scenario defined below. The latter is probably the most relevant parameter, since in the short run the policy only affects new cars, which represent each month 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 produce more effects. The identification of this impact relies on strong assumptions however, while the short-run impact can be identified under rather mild conditions.

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 $Y(d) \in \{0, ..., J\}$ denote the new car chosen by an individual between March and May 2008 with policy status d. As usual, 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 use of an alternative mean

[18]We focus on the period from March to May 2008 because, as mentioned previously, January and February are affected by the "undershooting" effects mentioned previously.

of transportation. For $j \in \{1, ..., J\}$, let $A_j(d)$ denote vehicle j average CO_2 emissions per kilometer. When $j = 0$, average emissions $A_0(d)$ is random and depend on the vehicle the individual already owns.[19] Because CO_2 emissions depend on the emissions per kilometer of cars chosen by the consumers, but also on mileages, we also define $N_j(d)$ as the mileage done by an individual with vehicle j between March and May 2008. Finally, we take into account emissions stemming from the manufacturing of new cars, and let M_j denote the emissions of producing car j (so that by definition, $M_0 = 0$). The emissions of an household with policy status d satisfy

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

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

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

where n is the number of potential buyers. To take into account heterogeneity among individuals in both the purchase of cars and annual mileages, we separate individuals according to some observable characteristics X, namely activity, geographical area and income (for more details on these variables, see Appendix A.2). Letting $X \in \{1, ..., K\}$, we then have $\Delta^{SR} = \sum_{x=1}^{K} \Pr(X = x)\Delta_x^{SR}$, with

$$\begin{aligned} \Delta_x^{SR} \;=\; n\Bigg[& s_{x0}(1)\overline{E}_{x0}(1) - s_{x0}(0)\overline{E}_{x0}(0) + \sum_{j=1}^{J}(s_{xj}(1) - s_{xj}(0))M_j \\ & + \sum_{j=1}^{J}(s_{xj}(1)A_j(1)\overline{N}_{xj}(1) - s_{xj}(0)A_j(0)\overline{N}_{xj}(0))\Bigg], \end{aligned} \tag{3.1}$$

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 $\overline{N}_{xj}(d) = E(N_j(d)|Y(d) = j, X = x)$.

To understand better the effects at stake, let us decompose this expression. We denote by $\overline{A}(1)$, $\overline{N}_x(1)$ and $\overline{M}$ the average emission of the new cars with the policy, the average mileage done by individuals with characteristics x using new cars with the policy and the average production emissions of these new cars, respectively. For any counterfactual variables $(U(0), U(1))$, we denote the impact of the policy on this variable by $\Delta U =$

[19] Because we do not have precise information on the emissions stemming from other means of transportation (such as buses or individuals using vehicles they do not own) in the Transportation Survey, we will neglect hereafter average emissions for individuals who do not own a car.

$U(1) - U(0)$. From Equation (3.1), we can obtain the following useful decomposition:

$$\begin{aligned}
\Delta_x^{SR} \;=\; & n\Big[\underbrace{\sum_{j=1}^{J} \Delta s_{xj}((A_j(1) - \overline{A}(1))\overline{N}_{xj}(1) + M_j - \overline{M})}_{\text{Composition effect}} + \underbrace{\overline{A}(1)\sum_{j=1}^{J} \Delta s_{xj}(\overline{N}_{xj}(1) - \overline{N}_x(1))}_{\text{Rebound effect}} \\
& \underbrace{+(\overline{A}(1)\,\overline{N}_x(1) - \overline{E}_{x0}(1))\sum_{j=1}^{J} \Delta s_{xj}}_{\text{Traveling scale effect}} + \underbrace{\overline{M}\sum_{j=1}^{J} \Delta s_{xj}}_{\text{Manufacturing scale effect}} \\
& \underbrace{+s_{x0}(0)\Delta\overline{E}_{x0} + \sum_{j=1}^{J} s_{xj}(0)\Delta(A_j\overline{N}_{xj})}_{\text{Second-order effect}}\Big]. \qquad (3.2)
\end{aligned}$$

The first component 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). We expect for instance 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 in average, so that the average emissions caused by the production of a new car should be smaller, $\Delta s_{xj}(M_j - \overline{M}) < 0$. However, three other effects may mitigate this positive composition effect. The feebate scheme is designed on (easily observed) emissions per mileage $A_j(1)$, but the result also depends on the final use of cars ($\overline{N}_{xj}(1)$). Because of the rebound effect, individuals may increase their mileages 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, the production of these new cars and the corresponding traveling emissions lead to a rise in CO_2 emissions. This is partly, but only partly, offset by the fact that these new cars in excess are used instead of older ones (the term $-\overline{E}_{x0}\sum_{j=1}^{J} \Delta s_{xj}$), 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 however expect the former to be negligible in the short run, and the latter to be small once controlled for observed heterogeneity X.

Let us now turn to long-run effects. Noteworthy, due to limitations in our data, we still abstract from supply side effects here. More generally, we assume that the automobiles supplied in the long run are those who were already proposed at the beginning of 2008. We also suppose that the sales of new cars and annual mileages remain constant each quarter after the beginning of 2008.[20] Hence, the only difference with the short run is that in this long-run scenario, the whole fleet of cars has been replaced.

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

$$\Delta_x^{LR} = n \sum_{j=1}^{J} (s_{xj}(1) - s_{xj}(0))M_j + (\widetilde{s}_{xj}(1)A_j(1)\overline{N}_{xj}(1) - \widetilde{s}_{xj}(0)A_j(0)\overline{N}_{xj}(0)), \qquad (3.3)$$

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 previously, we neglect emissions corresponding to other means of transportation here.

