Subsidizing electric cars during the transition: The role of vertical and horizontal preferences

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Abstract

Having shown that subsidies on electric vehicles (EVs) fail to replicate the work of Pigouvian taxes on polluting vehicles when both vertical (vintage) and horizontal (fuel type) preferences are present, we ask: How should we subsidize EVs during the energy transition? Should we continue subsidizing only new EVs and let the market spill these subsidies over second-hand EVs, or should we also begin directly subsidizing the latter? We shed light on these issues with a simple model of the car market and empirical analysis using data from the French market. Consistent with the theory, which shows subsidies on new and second-hand EVs to be complements, we find substantial efficiency and fiscal gains from employing both types of subsidies and adjusting them as the EV market share evolves.

Keywords: electric vehicles, subsidies, taxes, air quality

JEL Classification: ??

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1 Introduction

Decarbonizing transport is one of the key milestones of succeeding the net-zero objective for mid-century. Globally, 24% of CO_2 emissions are produced by the transport sector, 18% due to road transport. More than half of those road transport emissions are specifically due to private cars and light duty vehicles. In France, the impact of the transport sector is even more important, accounting for 31% of total emissions, given that nuclear generation has an important role in the energy mix. From these emissions, private cars account for 56%.

Herein we study the impact of policy incentives in the decarbonization of the private car fleet and to which extent the impact of those policies depends on preferences.

Numerous countries have implemented incentive policies to promote the renewal of the private car fleet by targeting the purchase of new electric vehicles (EVs). In the United States EV purchases are eligible for federal tax credits up to USD 7,500. Some states, such as California, offer additional incentives, including rebates (for details see U.S. Department of Treasury). China, the largest EV market, provides extensive subsidies and tax exemptions to encourage both production and adoption. Local incentives vary but commonly include purchase subsidies. In Norway, extensive tax exemptions have provoked that nearly 90% of new car sales are EVs today. In the EU, several countries have implemented purchase incentives, particularly in the biggest car markets like Germany, even if under revision nowadays, United Kindom (UK), Italy, France and Spain.

In particular, France has first implemented a fee-bate policy as from 2008. The policy has evolved since then to account for different car characteristics such as weight, and more recently, to include second-hand EVs (see Figure 1). The inclusion of subsidies to the purchase of used-EVs is quite novel. A few countries -such as Finland, Italy or Canada- subsidize used-EVs but conditionally on scrapping an old vehicle[1]. Most of the countries do not have the French-specific instrument since the subsidy (or tax credit) only applies once in the vehicle's lifetime. This is the case in the US where the tax credit implemented in 2023 also applied to EVs already in use (see US Department of Energy). In the UK there is a similar mechanism but only to specific-type of cars (see Plug-in-Vehicle Grant). Other than France, there have been only few exceptions that have implemented a used-EV incentive. From April 2022 to December 2023 New Zealand had a fee-bate called Clean Car Discount Scheme that applied when registering a car based on a vehicle's CO_2 emissions (both new and second-hand). The system successfully incentivized the registration of clean cars before being abandoned for budgetary reasons (see Ministry of Transport, New Zealand, 2024). Some German states (like Baden-Württemberg) have local initiatives to lower registration fees on used EVs. In the Netherlands, used EVs are subsidized since july 2020 with €2,000, which has drastically increased used-EV purchases. The relative importance of incentives to new versus used EVs is gaining momentum. In Luxembourg,

[1] For e.g. the French conversion bonus -up to 5,000€- that applies to used cars since 2018. In Canada, the SCRAP-IT program offers up to 3,000 Canadian dollars for used EVs if an old vehicle is scrapped. Finland and Italy provide up to €2,000 for a used EV if an older car is scrapped.

incentives for new and used electric vehicles (EVs) were recently revised as part of the mobility climate bonus program, effective from October 1, 2024. Before only new EVs where subsidized up to €8,000. Currently, the incentive for purchasing a new EV can reach up to €6,000 and for used EVs a subsidy of €1,500 has been introduced for vehicles older than three years.

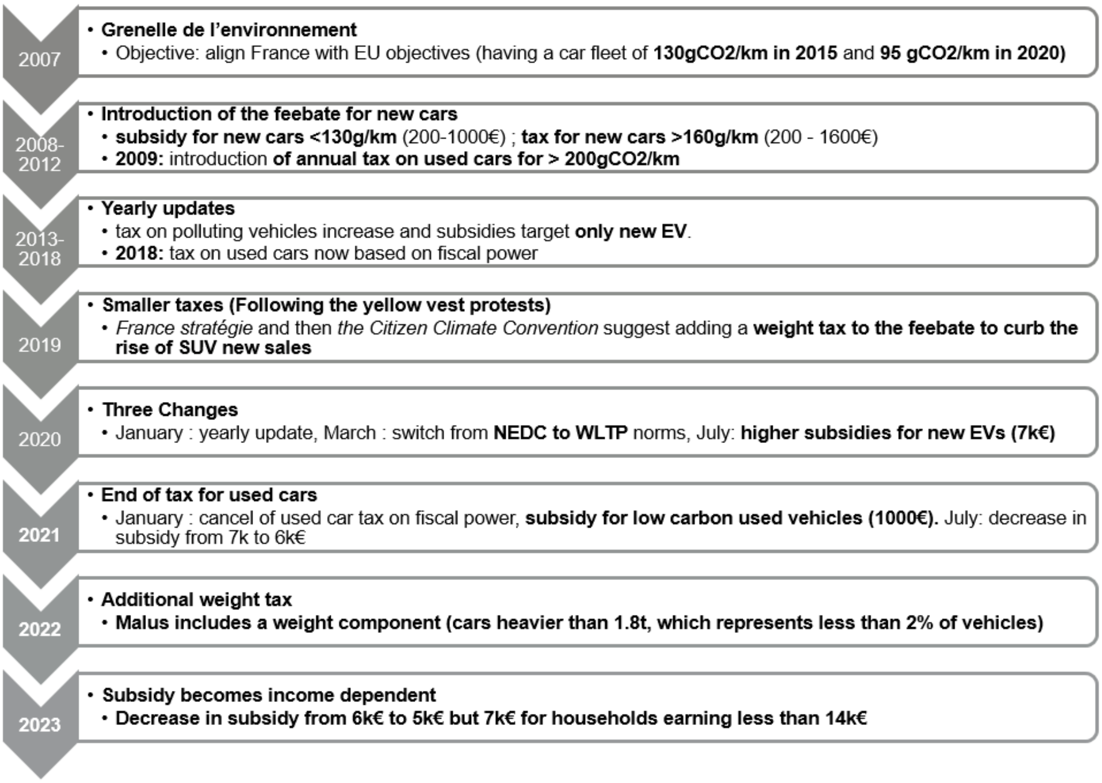

Figure 1: Evolution of EV incentive policies in France

The early surge of incentive policies for new EVs in France has been treated by the empirical industrial organization literature. In general, they find that feebates increase low-carbon cars' demand and have a small but significant impact on reducing CO_2 emissions (see Table 1 for details). Instead, the impact of incentives to used-clean-cars has yet to be theoretically modeled and empirically estimated. We fill this gap in this paper.