For the sake of interpretation we propose the same type of decomposition as above. First, it is useful to notice than in a steady-state equilibrium we have the following relationship between the share of the car j in the whole fleet and its share in the flow of new cars:

$$\widetilde{s}_{xj}(d) = T_{xj}(d)s_{xj}(d), \qquad (3.4)$$

where $T_{xj}(d)$ is the average lifetime of vehicle j when bought by individuals of type x under policy status d. We first consider a scenario where the cars' lifetime is the same for all

[20]Thus, we abstract from potential transitory effects in sales, i.e. that sales just after the reform may not correspond to sales a few months later. If the policy affects the optimal replacement of cars (as explained below), there is a decrease in the optimal lifetime of smaller cars and an increase in the optimal lifetime of bigger ones, so that many individuals find it optimal to replace their (small) car at the beginning of the period, while a large part of individuals with bigger cars postpone their decision to replace their car. As our estimation period started two months after the policy took place, most of these adjustments should have already been done. 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).

cars, and not affected by the reform (i.e. $T_{xj}(d) = \overline{T}_x$ constant). In this case, we obtain:

$$\begin{aligned}\Delta_x^{LR_1} &= n\Bigg[\underbrace{\sum_{j=1}^{J} \Delta s_{xj}\left[\overline{T}_x(A_j(1) - \overline{A}(1))\overline{N}_{xj}(1) + M_j - \overline{M}\right]}_{\text{Composition effect}} \\ &\quad \underbrace{+\overline{T}_x\,\overline{A}(1)\sum_{j=1}^{J}\Delta s_{xj}\left[(\overline{N}_{xj}(1) - \overline{N}_x(1))\right]}_{\text{Rebound effect}} \underbrace{+\,\overline{T}_x\,\overline{A}(1)\,\overline{N}_x(1)\sum_{j=1}^{J}\Delta s_{xj}}_{\text{Traveling scale effect}} \\ &\quad + \underbrace{\overline{M}\sum_{j=1}^{J}\Delta s_{xj}}_{\text{Manufacturing scale effect}} \underbrace{+\,\overline{T}_x\sum_{j=1}^{J} s_{xj}(0)\Delta(A_j\overline{N}_{xj})}_{\text{Second-order effect}}\Bigg]. \qquad (3.5)\end{aligned}$$

The change in emissions due to the production of new cars over a quarter is the same as in the short run, whereas the one of the composition effect is far larger, the first term in the brackets being multiplied by $\overline{T}_x$ (around 80 quarters in our sample) The rebound effect is also $\overline{T}_x$ times larger, while the traveling scale effect is multiplied by an even larger factor, as it is not mitigated anymore by the fact that in the short run, new cars substitute to older (and thus more polluting) ones.

This scenario suffers however from the fact that the price differential due to the feebate is likely to modify renewal choices. On a related issue, Adda & Cooper (2000) for instance present evidence that changes in the scrapping value have significant impact on cars lifetime. We expect that vehicles with a fee are kept on a longer period than those benefiting from a rebate, so that their share in the whole fleet is larger than their shares in total sales, partially offseting the impact of the policy (as $\Delta s_{xj}\Delta T_{xj} < 0$). On the other hand, larger average lifetimes means that the increase in total sales due to the policy does not increase that much the share of individuals owning a car, mitigating the traveling scale effects. This replacement rate effect is thus potentially ambiguous. To assess its importance, we still suppose that $T_{xj}(0) = \overline{T}_x$ but $T_{xj}(1) \neq T_{xj}(0)$. In this case, using (3.3), (3.4) and the equality $\Delta\widetilde{s}_{xj} = \Delta T_{xj} s_{xj}(1) + T_{xj}(0)\Delta s_{xj}$, we get:

$$\Delta_x^{LR_2} = \Delta_x^{LR_1} + \underbrace{n\sum_{j=1}^{J} s_{xj}(1)\Delta T_{xj} A_j(1)\overline{N}_{xj}(1)}_{\text{Replacement rate effect}}. \qquad (3.6)$$

3.2 A theoretical model of car and mileage choices

The short and long-run effects of the policy depend on several variables that are not observed directly in our dataset: the counterfactual variables $Y(0)$, $A_j(0)$ and $N_j(0)$, but also mileages $N_j(1)$ (we only observe, in the Transportation Survey, annual mileages in 2007). Several assumptions are thus needed to identify these effects. To this end, we develop a theoretical model that links car choice and mileage and takes into account consumers' heterogeneity. Let us consider an individual of type x under policy status d. We suppose that his indirect utility of choosing vehicle j and anticipating to travel N kilometers a year satisfies[21]

$$U(N,j,d) = N^{\frac{\gamma_x}{\gamma_x-1}}\alpha_x + \left(y(d) - p_j(d) - \frac{c_j(d)N}{r_x}\right)\beta_x + f_{1x}(Z_j)d + \xi_{xj}(d) + e_j, \qquad (3.7)$$

where y is the income, $p_j(d)$ corresponds to the transaction price of vehicle j with policy status d (including the feebate if $d=1$), r_x is the discount rate, Z_j is the fee of vehicle j under the feebate policy ($Z_j < 0$ if j benefits from a rebate)[22] and $\xi_{xj}(d)$ represents other observable and unobservable characteristics of the vehicle. $c_j(d)$ (resp. $c_0(d)$) is the cost per kilometer of vehicle j (resp. for an individual who chooses the outside option). We suppose that $0 < \gamma_x < 1$ and $\alpha_x < 0$, so that utilities are increasing, concave functions of N. The dependence in x of $(\beta_x, \gamma_x, r_x, f_{1x}, \xi_{xj}(d))$ reflects the heterogeneity in the way people value the corresponding characteristics of the car. Noteworthy, this specification allows for the possibility of a direct effect of feebates on demand (through $f_{1x}(Z_j)$), apart from their indirect effect through price variations. There is indeed evidence that the reform has had an impact on the environmental awareness of consumers beyond prices effects (see D'Haultfœuille et al., 2010). On the other hand, we suppose that $f_{1x}(0) = 0$, and impose that the policy has not affected fuel prices and automobiles characteristics other than prices.

Assumption 3.1 *(No short-run effect of the feebate on cars characteristics apart from price) For all x, j, ξ_{xj}, A_j and c_j do not depend on d.*

Assumption 3.1 implies in particular that manufacturers did not modify immediately average emissions of their vehicles because of the reform. As already discussed in Subsection 2.3, this condition is likely to hold here. Combined with the assumption on the cost per kilometer, it also implies that the fuel price is unaffected by the introduction of the feebate.

Individuals are supposed to maximize their utility both in N and j. For a given j, the optimal anticipated mileage N_j^* satisfies

$$N_j^* = \left(\frac{\beta_x(\gamma_x - 1)c_j}{r_x\alpha_x\gamma_x}\right)^{\gamma_x - 1}. \qquad (3.8)$$

[21]This model is close to standard models of vehicle choice (see, e.g., Berkovec & Rust, 1985, or Goldberg, 1995), except that we also take into account mileage here.