Moreover, we are the firsts to study the impact that feebates have on the existing fleet of cars instead of looking at the consumer choices when purchasing a new car. With this purpose, we get inspired by Barahona, Gallego, and Montero 2020's model of vertical preferences to study the impact of vintage-specific driving restrictions applied in Chile. A few other papers have examined consumers' inter-temporal car replacement decisions (Stolyarov 2002; Esteban and Shum 2007; Adda and Cooper 2000; Gavazza, Lizzeri, and Roketskiy 2014). Differently from these papers, we consider not only vertical (car vintages) but also horizontal preferences (fuel type) to study how incentives on new and used cars impact the pace at which the fleet is greened in a transition towards a net-zero objective. Due to limitations in individual data availability and computational challenges, there has been limited focus in the literature on the interplay between multidimensional consumer preferences and car fleet dynamics. Notably, Schiraldi 2011 estimates a dynamic structural model of car demand using detailed data on the small province of Isernia in Italy (1997-1998), and Gillingham et al. 2022 develop a dynamic equilibrium model of the automobile market that they estimate using individual ownership and transaction data from Denmark. In contrast to the last study, herein we use product-level data and we concentrate on essential car characteristics, enabling us to develop a tractable equilibrium model of the automobile fleet during the energy transition.

Table 1: Feebates & Fuel Taxes in France

Paper	**Methodology**	**Contribution & Policy Implication**
D'Haultfœuille, Givord, and Boutin 2014	Nested logit model with discrete-continuous choice	While consumers reacted strongly to the financial incentives of the 2008 feebate, the CO_2 emission level threshold was set too high and subsidies were too generous producing very thin impacts in terms of emission reduction.
D'Haultfœuille, Durrmeyer, and Février 2016	Nested logit model estimated on different socio-demographic groups	The feebate policy had a crowding-in effect on manufacturers product choices that may partially offset environmental benefits. The change in environmental preference is responsible for 40% of the emission decrease.
Givord, Grislain-Letrémy, and Naegele 2018	Nested logit model estimated on different socio-demographic groups	The willingness to pay of French consumers for fuel efficiency is low. This results in a significant but small impact of a simulated carbon tax on overall fleet fuel economy.
Durrmeyer and Samano 2018	Nested logit model to compare the French feebate and the US CAFE standards	Feebate policies welfare-dominate CAFE standard policies for both countries and for different levels of stringency.

Durrmeyer 2021	Random coefficient model	The feebate reduces carbon emissions but the 2008 design leads to the increase in local pollutants since it incentivizes the purchase of diesel vehicles. Winners are middle-income households.
Kessler et al. 2023	Replication of Durrmeyer and Samano 2018 with recent data	France is not in line with its CO_2 reduction ambitions but could be with a significant tightening of the current feebates.

The theoretical development of including vertical and horizontal preferences not only presents a complete representation or reality but also proves to be a crucial contribution since it breaks the equivalence between Pigouvian taxes and subsidies. Our main finding in this regard is that a subsidy on second-hand EVs must be implemented in the transition to net-zero emissions. This seems in contradiction with the well known theoretical result that a Pigouvian tax (or an equivalent subsidy) can implement the first-best on its own. This is the case because subsidies to new and used EVs work as complements in the implementation of the optimal policy.

To quantify the importance of the previous result, we then estimate the model using French data and simulate the impact of carbon taxes and subsidies. To this end we follow Grigolon and Verboven 2014, and D'Haultfœuille, Durrmeyer, and Février 2016 and design socio-demographics groups to account for consumer heterogeneity.

The paper is organized as follows. Section 2 describes the model with horizontal and vertical differentiation. Discussion of empirical strategy and data is in Section 3 where we show how we match car fleet data from private company AAA-data with used-car prices from French online sales website Leboncoin.fr to obtain a working sample of 27 million observations (72% of the French car fleet). Policy counterfactual analysis is in Section 4. Section 5 concludes.

2 Modeling the car market

Herein we model a durable-good market of vertical and horizontal differentiation. With this purpose we first present the general setting and then a simplified two-period illustration that we will use for simulating alternative policy options.

2.1 Market setting

Consider a market with two types of cars, electric vehicles (EV) and gasoline cars (G), each of which lasts for two periods, first as new and then as second-hand. For the purpose of this simple model, think of new cars as cars that are few years old and younger and second-hand as anything older than that. We will discuss the implications on our results of allowing cars to last for an endogenous number of periods.

There are three agents in the market: car producers, car dealers, and drivers. The cost of producing a new car is the same for both types of cars and equal to c. This is also the price at which perfectly competitive producers sell new cars to car dealers.[2] A large number of car dealers buy new cars from car producers and rent them, together with second-hand cars, to drivers.[3] In the second period, dealers have the option to either rent their cars or scrap them for a value which we normalize to zero (we will come back to this normalization below).[4]

In addition, there is a unit mass of drivers who vary in their vertical preferences for new *vs.* second-hand cars and their horizontal preferences for EVs *vs.* gasoline cars. These preferences are captured, respectively, by the variables θ and η, which, for simplicity, are assumed to be uniformly distributed over the unit square.[5] Thus, a driver with preferences θ and η who rents a type-i car, either EV ($i = EV$) or gasoline-based ($i = G$), of age a, either new ($a = 0$) or second-hand ($a = 1$), obtains

$$u(a, i; \theta, \eta) = \upsilon + \theta s_a - tx^i(\eta) - p^i_a \tag{1}$$

where υ is a positive constant, s_a is the car's quality, with $s_0 > s_1$, t is the Hotelling's transport cost (or horizontal differentiation) parameter, $x^i(\eta)$ is the "distance" of the consumer to its fuel-type renting choice i, either $x^i(\eta) = \eta$ if $i = G$ or $x^i(\eta) = 1 - \eta$ if $i = EV$, and p^i_a is the car's rental price paid by the consumer, which may differ from the rental price received by car dealers, denoted by $\tilde{p}^i_a$, in the presence of taxes and/or subsidies. The driver's problem is to decide in each period what age and fuel-type to rent so as to maximize (1).

Unlike EVs, gasoline cars emit all sorts of pollutants, some with global effects (e.g., CO_2) while other with local effects, i.e., effects at the city level lasting for a few hours (e.g. CO, HC, NO_x). Since polluting cars are more harmful as they age, even if they are driven less (Barahona, Gallego, and Montero 2020; Jacobsen et al 2023), we let h_a be the per-period pollution harm of a gasoline car of age a, with $h_1 > h_0$.

We restrict parameter values to ensure certain properties to hold in any market equilibrium (with and without policy interventions), namely, (i) full coverage (the fact that all drivers rent a car in equilibrium), (ii) a positive number of both new and second-hand gasoline cars being rented, and (iii) a positive number of second-hand cars of either type being scrapped, except during the transition, when there are no second-hand EVs. Given the durable-good nature of

[2]We could change the interpretation of c to represent marginal cost plus a mark up in non competitive markets and conclusions from the model would remain the same. The model's main mechanism is driven by the relationship between car dealers and drivers rather than between car producers and car dealers.

[3]Note that the renting assumption, which is also in Barahona et al (2020) and Bento et al (2009), is equivalent to assuming a frictionless second-hand market

[4]Considering a positive scrappage value doesn't change any of our results. It only introduces additional notation and, as we comment below, a slight bias in (optimal) policy interventions. Besides Barahona is 5%. ***Check****

[5]In the proof of Proposition 1 we show that our results remain for a ditribution F() with the following properties: A, B and C. To be done.

cars, the number of second-hand vehicles available for rental this period cannot be larger than the number of new cars brought to the market in the previous period. In any case, we provide more details on these restrictions as we characterize different market equilibria.