[22]For the outside option, $p_0(d) = 0$ and $Z_0 = 0$.

This relationship is at the basis of the so-called rebound effect, since it indicates that individuals will increase their mileage following a reduction of the cost per kilometer of their car (as soon as $\gamma_x < 1$). Plugging N_j^* into (3.7), the utility of choosing j is equal to

$$U(j, d) \quad = \quad (y(d) - p_j(d))\, \beta_x - c_j^{\gamma_x} \mu_x + f_{1x}(Z_j)d + \xi_{xj} + e_j,$$

where $\mu_x = \frac{\alpha_x}{\gamma_x - 1}\left(\frac{\beta_x(\gamma_x - 1)}{r_x \gamma_x \alpha_x}\right)^{\gamma_x}$. To recover the market shares of each product corresponding to the above utilities, we make some distributional assumptions on the residuals $\widetilde{e}_0, e_1, ..., e_j$ (where $\widetilde{e}_0 = c_0^{\gamma_x}\mu_x + e_0$).[23] To get realistic substitution patterns between the outside option and new cars, while keeping the model simple to estimate, we rely on a nested logit model specification, following, e.g., Berkovec & Rust (1985) or Goldberg (1995). The first nest is the set of all new cars, while the second nest is the outside option. We thus suppose that $\widetilde{e}_0, e_1, ..., e_j$ are identically distributed and follow a Gompertz distribution. $\widetilde{e}_0$ is independent of $(e_1, ..., e_j)$, while these latter are correlated through a common factor ζ:

$$e_j = \sigma_x \zeta + (1 - \sigma_x)\eta_j.$$

The $(\eta_j)_{j=1...J}$ are independent, follow a Gompertz distribution and are independent of ζ.[24] Under these conditions, we get

$$\begin{aligned} \ln(s_{xj}(d)) \quad &= \quad \frac{1}{1 - \sigma_x}\left[\ln(s_{x0}(d)) - \sigma_x \ln(1 - s_{x0}(d)) - \xi_{x0} - p_j(d)\beta_x \right. \\ &\qquad \left. - c_j^{\gamma_x}\mu_x + f_{1x}(Z_j)d + \xi_{xj}\right], \end{aligned} \tag{3.9}$$

where, as previously, $s_{xj}(d) = P(Y(d) = j|X = x)$. Finally, we posit the following relationship between $p_j(0)$ and $p_j(1)$.

Assumption 3.2 *(Dependence of transaction prices on the feebate scheme)*

$$p_j(1) = p_j(0) + f_2(Z_j) + f_3(\widetilde{Z}_j),$$

where $\widetilde{Z}_j$ *is the sum of fees of vehicles produced by the firm that produces* j *and* $f_2(0) = f_3(0) = 0$.

This assumption should be seen as a flexible approximation of a price model. We include $\widetilde{Z}_j$ because when fixing price of j so as to maximize its profit, the firm should take into account its effect on the profit stemming from j but also from the other cars it produces.

[23] We consider $\widetilde{e}_0$ instead of e_0 because $c_0^{\gamma_x}$ is a random term which varies from one individual to another (contrary to $c_j^{\gamma_x}$). It should therefore be included in the error term.

[24] The distribution of ζ is implicitly defined by those of e_j and η_j and this independence restriction. Cardell (1997, Theorem 2.1) shows that there exists a unique distribution satisfying these conditions, for each value of $\sigma_x \in [0, 1]$.

3.3 Identification strategy

To identify the short-run effects, we have to recover average quarterly mileages, outside emissions and the counterfactual market shares. Long-run effects rely on additional restrictions which are detailed separately.

3.3.1 Average mileages

Our theoretical model provides us with a convenient form for average quarterly mileages, that vary according to individual characteristics and the cost per kilometer of the chosen cars. Real data do not exactly correspond to this stylized model however, and we have to take into account differences between the deterministic rule given by Equation (3.8) and actual data. We postulate the following relationship between anticipated and actual mileages (denoted N_t hereafter). Because we use the Transportation survey which measures mileages at a different period (the year 2007), we introduce a period index t hereafter. t_1 refers to the quarter between March and May 2008, while t_0 corresponds to the quarter between September and November 2007.

Assumption 3.3 *(Link between anticipated and actual mileages) We have*

$$\ln N_t = \ln N^*_{Y_t(d)t} + \delta_x + \nu_t,$$

where δ_x is a x-specific constant, ν_t is independent of $(Y_t(d), A_{0t}(d), c_t)$ conditional on X, $E(\nu_t|X = x) = 0$ and the distribution of ν_t does not depend on t.

The important restrictions are that the distribution of the error term does not depend on t, and is independent of the car choice and the cost per kilometer.[25] As a consequence, the average mileage $\overline{N}_{xjt}$ for car j is only determined by the cost per kilometer and does not depend on the policy. This means that we neglect here the aforementioned selection effects that may affect the second-order term in (3.2) and (3.5). We come back to this issue in Subsection 4.3.

By Equation (3.8) and Assumption 3.3, we have

$$\ln N_{t_0} = \widetilde{\delta}_x + (\gamma_x - 1) \ln c_{t_0} + \nu_{t_0}. \tag{3.10}$$

where $\widetilde{\delta}_x$ is a x-specific constant. Under Assumption 3.3, $E(\nu_{t_0}| \ln c_{t_0}, X) = 0$. This means that we can estimate by OLS γ_x, that will correspond to the extent of the rebound effect, $\widetilde{\delta}_x$

[25] On the other hand, Assumption 3.3 allows for both biased and unbiased anticipations, the latter holding when $E(\exp(\delta_x + \nu_t)|N^*_{Y_t(d)t}) = 1$.

and the distribution of the residuals ν_{t_0}. These parameters will provide us with a measure of the average mileage by type of individual $\overline{N}_{xjt_1}$ using (see Appendix A.4 for the proof)

$$\overline{N}_{xjt_1} = E\left(\exp(\nu_{t_0})|X = x\right)\exp(\widetilde{\delta}_x)c_{jt_1}^{(\gamma_x - 1)}. \tag{3.11}$$

3.3.2 Outside emissions

Recall that the outside option is the decision not to buy a new car at a given period. Total emissions corresponding to this option depend on the share of individuals who do not have a car, and on the distribution of average emissions on the stock of existing cars. In the long run, both are likely to be affected by the feebate policy. On the other hand, it seems very plausible that they remain constant in the short run. We state this formally in Assumption 3.4. We let hereafter $F_{0t}(d)$ denote the type of fuel of the car owned by an individual when choosing the outside option ($F_{0t}(d) = 2$ for a gasoline car, 1 for a diesel one and 0 if the individual does not have a car).