2.2 Market equilibrium

We are interested in two possible equilibria depending on the market share of EVs. One is the steady-state equilibrium, when there are both new and second-hand EVs in the market. The other is the transition equilibrium, when there are only new EVsin the market. In our two-period setting, where the transition lasts only one period, the two equilibria can be treated separately.

There are two conditions that must hold in equilibrium for car dealers, with and without policy interventions. The first is that when a dealer brings an extra car to the market, he or she expects to break even, that is,

$$c = \tilde{p}_0^i + \delta \tilde{p}_1^i \tag{2}$$

for $i = EV, G$ and where $\delta < 1$ is the discount factor (we will come back to this break-even condition for when cars may last for more than two periods). The second condition is that dealers must be indifferent between scrapping a second-hand car or renting it for the last time. Whether we are in the transition or in steady-state, these two conditions imply that in equilibrium dealers face rental prices $\tilde{p}_0^i = c$ and $\tilde{p}_1^i = 0$ (recall we have normalized to zero the scrappage value of a car).

In the absence of any policy intervention, consumers face the same prices as dealers (i.e., $p_a^i = \tilde{p}_a^i$), so their decisions, summarized in Figure 2, are easy to characterize. Focus first on the panel on the left, describing the steady-state equilibrium. Consumers with high valuation for quality, those with $\theta > \theta_G \equiv (p_0^G - p_1^G)/\Delta s = (p_0^{EV} - p_1^{EV})/\Delta s \equiv \theta_{EV} = c/\Delta s$ (with $\Delta s \equiv s_0 - s_1$), rent new cars ($a = 0$) of either type in each period, while consumers with a lower valuation for quality, $\theta < \theta_G = \theta_{EV}$, rent second-hand cars ($a = 1$). As for their horizontal choices, consumers located closer to the gasoline option, $\eta < \eta_0 \equiv 1/2 + (p_0^{EV} - p_0^G)/2t = 1/2 + (p_1^{EV} - p_1^G)/2t \equiv \eta_1 = 1/2$, rent gasoline cars, while those closer to the EV option, $\eta > \eta_0 = \eta_1$, rent EVs.

Note that necessary conditions for ensuring properties (i) and (iii) above to hold are $\upsilon > t/2$, and $\Delta s > 2c$, respectively. Property (ii) holds automatically, given the symmetry of the no-intervention outcome. This property will become more demanding as the social planner targets gasoline cars, whether directly by taxing them or indirectly by subsidizing clean ones.

Consider now the panel on the right of Figure 2, describing the transition equilibrium. The only difference with the panel on the left is the absence of second-hand EVs, which explains the relatively larger share of new EVs (EV_0) and of second-hand gasoline cars (G_1). In reality, given the steady decline in their costs, the number of new EVs coming to the market during the early years of the transition could be certainly smaller than the number when the steady-state is reached. However, we do not want to enter into this possibility here. We want to concentrate on

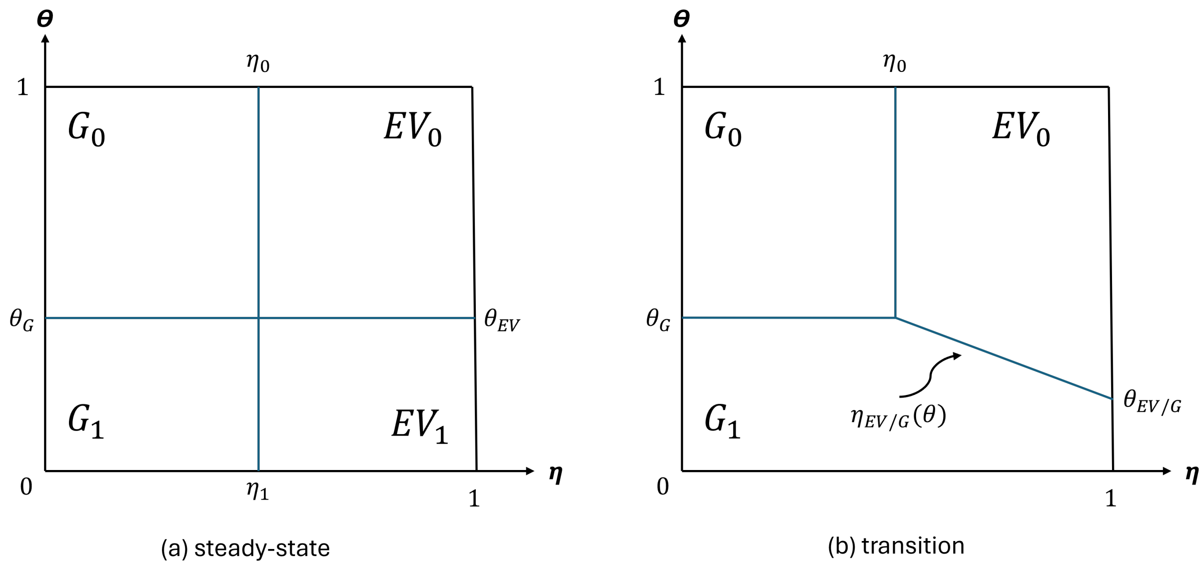

Figure 2: The no-intervention equilibrium

policy design while keeping all else constant (we will come back to this declining-cost possibility in the empirical section).

The absence of second-hand EVs in Figure 2(b) has also created consumers indifferent between a new EV and a second-hand gasoline car. Their preferences lie over the line $\eta_{EV/G}(\theta) \equiv 1/2+(p_0^{EV}-p_1^G-\theta\Delta s)/2t = 1/2+(c-\theta\Delta s)/2t$. The way this indifference line is drawn assumes that vertical preferences are stronger than horizontal preferences in that $\theta_{EV/G} \equiv (c-t)/\Delta s > 0$.

Given that the car market is perfectly competitive, it is not entirely surprising that the no-intervention equilibrium depicted in Figure 2 is socially optimal in the absence of pollution, i.e., whenever $h_0 = h_1 = 0$. To see it formally, ask yourself about the impact of introducing an arbitrarily small tax, say of ε, on one of the four rental options, say on new gasoline cars. The consumer rental price of these cars has now increased to $p_0^G = \tilde{p}_0^G + \varepsilon = c + \varepsilon$, while the remaining rental prices have stayed the same.

As shown in Figure 3, the increase in the price of new gasoline cars has moved the vertical and horizontal preferences of the indifferent consumers by $\varepsilon/\Delta s$ and $\varepsilon/2t$, respectively. These moves have welfare implications of different nature, giving rise to marginal gains and losses, which amount, respectively, to (only first-order effects are relevant)

$$\Delta W^{(+)} = \frac{\varepsilon}{2t}(1-\theta_G)\,c + \frac{\varepsilon}{\Delta s}\eta_0 c \tag{3}$$

and

$$\Delta W^{(-)} = \frac{\varepsilon}{2t}(1-\theta_G)\,c + \frac{\varepsilon}{\Delta s}\eta_0\theta_G\Delta s + \frac{\varepsilon}{2t}\int_{\theta_G}^{1}(1-2\eta_0)t\,d\eta \tag{4}$$

where $\theta_G = c/\Delta s$ and $\eta_0 = 1/2$. The two terms in eq. (3) correspond to savings from fewer new gasoline cars entering the market, in response to some individuals switching to new EVs (the first term) and some others switching to second-hand gasoline cars (the second term). These gains are completely offset by the first two terms in (4), as the result of more new EVs in the market (the first term) and of some individuals suffering a vertical (i.e., quality) downgrade (the second term). The last term in (4) captures the horizontal losses suffered by individuals who switch from new gasoline cars (their preferred no-intervention option) to new EVs. Since these individuals are located right at the middle of the horizontal space (at $\eta_0 = 1/2$), their losses vanish.