Assumption 3.4 *(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 Assumptions 3.3-3.4, average outside emissions at period t_1 are identified by (see Appendix A.3 for the proof)

$$\overline{E}_{x0t_1}(1) = \overline{E}_{x0t_1}(0) = I_1^{\gamma_x - 1}P(F_{0t_0}(0) = 1)\overline{E}_{x0t_0,1}(0) + I_2^{\gamma_x - 1}P(F_{0t_0}(0) = 2)\overline{E}_{x0t_0,2}, \tag{3.12}$$

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 $F_{0t_0}(0) = f$:

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

3.3.3 Counterfactual market shares

Finally, we have to recover the counterfactual market shares at period t_1, $s_{xjt_1}(0)$, to identify short-run effects. For that purpose, we differentiate Equation (3.9) over time (to eliminate any fixed effect) and replace prices by their expression given in Assumption 3.2. This reduced form is sufficient to obtain the counterfactual market shares that appear in the short and long-run effects. Besides, an advantage of this approach over the traditional separate estimation of demand and supply is that we need not observe the real transaction prices, which are necessary for a correct estimation of the price model. As emphasized in Subsection 2.3, it is likely that the measurement error resulting from the use of list prices is correlated with the feebate. Our approach does not suffer from this endogeneity issue. We rely instead on the following exogeneity condition.

Assumption 3.5 *(Exogenous residuals in market shares and no systematic trend in the short run)* $E(\varepsilon_{xj}|Z_j, \widetilde{Z}_j, c_{jt_1}, c_{jt_0}) = 0$, *where* $\varepsilon_{xj} = \xi_{x0t_1} - \xi_{x0t_0} - (\xi_{xjt_1} - \xi_{xjt_0}) + \beta_x(p_{jt_1}(0) - p_{jt_0}(0))$.

This condition is satisfied if the evolution of the characteristics of vehicle j (the term ξ_{xjt}) are unrelated to its feebate and to its cost per kilometer. As detailed in Subsection 4.3, we can partially test for this assumption by checking that variations in market shares between two years preceding the feebate introduction do not depend on classes of emissions.

Note that $\ln(s_{x0t}(d))$ is very small in absolute value compared to $\ln(1 - s_{x0t}(d))$ (around -0.006, compared to -5.1), so we neglect it in (3.9). Under these conditions, we obtain

$$\ln(s_{xjt_1}(1)/s_{xjt_0}(0)) = \ln\left(\frac{1 - s_{x0t_0}(0)}{1 - s_{x0t_1}(1)}\right)\frac{\sigma_x}{1 - \sigma_x} + f_{4x}(Z_j) + f_{5x}(\widetilde{Z}_j) - \left(c_{jt_1}^{\gamma_x} - c_{jt_0}^{\gamma_x}\right)\widetilde{\mu}_x + \varepsilon_{xj}, \tag{3.13}$$

where $f_{4x}(z) = (f_{1x}(z) - f_2(z)\beta_x)/(1-\sigma_x)$, $f_{5x}(z) = -f_2(z)\beta_x/(1-\sigma_x)$ and $\widetilde{\mu}_x = \mu_x/(1-\sigma_x)$. To estimate this equation, we use the estimate of γ_x obtained before. We also assume for simplicity (although not needed for identification) that $\sigma_x/(1 - \sigma_x) = x'\lambda$, $f_{4x}(z) = \sum_{l=1}^{7} \mathbb{1}\{z = z_l\}\theta_l$ (where $(z_l)_{l=1...7}$ denotes the different nonzero values for the feebate) and $f_{5x}(z) = z\kappa$. We can then identify these parameters by simple OLS.[26] Using Equation (3.9) and Assumption 3.1, it is then possible to recover the counterfactual market shares for individuals of type x (see Appendix A.4 for details).

3.3.4 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 $\widetilde{s}_{xjt_1}(d)$. By Equation (3.4), this depends in turn on $T_{xjt_1}(d)$, the average lifetime of vehicle j when bought with individuals of type x at t_1 under policy status d.

Unfortunately, as far as we know, no French data provide recent information on cars lifetime. In particular, the data used by Adda & Cooper (2000) no longer exist. 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

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

[26] λ is identified because $f_{4x}(0) = f_{5x}(0) = 0$.

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 the official statistics (the monthly flow of new cars represents 0.5% of the stock of cars less than 15-year old, leaving us with an estimated value of 67 quarters).[27] We also assume that average lifetimes at t_1 without the policy would have remained the same as in t_0, so that $T_{xjt_1}(0) = \overline{T}_{t_0}$

Finally, to identify lifetimes at t_1 with the policy, we consider two scenarios, consistent with the two decompositions (3.5) and (3.6). In the first, we assume that the policy does not modify replacement rates.

Assumption 3.6 *(No effect of the feebate on average lifetimes) For all* $j \in \{1, ..., J\}$, $x \in \{1, ..., K\}$ *and* $d \in \{0, 1\}$, $T_{xjt_1}(d) = \overline{T}_{t_0}$.

This scenario implies that the increase in sales observed in the short run leads to a proportional overall increase in the equipment rate of the French population. If extreme, this assumption is not fully unrealistic. If the share of the French households with at least one car is rather stable in recent years (slightly above 80%), the multiequipment rates has more than doubled in less than thirty years : 35.8% of French households has at least two cars in 2008 while this rate was only 16.5% in 1980, and policies such as the feebate may still increase this multi-equipment rate.

We also consider a scenario where lifetimes adjust to the policy. We propose in appendix a simple model inspired by Engers et al. (2009), which leads to the following approximation:

Assumption 3.7 *(Impact of the policy on cars lifetime before scrapping) For all* $j \in \{1, ..., J\}$ *and* $x \in \{1, ..., K\}$, $T_{xjt_1}(0) = \overline{T}_{t_0}$ *and*

$$T_{xjt_1}(1) = \frac{\ln\left[1 - \left(1 - (r_2 r)^{\overline{T}_{t_0}}\right) \frac{p_{jt_1}(1)}{p_{jt_1}(1) - Z_j}\right]}{\ln(r_2 r)}.$$

Simple algebra shows that behicles benefitting from a rebate are renewed more often, as expected. The importance of the adjustment 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 use of a vehicle, r_2, and sale prices $p_{jt_1}(d)$. In practice, we set $r = r_2 = 0.987$, corresponding to an annual interest rate (resp. depreciation rate) of 5%.