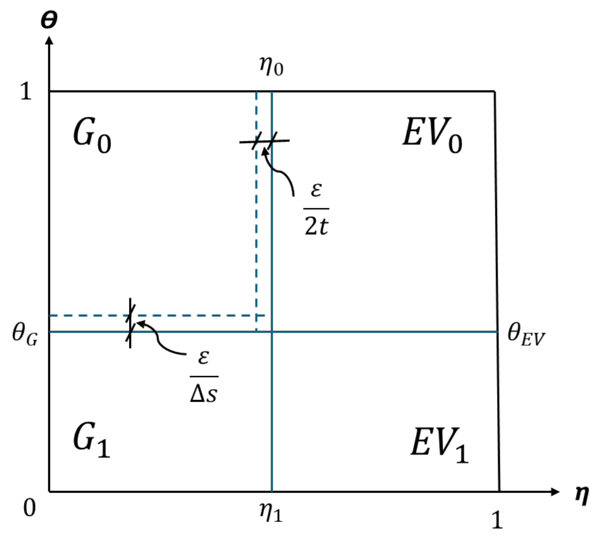

Figure 3: Social optimality of the no-intervention outcome in the absence of pollution

It is easy to anticipate that any other marginal adjustment in prices will also lead to no welfare changes at the margin, confirming the social optimality of the no-intervention outcome in the absence of pollution. This conclusion also extends to the transition phase shown in Figure 2(b).[6]

2.3 Policy interventions

We now turn to the case when gasoline cars pollute, as happens in reality, i.e., when $h_1 > h_0 > 0$. Clearly, in the absence of any policy intervention the market equilibrium described above would result in socially inefficient levels of pollution. We will consider two types of price-based interventions: taxes on gasoline cars and subsidies on electric cars.[7] There is no gain in considering quantity instruments. With enough prices, the social planner can arrive at any arbitrary allocation of cars.

[6]There is an instance, however, when there is room to improve upon the no-intervention outcome despite it builds on perfect competition and no externalities. It is when the scrappage value of a second-hand car is strictly positive, say $v > 0$. In this case the p=0 and p=0. More interesting, there is too much entry, so a tax in new cars is warranted. (footnote with v>0, here). We don't want to introduce this distortion in the analysis. Does is hold when we have 10 periods? Can be done in Matlab.

[7]We rule out lump-sum subsidies. A tax policy can always be replicated with lump-sum subsidies by making them large enough transfers to all individuals so as to cover the largest possible tax.

As prescribed by Pigou almost hundred years ago, one way for the social planner to improve upon the no-intervention outcome is to tax drivers of polluting cars an amount equal to the externality their driving impose on the rest of society; here, to place taxes $\tau_0 = h_0$ and $\tau_1 = h_1$ on new and second-hand gasoline cars, respectively.[8] It turns out, not surprisingly, that doing so restores the first-best.

Proposition 1 *Taxing gasoline cars at their Pigouvian levels, $\tau_0 = h_0$ and $\tau_1 = h_1$, restores the social optimum (i.e., first-best).*

Proof. See the Appendix (the proof ends with an extension to a general distribution function for preferences θ and η). ■

Figure 4(a) illustrate how placing taxes τ_0 and $\tau_1 > \tau_0$ on gasoline cars affect the steady-state market-equilibrium outcome. Given their higher rental prices, $c + \tau_0$ and τ_1, new and second-hand gasoline cars see their market shares reduced significantly. Note that we require $t > h_1$ for these shares to remain strictly positive under Pigouvian taxation. The figure also assumes that a fraction of second-hand cars, particularly EVs , continue to the scrapped in equilibrium.

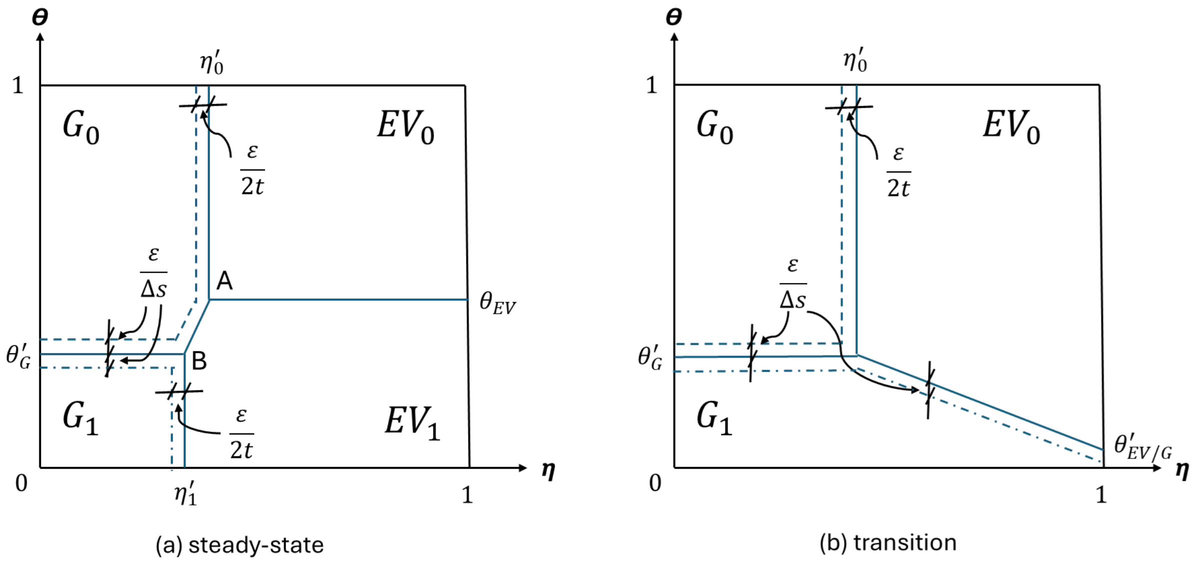

Figure 4: First-best allocation

The first part of the proof of Proposition 1 consists precisely in showing that there are no gains of adjusting either tax away from its Pigouvian level by a marginal amount. Proceeding as above (with the only difference that now we must also account for changes in pollution), the marginal gains of doing so would be

$$\Delta W_{\tau_0} = \frac{\varepsilon}{2t\Delta s}(t - \tau_1)(\tau_1 - h_1 - \tau_0 + h_0) + \frac{\varepsilon}{2t\Delta s}(\Delta s - c - \tau_1 + \tau_0)(h_0 - \tau_0) \tag{5}$$

[8]Explain that for CO2, the Pigouvian tax is gasoline tax. For local pollutant, such tax doesn't exist But based on expected pollution. Barahona et al shows 79%.

when adjusting τ_0, and

$$\Delta W_{\tau_1} = \frac{\varepsilon}{2t\Delta s}\left(t-\tau_1\right)\left(h_1-\tau_1-h_0+\tau_0\right)+\frac{\varepsilon}{2t\Delta s}\left(c-\tau_1+\tau_0\right)\left(h_1-\tau_1\right) \tag{6}$$

when adjusting τ_1 (see the Appendix for details). It is immediate that these marginal gains go to zero when $\tau_0 = h_0$ and $\tau_1 = h_1$. These results extend straightforwardly to the transition phase, pictured in Figure 4(b), so they are omitted.

The second part of the proof requires showing that the planner cannot do better with an additional price instrument, say a subsidy on one of the EVs , which is what would be needed to arrive at any arbitrary allocation of cars. The latter already sheds some light on why two subsidies on EVs may not be enough to replicate the work of two taxes.

One goal of this paper is to understand to what extent subsidies on clean technologies can replicate the allocative work of Pigouvian taxes on polluting technologies. In most instances taxing pollution is equivalent—from a welfare perspective—to subsiding pollution reduction.[9] According to the existing literature there are few situations in which they are not. One is when public funds are costly to raise (see, e.g., Bovenberg and Goulder, 1996). Taxing pollution allows the government to reduce distortionary taxation somewhere else in the economy, while giving subsidies to clean technologies (or pollution reduction) asks for more of such distortionary taxation.[10] Another situation emerges in a long-run context with free entry and exit of economic agents (see, e.g., Baumol and Oates 1988, Spulber 1995). Since any economic gain or loss is dissipated in the long-run, subsidies necessarily lead to more entry than taxes, therefore they must be set below their Pigouvian levels. In other words, subsidies cannot properly handle both short and long-run decisions, i.e., pollution and entry decisions.

None of these considerations apply to our model (and empirical application). Besides abstracting from costly public funds, our economic agents' only decision is which technology to adopt at any given point in time. There is no exit and entry in our setting; all individuals obtain positive surplus at all times. Yet, our market setting is another instance in which the allocative equivalence of taxes and subsidies breaks down.

Proposition 2 *Subsidies on new and second-hand EVs , σ_0 and σ_1, respectively, cannot replicate the work of Pigouvian taxes.*

Proof. See the Appendix ■

By lowering their rental prices, placing subsidies σ_0 and $\sigma_1 > \sigma_0$ on EVs can certainly take us to a car allocation similar to that shown in Figure 4(a). To find the optimal subsidies we can proceed as above and ask what would be the marginal gains of adjusting them away from their optimal levels. These gains would be

$$\Delta W_{\sigma_0}(\sigma_0,\sigma_1) = \frac{\varepsilon}{2t\Delta s}(t+\sigma_0)(\sigma_1-\sigma_0)+\frac{\varepsilon}{2t\Delta s}(\Delta s-c-\sigma_1+\sigma_0)(h_0-\sigma_0) \tag{7}$$

[9] This holds even under asymmetric information, when the planner doesn't know if you don't know the baseline. You just include a large baseline. See Montero (2002) for an explan

[10] (Montero information rents. for subsidies. Voluntary participation.

from adjusting σ_0, and

$$\Delta W_{\sigma_1}(\sigma_1, \sigma_0) = \frac{\varepsilon}{2t\Delta s}(h_0 - t - \sigma_0 - \sigma_1)(\sigma_1 - \sigma_0) + \frac{\varepsilon}{2t\Delta s}c(h_1 - \sigma_1) \tag{8}$$

from adjusting σ_1 (see the Appendix for details). The optimal subsidies solve the system $\Delta W_{\sigma_0} = \Delta W_{\sigma_1} = 0$, which clearly fail to implement the first-best, unlike taxes. While $\Delta W_{\sigma_0} = 0$ calls, for example, for $\sigma_1 = \sigma_0 = h_0$, $\Delta W_{\sigma_1} = 0$ calls for $\sigma_1 = \sigma_0 = h_1$. This example serves also to establish the following result that we will use later.

Lemma 1 *Let σ_0^* and σ_1^* be the optimal steady-state subsidies, i.e., those that solve the system $\Delta W_{\sigma_0} = \Delta W_{\sigma_1} = 0$. Then, $h_0 < \sigma_0^* < \sigma_1^* < h_1$.*

Proof. See the Appendix. ■

Some intuition of why subsidies on clean technologies fail to implement the first-best can be conveyed by illustrating how to fix them. We need a third price intervention to be placed on some of the gasoline technologies, whether a tax or a subsidy. One option is to place a tax $\tau_1 = h_1 - h_0$ on second-hand gasoline cars in addition to subsidies $\sigma_0 = \sigma_1 = h_0$ on EVs. Another option is to place a subsidy $\sigma_0^G = h_1 - h_0$ on new gasoline cars in addition to subsidies $\sigma_0 = \sigma_1 = h_1$ on EVs .[11] Both of these three-price options lead to the exact same relative rental prices as Pigouvian taxes do.

So, what is it about our setting that makes subsidies for pollution reduction fail to replicate the work of taxes on pollution? We know, for example, that taxes and subsidies are welfare equivalent in the standard setting of heterogeneous polluting firms with different business-as-usual levels of emission and costs of abatement. Even if the social planner is clueless about these emission levels and costs, she can implement the first-best with a tax or subsidy equal to the social cost of an additional unit of pollution.[12] This equivalence extends to technology choices in the car market; see, for example, Barahona, Gallego and Montero (2020) and Barahona et al (2024).

What makes our setting different is the simultaneous presence of both horizontal and vertical preferences—Barahona, Gallego and Montero (2020) considers only vertical preferences, while Barahona et al. (2024) only horizontal preferences. The inclusion of both types of preferences disrupts the one-dimensional sorting property prevalent in the examples above, where it suffices to contrast each decision with just two alternatives or outside options. In the case of polluting firms, it is either a more expensive (and cleaner) or cheaper (and dirtier) abatement option.

[11] This second option resembles charging pollution taxes in combination with lump-sum subsidies to all individuals and large enough to cover even the largest possible tax payment. This way of replicating Pigouvian taxation with subsidies is not only misleading—since behavior is still driven by taxes, not subsidies—but little realistic. For one, the subsidies involved would need to be substantial; and for another, consumers may perceive these two instruments as acting separately rather than in tandem. For a discussion on the latter see AAA (2024) (Matti's student).

[12] If this social cost is increasing with the overall level of pollution then the regulator must consider information rents.

For vehicles of the same fuel type, it is either a newer (and less polluting) or older (and more polluting) option. And for vehicles of the same vintage, it is either a dirtier or cleaner option.

Since our drivers are willing to tradeoff vertical for horizontal attributes, there are more alternatives to consider. For example, as shown in Figure 4(a), the best alternative to a new gasoline car could be a new EV (EV_0) for some consumers, a second-hand gasoline car (G_1) for others, or a second-hand EV (EV_1) for yet others. Given this larger outside-option set, subsidies on clean technologies are not capable of properly ordering outside options according to their pollution impact, and hence, preventing individuals of properly internalizing the externality associated to their technology choices.

To see this, take individual A in Figure 4(a), who is indifferent between G_0, EV_0 and EV_1. To ensure this individual correctly internalizes the external cost of his choice, we need $\sigma_0 = \sigma_1 = h_0$. Individual B, on the other hand, is indifferent between G_0, G_1 and EV_1. However, no subsidies can ensure that this individual correctly internalizes the external cost of her choice—certainly not $\sigma_0 = \sigma_1 = h_0$.

While we have shown the welfare limitations of subsidies in the steady state, it is not hard to anticipate that this limitation would also be present during the transition phase. With this in mind, we dedicate the rest of the section to examining the planner's problem in a world with limited access to price instruments—specifically, a world where the planner may have no or limited access to taxes and possibly faces budget constraints on the subsidies she can allocate.

In this planner's problem, it is clear from expressions (7) and (8) that subsidies for both new and second-hand EVs are needed. So one might speculate that if, for some reason, the planner cannot rely on subsidies for second-hand EVs, she would need to be more aggressive with subsidies for new EVs. A key observation for the design of these subsidies, however, points to the exact opposite: subsidies work as complements, not as substitutes.