[27] Official statistics are available for cars less than 15-year old only, and are not restricted to cars owned by households, both leading probably to a negative bias of the true lifetime we aim to estimate.

4 Results

We now turn to the estimation of our model. We follow the steps of our identification strategy. First, we estimate the mileage demand corresponding to Equation (3.10) from the Transportation Survey. This provides us with an estimate of the parameter γ_x reflecting the dependency of mileage in the cost per kilometer. We can then compute outside emissions from Transportation survey, using (3.12). Second, we estimate the reduced-form of the demand model (Equation (3.13)) that links the change in market share of cars to the introduction of the feebate, using the dataset on new cars registrations. This provides us with the counterfactual market shares that would have prevailed in the absence of the feebate policy. Finally, the short and long-run effects are computed.

4.1 Mileage and outside option emissions

We first use the Insee Transportation Survey to estimate the dependence between mileage, the cost per kilometer and the household characteristics (as expressed in Equation (3.10)). This allows us to compute average mileages (defined in Equation (3.11)), average outside emissions (see Equation (3.12)) and to obtain an estimator of γ_x that we then plug in the market shares Equation (3.13). Actually, we suppose that this elasticity of the mileage to the cost per kilometer γ_x does not depend on the type of household x (interaction terms introduced in the regression between X and the cost per kilometer were not significant at the 5% level). We also suppose that the household characteristics $\widetilde{\delta}_x$ are linear in the dummies of activity, geographical area and income. Results are displayed in Table 4.

Table 4: Estimates of the mileage model (log) according to households characteristics and cost per kilometer.

Variables	Estimate
Intercept	10.44^{***} (0.191)
Non working	-0.364^{***} (0.015)
Rural and suburban area	-0.013 (0.014)
Income in 2nd quintile	0.077^{***} (0.027)
Income in 3rd quintile	0.141^{***} (0.025)
Income in 4th quintile	0.21^{***} (0.024)
Income in 5th quintile	0.245^{***} (0.024)
Cost per kilometer $(\gamma - 1)$	-0.536^{***} (0.027)

Reading note: Mileages are computed on the whole 2007 year. Significance levels: *** 1%, ** 5%, * 10%.

We thus obtain $\widehat{\gamma} - 1 \simeq -0.54$. To compare this estimate with previous results, mostly based on variations in fuel price (either with macro or micro data), recall that the actual cost per kilometer satisfies $c_{Y_{it}t} = f_{Y_{it}t} A_{Y_{it}t}$, where f_{jt} is the fuel price for vehicle j at date t. A change in the fuel price induces both a modification of $c_{Y_{it}t}$ and $A_{Y_{it}t}$, because individuals may change their car according to fuel price fluctuations. Thus, by Equation (3.10), and letting ε_N (resp. ε_A) denote the price elasticity of mileage (resp. of average emissions per kilometer), we get

$$\gamma - 1 = \frac{\varepsilon_N}{1 + \varepsilon_A}.$$

We thus expect $\gamma - 1$ to be smaller in absolute value than the price elasticity of fuel consumption, which is equal to $\varepsilon_N + \varepsilon_A$. Our results are consistent with this prediction, the usual estimates of the long-run elasticities lying between -0.8 and -0.6 (see, e.g., Graham & Glaister, 2002 for a survey).[28] Interestingly, it is also very close to the estimates given by Johansson & Schipper (1997), who separately estimate ε_N and ε_A on 12 OECD countries and obtain for France $\varepsilon_N = -0.33$ and $\varepsilon_A = -0.38$, leading to $\varepsilon_N/(1 + \varepsilon_A) \simeq -0.53$.

[28] These estimates are usually obtained on macro data. Noteworthy, our result is also smaller in absolute value than the price elasticity obtained on micro data by Clerc & Marcus (2009) in France, namely -0.70.

4.2 Effect on CO_2 emissions

To evaluate the impact of the measure on market shares, we estimate the reduced form of our nested logit model, using Equation (3.13).

Table 5: Impact of the feebate on market shares (OLS estimates of Equation (3.13)).

Parameter	Estimate
Substituability terms (λ)	
Intercept	2.035^{***} (0.258)
Non working	-0.0001 (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	-3.763^{***} (0.141)
Rebate = 1.000 €	0.3847^{*} (0.2086)
Rebate = 700 €	0.6982^{***} (0.0292)
Rebate = 200 €	0.0113 (0.0288)
Fee = 200 €	-0.257^{***} (0.0374)
Fee = 750 €	-0.2808^{***} (0.0221)
Fee = 1.600 €	-0.1484^{***} (0.0328)
Fee = 2.600 €	-0.1468^{***} (0.0491)
Sum of fees of the firm	0.003^{***} (0.0004)

Reading notes: significance levels: *** 1%, ** 5%, * 10%.

As expected, market shares of vehicles benefiting from a bonus increase at the expense of those affected by a penalty (Table 5). The penalty effect appears however strongly concave, as the negative impact of the fee is not significantly different for almost all classes penalized by a fee. Finally, and as expected, the estimated coefficient of the cost per kilometer is significant and negative (-3.76).

We check informally the quality of our demand and price models by comparing the market shares observed in 2007 with those predicted by our model in absence of the feebate policy. The model reproduces quite accurately the market shares observed in 2007 (see Table 6). We observe slight (but insignificant) differences for some classes, as the model indicates that the share of classes C+ and D would also have increased, absent the reform. On the other hand, the share of the most polluting cars would have decreased. Such predictions are consistent with the sharp increase in fuel price observed at the beginning of 2008 (the gasoline price was for instance 15% higher than in September-November 2007). Overall, the average gain in terms of CO_2 emissions of new vehicles is equal to 3.9%, 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 increase in sales of 13.4% observed between September-November 2007 and March-May 2008. It will prove to have large consequences on the effect of the policy on total emissions.

Table 6: Comparison between the observed market shares and those predicted by the model (%).