Proposition 3 *Subsidies for new and second-hand EVs act as complements: $d\sigma_a^r(\sigma_{a'})/d\sigma_{a'} > 0$, where $\sigma_a^r(\sigma_{a'})$ is the value of σ_a that solves $\Delta W_{\sigma_a}(\sigma_a, \sigma_{a'}) = 0$ with $a' \neq a$ and $a, a' = 0, 1$, i.e., the optimal subsidy for age a EVs given some subsidy $\sigma_{a'}$ for age a' EVs.*

Proof. See the Appendix. ∎

A hint of the proof can be provided with help of expression (7). Let $\sigma_0^r(\sigma_1)$ be the value of σ_0 that solves $\Delta W_{\sigma_0}(\sigma_0, \sigma_1) = 0$ for any $\sigma_1 > \sigma_0$. As shown in the Appendix, $\partial \Delta W_{\sigma_0}(\sigma_0, \sigma_1)/\partial \sigma_0 < 0$ and $\partial \Delta W_{\sigma_0}(\sigma_0, \sigma_1)/\partial \sigma_1 > 0$. These two inequalities imply that $d\sigma_0^r(\sigma_1)/d\sigma_1 > 0$. The proof proceeds likewise with (8) to show that $d\sigma_1^r(\sigma_0)/d\sigma_0 > 0$, where $\sigma_1^r(\sigma_0)$ is the solution of $\Delta W_{\sigma_1} = 0$, and then continues with cases where $\sigma_0 > \sigma_1$ in the relevant range.

A case particularly illustrative of the implications of Proposition 3 is when the planner considers allocating the majority of the subsidy budget to new EVs. Figure 5 depicts the specific case of $\sigma_0 > 0$ and $\sigma_1 = 0$, where $\eta_0'' = 1/2 - \sigma_0/2t$ and $\theta_{EV}'' = (c - \sigma_0)/\Delta s$. Estimating the net gains from marginally increasing σ_0 and letting these gains go to zero yields the first-order condition

$$(\Delta s - c)(h_0 - \sigma_0) = \sigma_0^2 + \sigma_0(t - h_1) \tag{9}$$

with its positive root being the relevant solution (recall that $\Delta s > c$ and $t > h_1$).

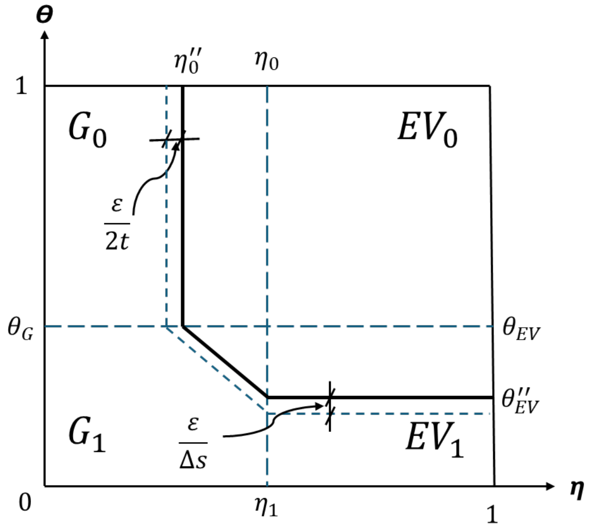

Figure 5: Subsidies on new EVs only

The comparative statics of condition (9) are clear: higher values of either h_0, h_1 or Δs call for a higher (optimal) σ_0, further displacing polluting cars and making the (vertical) upgrade to a new greenmore attractive. On the other hand, higher values of either c or t call for a lower σ_0, saving on production costs and horizontal losses. More striking in this comparative statics analysis is the fact that if new gasoline cars are relatively clean (as is often the case for local pollution), condition (9) suggests that the subsidy for new EVs should be zero when $h_0 \approx 0$, provided there are no subsidies for second-hand EVs. Allocating subsidies to new EVs in this case, even if the subsidy budget permits it, would be not only a waste of fiscal resources but also inefficient.

Why is this? The answer is in Figure 5. A subsidy on new EVs has a relatively minor impact on second-hand gasoline cars. Pushing too hard on this is costly, as it distorts decisions not only regarding second-hand EVs but also new gasoline cars, especially if the latter are relatively clean.

But there is more, somewhat hidden in our two-period setup. If we let the time at which old cars are scrapped and retired from the market to be endogenous, say, after T years, then increasing subsidies for new EVs has the perverse consequence of extending the life of old gasoline cars. The reason is implicit in condition (2). Car dealers must break even in equilibrium. Since in an endogenous-T setup an increase in the subsidy for new EVs necessarily depresses the rental price of new gasoline cars, this leads to an increase in the rental price of older gasoline cars. As a result, it becomes more attractive for dealers to keep these older and polluting models on the market longer rather than scrapping them.[13]

For the same break-even reason, extending subsidies to second-hand EVs depresses the rental price of second-hand gasoline cars (and increases the rental price of new gasoline cars), accelerating their exit from the market. This further speaks of the strong complementarity of subsidies for new and second-hand EVs. We come back to these price adjustments in the empirical section.

So far we have focused on the steady-state outcome, when there are enough second-hand cars of either type. Issuing subsidies for second-hand cars that don't yet exist in the market is obviously not possible, raising questions about the recommendations outlined above for the transition phase, i.e., when there is a limited or nonexistent presence of second-hand EVs, as in our two-period setting. Unlike in the steady state, the planner should be more aggressive with subsidies for new EVs during the transition phase.

Proposition 4 *Subsidies on new EVs should decline over time with the presence of second-hand EVs in the market: $\sigma_0^{**} > \sigma_0^*$, where σ_0^{**} and $\sigma_0^* \equiv \sigma_0^r(\sigma_1^*)$ are the optimal subsidies for new EVs during the transition phase and in steady state, respectively.*

Proof. See the Appendix ■

Some intuition for the proposition can be conveyed with the aid of Figure 6, where $\theta'''_{EV} = (c - t - \sigma_0)/\Delta s$, from which we arrive at the first-order condition

$$(\Delta s - c)(h_0 - \sigma_0) = \sigma_0^2 + \sigma_0(t - h_1) - th_1 \tag{10}$$

that solves for σ_0^{**} (see the Appendix for details). The gap between σ_0^{**} and σ_0^* can be viewed as the result of two opposing effects: "only-new" and "new-and-used" effects. When the planner decides to rely exclusively on (optimal) subsidies for new EVs (i.e., $\sigma_1 = 0$), it is natural to expect these subsidies to decline over time, as these subsidies become less effective at reaching holders of second-hand gasoline cars (see Figures 5 and 6). This result—that $\sigma_0^{**} > \sigma_0^r(\sigma_1 = 0)$—can be formally seen by comparing first-order conditions (10) and (9). This is the "only-new" effect.

Acting in the opposite direction is the "new-and-used" effect, which stems directly from the complementarity of subsidies for new and used EVs established in Proposition 3. As the used or second-hand greenmarket expands, the planner finds it optimal to increase the subsidies on used models, which in turn makes it optimal to increase the subsidies on new EVs as well, i.e., $\sigma_0^* > \sigma_0^r(\sigma_1 = 0)$. As stated in the proposition, however, this new-and-used effect is not large enough to fully offset the only-new effect.