Class	Observed in 2007	Prediction (without bonus)
A	0.02	0.02 (0.03)
B	21.56	21.35 (4.19)
C-	11.39	11.66 (2.78)
C+ and D	48.84	50.95 (5.53)
E-	2.61	2.01 (0.63)
E+	12.87	11.92 (2.06)
F	1.98	1.56 (0.36)
G	0.72	0.53 (0.17)
Total	*100.00*	*100.00*

Reading notes: the market shares do not include the outside option and thus sum to 100%. Standard errors were computed by bootstrap (with 1,000 simulations).

The overall effects of the policy, both in the short and long run, are displayed in Table 7, while the decomposition of these effects are 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 environment (see ADEME, 2010).

In the short run, the composition effect of the change in the composition of the new cars' sales reaches approximately -80.4 kilotons of quarterly CO_2 emissions, well above (in absolute value) the rebound and traveling scale effects. Hence, the measure would have been positive without the manufacturing effects. However, this latter effect dominates in the short run, representing around 232.1 kilotons of quarterly CO_2 emissions. As a result, we obtain a significant increase in the short run of around 168.4 kilotons per quarter. With a cost of the ton of CO_2 fixed at 32 euros (consistent with Yohe et al. (2007) meta-analysis), the overall environmental short-run cost of the measure would reach 5.4 million euros per quarter.

Table 7: Short and long-run effect of the feebate policy.

Parameter	Estimates		
	Kilotons	Million of euros	% of total emissions
Short-run effect Δ^{SR}	168.4^{***} (52.4)	5.4^{***} (1.7)	$1.2\%^{***}$ (0.4%)
Long-run effect Δ_1^{LR}	$1,524.3^{***}$ (440.6)	48.8^{***} (14.1)	$13.7\%^{***}$ (4.3%)
Long-run effect Δ_2^{LR}	$1,029.8^{***}$ (365.7)	33^{***} (11.7)	$9.3\%^{***}$ (3.5%)

Note: 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%.

Table 8: Decomposition of the short and long-run effects.

Parameter	Estimates (kilotons) short run	Estimates (kilotons) long run
Composition effect	-80.4^{***} (16.1)	-895.0^{***} (184.7)
Rebound effect	6.1^{***} (1.5)	496.0^{***} (119.4)
Traveling scale effect	10.4^{***} (2.8)	$1,691.0^{***}$ (448.0)
Manufacturing scale effect	232.1^{***} (61.1)	232.1^{***} (61.1)
Replacement rate effect		-495^{***} (123.1)

Note: 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 higher effects in the long run. When ignoring the potential impact of the feebate on cars lifetime, the impact on quarterly emissions is higher by a factor 9. While in the short run, the main component of the negative impact is the manufacturing emissions, traveling emissions predominates in the long run. As a result, we estimate that the introduction of the feebate accounts for an increase of 13.7% in total automobile emissions.

Our results also indicate that taking into account lifetime adjustments is important. We estimate significant lifetime changes, the average lifetime of class B vehicles decreasing by 14% while the one of class G cars increasing by 23%. 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 initial price $p_{jt_1} = 12,000$ euros, and of 30 years for a class G vehicle taxed by 2,600 euros with initial price $p_{jt_1} = 30,000$ euros. These modifications do not alter our basic conclusion, however. We still predict an increase of quarterly emissions, even if this increase is reduced by one third (1,029.8 Kilotons of CO_2). This reduction mostly stems from the fact that the average lifetime over the whole stock decreases. As a result, the policy would lead in this scenario to a 8.4% increase of the whole stock, far smaller than the 13.2% increase corresponding to the previous scenario.

4.3 Robustness checks

Several tests are performed to assess the robustness of our results. The first is related to the rebound effect. This effect is commonly evoked in cases where the sole energetic efficiency is affected (for instance in the case of the choice of a heating system). However, the car choice may also affect mileage through other channels than the cost per kilometer. One could imagine that the rebound effect may be partially offset by a comfort effect: people choosing smaller vehicles may decrease their mileage because these vehicles are less comfortable. To assess the importance of the rebound effect in our final results, we fix γ to 1 and estimate the demand model (3.13) and total emissions under this constraint. Results, displayed in Table 9, show that the policy still leads to an increase of CO_2 emissions in the short and long run under this favorable assumption.

Table 9: Robustness checks: Short and long-run effects on quarterly emissions under alternative assumptions.

Alternative Assumptions	Estimates (in kilotons) Δ^{SR}	Δ_1^{LR}	Δ_2^{LR}
Baseline	168.4^{***} (52.4)	$1,524.3^{***}$ (440.6)	$1,029.8^{***}$ (367.3)
No rebound effect	160.4^{***} (51.9)	$1,071.6^{***}$ (349.5)	734.1^{**} (298.2)
Manufacturers reaction	169.5^{***} (53.4)	$1,230.2^{***}$ (436.8)	757.4^{**} (382.6)
2006-2007	-12.5 (26.4)	-131.4 (229.2)	-106.2 (271.4)

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

Related to this, we have ignored so far selection effects by supposing that individuals choosing vehicle j with the policy made the same number of kilometers than those choosing vehicle j without the policy ($\overline{N}_{xj}(1) = \overline{N}_{xj}(0)$). This may not be the case, however, as the two populations are likely to differ. If it is very difficult to measure precisely such effects, we try to assess the sensitivity of our results to these effects by supposing that $\overline{N}_{xj}(1) = (1-\chi)\overline{N}_{xj}(0)$ and computing χ so that $\Delta^{SR}, \Delta_1^{LR}$ or Δ_2^{LR} are equal to zero. We obtain $\chi^{SR} \simeq 0.37$, $\chi_1^{LR} \simeq 0.13$ and $\chi_2^{LR} \simeq 0.08$. These estimates would imply an increase in the long run of the total number of kilometers traveled of respectively 2 and 1.7%. This seems implausible given the important estimated increase in the stock of car (respectively

13.2% and 8.4%) and the possibility of rebound effects.[29] In other words, it seems to us that selection effects cannot reverse the overall result that the policy increases total CO_2 emissions.