In the next sections we take these propositions to the French car market and examine their fiscal and welfare implications. As a preview, we can generate some numbers with our theory illustrating that some magnitudes can be important. For instance, let $\Delta s = 4$, $c = 1$,

[13] This break-even condition is also behind many of the results in Barahona, Gallego, and Montero (2020), although in a pure vertical-differentiation context.

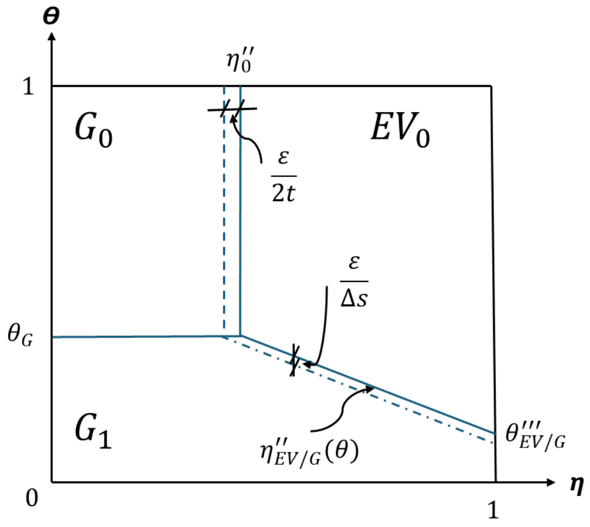

Figure 6: Transition phase

$t = 1/2$, $h_1 = 1/4$, and $h_0 = 1/8$. These parameter values ensure that properties (i), (ii) and (iii) hold across all equilibria. Based on these values, the optimal subsidy for new EVs during the transition phase reaches $\sigma_0^{**} = 0.15$, which drops somewhat to $\sigma_0^* = 0.14$ in steady state, provided it is combined with an optimal subsidy for second-hand EVs, set at $\sigma_1^* = 0.20$. However, if the planner neglects this second-hand subsidy, the optimal subsidy for new EVs should be much lower, not higher—27% lower, or $\sigma_0^r(\sigma_1 = 0) = 0.11$.

3 Empirical Method

To better inform on the dynamics that we just showed theoretically, we now use French data to estimate horizontal and vertical preferences and simulate the impact of taxes and subsidies on the composition of the car fleet as well as the welfare consequences.

3.1 Inference

In the spirit of Duch-Brown et al. 2023, we approximate the theoretical model of horizontal and vertical differentiation using a nested logit model that we estimate, first at the national level, and then for different socio-demographic groups. Our empirical strategy is close to D'Haultfœuille, Durrmeyer, and Février 2016 who estimate a nested logit model in socio-demographic groups defined by income, age and location to explain the change in CO_2 preferences after the introduction of the French fee-bate. The nested structure of our model, presented in Figure 7, accounts for the two product dimensions of the theoretical model.

We assume that each year, consumers can choose among J products. We consider 2 fuel types (horizontal preference) k={EV, gasoline}, 4 vintage groups (vertical preference) a={new, below 5, 6-10, and above 10 years old.}, and 4 car segments (small, medium, large, and SUV),

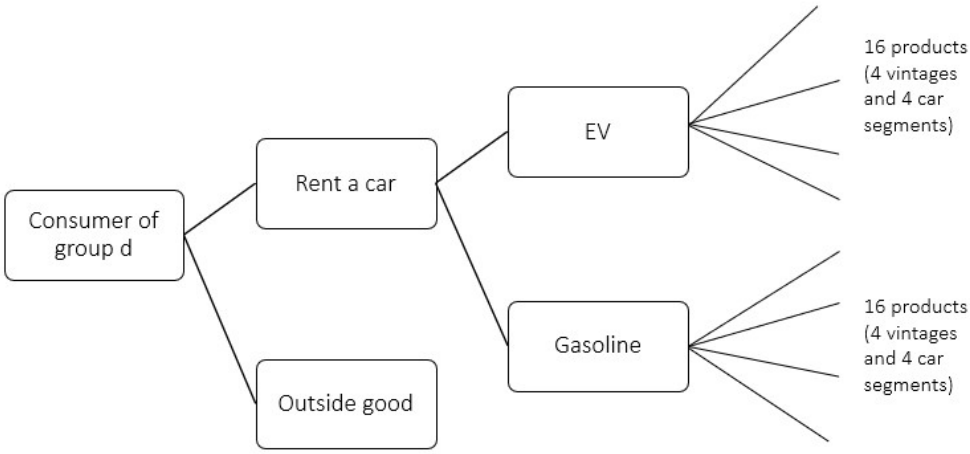

Figure 7: Nested structure of the car fleet, used for the estimation. The outside good corresponds to not renting a car. It contains other modes of transport, for e.g. public transport and bikes.

hence J=32. For the remaining of the paper, the *EV* nest includes battery electric, hybrid and plug-in hybrid vehicles, while the *gasoline* nest includes gas, diesel and petrol cars. We observe these 32 products in 10 separated markets. Utility of consumer i for aggregated product j in a given demographic group is:

$$u_{ij} = \delta_j + \sum_k d_k \epsilon_{ik} + (1 - \rho_k)\tilde{\epsilon}_{ij} \tag{11}$$

$\delta_j = \sum_a d_a \beta^a - \alpha p_j + \xi_j$ is the mean utility of product j, β^a is the preference for vintage a={below 5, 6-10, above 10} compared to vintage *new*, α is the price sensitivity, ξ is the unobserved quality (for e.g. advertising). d_k is a dummy equal to 1 if the fuel-type is k, ϵ_{ik} is the fuel-type-specific shock, ρ_k gives the degree of correlation within a fuel-type nest. The nested model is consistent with random utility maximization for $0 \leq \rho_k \leq 1$ (McFadden 1978). $\tilde{\epsilon}_{ij}$ is the consumer specific *taste for products*. It is type I extreme value distributed. As a result, the probability of choosing product j conditional on fuel-type nest k is

$$s_{j|k} = \frac{e^{\delta_j/(1-\rho_k)}}{\sum_l e^{\delta_l/(1-\rho_k)}}$$

The probability of choosing fuel type k is:

$$s_k = \frac{(\sum_l e^{\delta_l/(1-\rho_k)})^{1-\rho_k}}{\sum_n (\sum_l e^{\delta_l/(1-\rho_n)})^{1-\rho_n}}$$

The probability of choosing product j is then:

$$s_j = s_{j|k} s_k$$

The equation that we take to the data is:

$$log(s_j) - log(s_0) = \delta_j + \rho_k log(s_{j|k}) \tag{12}$$

We estimate the nested logit model using the Generalized Method of Moments (GMM). As in the seminal work of Berry 1994, price and $log(s_{j|k})$ are endogenous. We build instrumental variables z_j correlated with price and $log(s_{j|k})$ but uncorrelated with the unobserved quality ξ_j, to compute the aggregate moments $\mathbf{E}(\xi_j|z_j) = 0$. We use traditionnal nested logit instruments like the sum of exogenous product characteristics within the nest.

3.2 Database

Herein we introduce the database constructed to study vertical and horizontal preferences in the French used and new car market.

3.2.1 Car fleet

We build a novel dataset of the French private car fleet for the year 2019. To do so we combine car registration data at the district level obtained from *AAA data* and used-car prices and mileage obtained from the online sales website *Leboncoin.fr*. We then extract fuel prices, socio-economic and demographic data from the National Institute of Statistics and Economic Studies (INSEE). Finally, we fill the few missing values using technical data from *Argus.fr* and the French Energy Transition Agency (ADEME).