Another potential limitation of our estimates is that they do not account for the possibility of manufacturers reactions. As noted previously, extra data would be necessary to address this question in details. Still, it is possible to check whether this effect is likely to reverse our conclusions. We consider a situation where the policy would lead to a 5% reduction of all average emissions. This reduction is very important, 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 4). Such a decrease would have several impacts on the stock of automobiles. Looking at the decompositions (3.2) and (3.5), it would increase (in absolute value) the composition effects but also the rebound, traveling and manufacturing scale effect. At the end, however, and as expected, the first effect dominates the others, and the policy would lead to a smaller increase of CO_2 emissions (169.5 kilotons in the short-run, 757.4 kilotons in the long-run with changes in replacement rates). Still, our basic conclusion remains unchanged.

Finally, underlying our identification strategy is the idea that feebates Z_j in Equation (3.9) only captures changes in prices (and possibly a direct effect of the feebates themselves) following the introduction of the policy. We rule out by Assumption 3.5 the possibility that Z_j captures changes on other characteristics of the cars. If this were the case, we would wrongly attribute the observed changes to the impact of the feebate system. Of course, we cannot directly test this assumption, but we perform hereafter a falsification test, using the 2006-2007 period instead of 2007-2008. More specifically, we make as if the measure had been adopted in 2007 instead of 2008, falsely attributing the corresponding feebates to cars in 2007. If our assumption is true over the all period, the coefficients corresponding to the emissions classes should be equal to zero. Table 10 shows that their estimates are far smaller than those obtained for 2007-2008, even if several remain significant.[30] For instance the parameter corresponding to the class B is more than 7 times smaller than when comparing 2007 to 2008. Next, computing the short and long-run placebo estimates, we obtain estimates not significantly different from zero (the point estimates are respectively -12.5 kilotons and -106.2 kilotons, i.e. around 10 times lower in magnitude than our estimates on 2007-2008). Overall, this test strongly suggests that the possible bias underlying our identification strategy does not question our final results.

[29] χ^{SR} is even less realistic, as it would predict a decrease of the total mileage in the short-run.

[30] This may be due to long-run evolutions in preferences for low emitting cars among French consumers. See D'Haultfœuille et al. (2010) for a detailed analysis on this issue.

Table 10: Estimates of the demand model on 2006-2007.

Parameter	Estimate
Rebate = 1,000 €	*not identifiable*
Rebate = 700 €	-0.091^{***} (0.027)
Rebate = 200 €	-0.155^{***} (0.025)
Fee = 200 €	0.081^{***} (0.031)
Fee = 750 €	0.074^{***} (0.019)
Fee = 1,600 €	0.047^{*} (0.024)
Fee = 2,600 €	0.123^{***} (0.041)
Sum of fees of the firm	-0.00007 (0.0003)

Reading notes: OLS estimates of the coefficients on Z_j and $\widetilde{Z}_j$ in Equation (3.13) on 2006-2007. Significance levels: *** 1%, ** 5%, * 10%.

5 Conclusion

Overall, the impact of the policy is much disappointing. If this kind of evaluation necessarily relies on several assumptions (especially for a long-run assessment), our global conclusion that the policy increases CO_2 emissions appears robust to several changes in the specifications. This does not invalidate, however, feebate systems as efficient tools for environmental policy. French consumers have strongly reacted to financial incentives created by the policy. The problem rather comes from the design of this feebate. In the French case, the first-order terms in the policy effect are manufacturing or traveling scale effects. The most important point, to ensure a positive environmental effect of such feebate policies, should thus to calibrate it in order to decrease or keep constant total sales. Simulations indicate for instance that if the rebates had been shifted (i.e., 700 € instead of 1,000€ for class A-, 200€ instead of 700€ for class B, 0€ instead of 200€ for class C+), the policy would not have had any significant impact on CO_2 emissions (see Appendix A.5 for more details).

One limitation of our study, due to a lack of appropriate data, is that we do not include manufacturers reactions. Even if, as mentioned before, these reactions are unlikely to modify our conclusions, stimulating innovation in favor of less polluting cars was another objective of the measure. We leave the evaluation of these supply-side effects for future research.

A Appendix

A.1 Definition of products

As detailed above, we model the automobile market as a market of differentiated products, where potential buyers will have different valuation for cars given characteristics such as brand or type of fuel. In practice, we define a product by a set of characteristics. An important issue is then to choose which characteristics one should keep in this definition. On the one hand, if products are defined with few 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, keeping too many characteristics leads to small market shares for each product, or even null markets shares as exactly similar cars are often not sold each month. The theoretical model presented before links the logarithm of the markets shares with the observed characteristics. Thus, null sales are not used, which leads to a selection bias.[31] 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. This selection leads to define 950 different products (see Table 11) for the period between September and November 2007. 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 12). 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 have not been sold between March and May 2008).

[31] 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 11: Number of products and number of 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		
Gasoline	453	80,390
Diesel	497	159,216

Table 12: Dispersion of prices, CO_2 emissions and fiscal power of new cars registered between September and November 2007

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

A.2 Construction of drivers categories

As mentioned above, we observe in the registration dataset the age, activity and city of the owners. However, income, which is likely to drive an important part of the heterogeneity of preferences, is not available. In order to proxy this income, we impute to each purchaser the median income of his age class in his city, using fiscal data.[32] Using data from the French national institute of statistics (INSEE), we also included in our final dataset the

[32]This information is only available for towns of at least 2,000 inhabitants. For cities of more than 50 households but less than 2,000 inhabitants, only the median income is known. In this case, or if the age of the buyer is unknown, we impute the median income of the city. Sales to individuals living in less than 500 inhabitants cities have been dropped, as the median income is missing in this case. Note that such sales only represent 5% of the data.

type of area (urban versus rural or suburban) to which the purchaser belongs. Table 13 displays the average characteristics of new car purchasers in terms of age, income, rate of activity and type of location computed from the Transportation Survey. Not surprisingly, these individuals are on average older, belong to richer households and work more often than the rest of the population.

Table 13: Comparative statistics between characteristics of the buyer of new cars and 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

To compute market shares, we also need to define potential markets. We suppose here that they correspond, for the subpopulation with characteristics x, to the number of individuals with a driving 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 $N_{t_0}^1$ (resp $N_{t_0}^2$) corresponds to the mileage in urban area (resp. on high roads) in 2007. We only observe in the CCFA dataset the average emissions $A_j = (A_j^1 + T_j^2)/2$ 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 between the two mileages:

$$N^*_{t_0} = pN^1_{t_0} + (1-p)N^2_{t_0}, \text{ where } p = \frac{2A^1_{Y_{t_0}}}{A^1_{Y_{t_0}} + A^2_{Y_{t_0}}}.$$

Quantities A^1_j and A^2_j have been obtained on the ADEME website. Note that we do not observe directly $N^1_{t_0}$ and $N^2_{t_0}$ in the Transportation Survey. To compute them, we consider that 80% of "regular" travels (all travels except those made for professional purpose outside commuting, or for vacation) are made in urban areas for people living in a urban area, and on highways for people living in a rural or suburban area. We consider that other travels consist of 90 % of highways and 10 % of urban area. These assumptions allow us to compute $N^1_{t_0}$ and $N^2_{t_0}$ from the total mileage $N^1_{t_0} + N^2_{t_0}$.

A.4 Proofs of Subsection 3.3

A.4.1 Equations (3.11) and (3.12)

Using notations of the model described in Section 3.3, let

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

Note that by Assumption 3.3, g_x does not depend on t. Moreover, it is identified using the residuals of Equation (3.10). We then have

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

where the third equality stems from Assumption 3.3. Equation (3.11) follows.

First, by the law of iterated expectations,

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

Second, by Equation (3.10) and Assumption 3.1, we have, for $f \in \{1, 2\}$,

$$\overline{E}_{x0t_1,f}(0) = I_f^{\gamma_x - 1}\overline{E}_{x0t_0,f}(0). \tag{A.2}$$

Third, by Assumptions 3.1 and 3.4, $E_{x0t_1}(0) = E_{x0t_1}(1)$. This, together with (A.1) and (A.2), proves Equation (3.12).

A.4.2 Counterfactual market shares

We omit indices x and t here to alleviate the notational burden. In a nested logit where the utility of individual i for product j satisfies $U_{ij} = \delta_j(d) + \varepsilon_{ij}$, the market share of j satisfies (see, e.g., Berkovec & Rust, 1985)

$$\begin{aligned} \ln\left(\frac{s_j(d)}{s_0(d)}\right) &= \delta_j(d) - \sigma \ln\left(\frac{s_j(d)}{\sum_{k\in g(j)} s_k(d)}\right) \\ s_j(d) &= \frac{\exp(\delta_j(d)/(1-\sigma))}{D_{g(j)}(d)^{\sigma}\sum_{g=1}^{G} D_g(d)^{1-\sigma}}, \end{aligned} \tag{A.3}$$

where $g(j)$ denotes the group of product j and $D_g(d) = \sum_{k\in g} \exp(\delta_k(d)/(1-\sigma))$ for any group g. Here we have two groups, one for the whole set of products and the other for the outside option. Thus,

$$s_j(0) = \frac{\exp(\delta_j(0)/(1-\sigma))}{\left[\sum_{k=1}^{J} \exp(\delta_k(0)/(1-\sigma))\right]^{\sigma} + \left[\sum_{k=1}^{J} \exp(\delta_k(0)/(1-\sigma))\right]}.$$

By definition of f_4 and f_5, we have here $\delta_j(0) = \delta_j(1) - (1-\sigma)\left(f_4(Z_j) + f_5(\widetilde{Z}_j)\right)$. Thus, using (A.3) with $d = 1$, we get, after some algebra

$$s_j(0) = \frac{s_j(1)\exp(-f_4(Z_j) - f_5(\widetilde{Z}_j))}{\frac{s_0(1)}{(1-s_0(1))^{\sigma}}\left[\sum_{k=1}^{J} s_k(1)\exp(-f_4(Z_k) - f_5(\widetilde{Z}_k))\right]^{\sigma} + \left[\sum_{k=1}^{J} s_k(1)\exp(-f_4(Z_k) - f_5(\widetilde{Z}_k))\right]}.$$

A.4.3 Effect of the feebate on cars lifetime

We rely on a similar model as Engers et al. (2009). In a dynamic setting, let us assume that at a quarter k (the purchase of the car occuring at period t), a car can either be sold on the second market at 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:

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

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

$$\widetilde{p}_{jt+k} = \max\{\widetilde{p}_{jt+k+1}, s_j\},$$

where s_j 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 define by T_{jt} this final period. We assume that the current net surplus decreases at a constant rate r_2 over time, so that $v_{jt+k} = v_j r_2^k$. We then get the following system:

$$\widetilde{p}_{jt+k} = \begin{cases} v_j r_2^k + r\widetilde{p}_{jt+k+1} & \text{if } 0 \le k < T_{jt}, \\ s_j & \text{if } k = T_{jt}. \end{cases}$$

After a little algreba,

$$p_{jt} = v_j \frac{1-(r_2 r)^{T_{jt}}}{1-r_2 r} + r^{T_{jt}} s_j. \tag{A.4}$$

For standard values of s_j (i.e., between 0 and 200 euros), the second term in the right-hand side is negligible. Writing Equation (A.4) with and without the policy, we obtain $T_{jt_1}(1)$ as a function of $T_{jt_1}(0)$:

$$T_{jt_1}(1) = \frac{\ln\left[1-\left(1-(r_2 r)^{T_{jt_1}(0)}\right)\frac{p_{jt_1}(1)}{p_{jt_1}(0)}\right]}{\ln(r_2 r)}.$$

In the right-hand side, we approximate the car price without the policy by the observed price minus the malus, $p_{jt_1}(0) \simeq p_{jt_1}(1) - Z_j$.

A.5 Long-run effects of another feebate scheme

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 ($f_4(z)$) 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 (i.e., 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 14 below the effect of a feebate scheme where all rebates are shifted compared to the 2008 ones (i.e., 700 € instead of 1,000€ for class A-, 200€ instead of 700€ for class B, 0€ instead of 200€ for class C+). This scheme may be seen as an intermediary 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 traveling scale effect is sharply reduced. As most of the parameter estimates, the estimate of Δ_2^{LR} is not significantly different from zero, however.

Table 14: Long-run effects of an alternative feebate scheme.

Parameter	Estimates (kilotons)
Composition effect	-155.0 (169.7)
Rebound effect	73.0 (112.4)
Traveling scale effect	210.5 (434.4)
Manufacturing scale effect	28.9 (59.4)
Long-run effect Δ_1^{LR}	157.1 (426.2)
Replacement rate effect	-201.0^{*} (112.0)
Long-run effect Δ_2^{LR}	-43.8 (377.8)

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

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