The car registration dataset contains all private vehicle registrations in 2019 at the supra-municipality level, hence 38.3 million vehicles. We restrict this dataset to the 35 brands that make up 99% of the fleet and drop cars older than 20, luxury and sports cars, and clean for empty values. For each remaining car, we observe power (in kW), fuel type and unit consumption (l/100km), CO_2 emissions (g/km), brand, model, first registration date, and new car prices, including tax and subsidy amounts for 2019. We build fuel cost per kilometer (€/100km) using fuel prices from INSEE databases. We match the car registration dataset with used-car prices and mileages from the online sales website *Leboncoin.fr*. Since the prices dataset does not contain all the models, we drop all models that have no prices, which represents 6% cars.

Mainland France has 34,968 municipalities, and municipalities that are larger than 5,000 inhabitants are subdivided into districts. Herein, we select the 41,414 districts for which we find available demographic data. Our final dataset contains 27,644,447 vehicles, hence 72% of the French car fleet. We partition the districts into 10 groups based on median income at the district level. We assume that all cars within an income group have been purchased by an average consumer, such at, in the end, it looks like we have 10 different French consumers renting cars each year. The average income in each group is described in Table 2.

Table 2: Average income of each income decile in 10k€ 2019

Decile	1	2	3	4	5	6	7	8	9	10
Average income	1.62	1.91	2.01	2.09	2.16	2.24	2.32	2.43	2.60	3.18

We build two fuel-type groups, EVs and gasoline cars, four car segments, small, medium, large, and SUV, and four vintage groups, new, less than 5 years old, 6-10 years old, and old vehicles (11-20). For the estimation, we aggregate the dataset by fuel type, segment, and vintage groups, resulting in 32 products. Product characteristics variables are constructed as a fleet-weighted average of the characteristics of products sharing the same fuel type, segment and vintage. As in Barahona, Gallego, and Montero 2020, we construct a rental-price variable using the no-arbitrage condition given by

$$p_{ja} = P_{ja} - \delta P_{j,a+1}$$

with P_{ja} the price of product j belonging to vintage group a, δ the discount factor, which we set at 0.9 per year.[14] For the simulations, we reduce the number of cars to 8 by aggregating the 32 products by fuel type and vintage groups. We calibrate the survival rates γ_{ka} for each energy k and vintage group a, using fleet data from 2019.

Table 3: Fleet parameters γ_{ka} for gasoline cars and EVs. Parameters are calibrated using fleet data from 2019. They reflect both the survival rate of each vintage-energy combination as well as the different sizes of each vintage-energy group.

	Gasoline	EV
1-5	2.38	1.52
6-10	0.74	0.093
11-20	0.449	0.0995

3.2.2 CO_2 data

We observe tailpipe CO_2 emission levels (g/km) for each car in the dataset. In the estimation, we use the fleet-weighted average value for the 32 products and estimate the preference for CO_2 emission level in 2019, and in the simulations, we do the same for the 8 aggregated products. We then calculate the average annual amount of CO_2 emitted per product as in Barahona, Gallego, and Montero 2020. Only there, we consider that EVs do not emit CO_2. We denote E_{ka} the total emissions from product of fuel type k and vintage group a in a given year.

$$E_{ka} = q_{ka} e_{ka} x_k$$

[14]Considering that our vintage groups are {new, 1-5 years old, 6-10, 11-20 years old}, we get $p_{j,old} = P_{j,old} - \delta^{15} P_{j,a>20}$ for the last vintage group. To compute prices of cars over 20 $P_{j,a>20}$, we consider that old cars lose about 5% of their value each year.

With q_{ka} and e_{ka} the number of cars and the CO_2 emission level (g/km) of each fuel-vintage type, which we observe in the fleet dataset, and x_k the average number of kilometers driven by a car of energy k, which we get from French government data (Ministry of Environment, 2023). In 2019, an average gasoline car is driven 11,909 kilometers per year. To obtain zero emissions for EVs, we assume that EVs are not driven, so that total emission per year are zero. The main focus of this paper is on CO_2 which is a global pollutant so we do not differentiate CO_2 harm by location. According to the Quinet Report, the value of a tonne of CO_2 emitted in 2050 should be 776€. The variation in pollution harm is then:

$$\Delta H = h \sum_k \sum_a \Delta E_{ka}$$

3.2.3 Descriptive statistics

The main variables used in the estimation are described in Table 4. Table 5 presents the number of cars for each fuel-vintage combination.

Table 4: Descriptive statistics of the fleet dataset.

	prices	**fuel costs**	**CO_2**	**weight**	**power**
mean	14,547	8.09	137	1239	78
min	150	0.86	0	620	29
25%	6022	6.62	115	1,065	58
median	12,743	7.7	134	1,220	75
75%	19,965	9.1	153	1,395	91
max	153,100	27.48	428	2,615	405

Table 5: Car volume per energy type and vintage group.

Energy	**vintage**	**volume**
	new	5,984,413
gasoline	1-5	14,225,691
	6-10	4,870,809
	above 10	2,186,487
	new	139,274
EV	1-5	215,853
	6-10	19,937
	above 10	1,983
total		27,644,447

As we see in Table 5, there are very few old EVs in the 2019 fleet. In some of the income groups, the volumes of old EVs of a certain car segment is null, bringing difficulties in using the nested logit model. To tackle down this issue, one option could be to remove the old EVs, from the sample, but this would lead to selection bias and this would prevent us from estimating the preference for these vehicles, which is key in our model. Instead, we follow D'Haultfœuille, Durrmeyer, and Février 2016 and use the following corrected market shares $\tilde{s}_j^d = \frac{n_j^d+\epsilon}{N^d}$, with n_j^d the volumes of product j in demographic group d, ϵ a small value inferior to one[15], and N^d the potential market in demographic group d. Since we study the car fleet and not car purchases, we follow Barahona, Gallego, and Montero 2020 and assume that the potential market is the entire population within the demographic group, and not one fourth of the number of household, as is usually the case in the literature.

3.3 Estimation results

Table 6: Estimation results. $^+$ indicates a 10% significance level, * a 5% and ** a 1%. Coefficients are marginal utilities for the variables in the first column. The second column displays the estimates for the total population and the other columns gives the estimates for the 10 income groups from the poorest decile (1) to the richest (10). Price is the rental price in 10k€, CO_2 is the level of tailpipe emissions in g/km, vintage groups 1-5, 6-10 and *old* are dummy variables taken against the reference category *new cars*. ρ is the nesting parameter. The Hansen test validates all the models.

		Income deciles									
Var	Mean	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
intercept	-0.47	-1.57	-2.19	-0.02	-1.83	-1.69	-1.59	-1.57	0.79	-1.43	0.06
price	-6.41**	-6.93**	-6.31**	-6.98**	-6.26**	-6.18**	-6.06**	-5.90**	-6.46**	-5.52**	-5.74**
CO_2	0.06**	0.07**	0.07**	0.06**	0.07**	0.07**	0.06**	0.06**	0.05**	0.06**	0.05**
1-5	-1.73**	-1.81^+	-1.61	-1.90^+	-1.60	-1.59	-1.56	-1.52^+	-1.80^+	-1.43^+	-1.58^+
6-10	-6.62**	-7.35**	-6.85**	-7.16**	-6.82**	-6.69**	-6.56**	-6.37**	-6.44**	-5.87**	-5.64**
old	-10**	-11.16**	-10.66**	-10.69**	-10.61**	-10.47**	-10.23**	-9.91**	-9.47**	-9.19**	-8.35**
ρ	0.60**	0.47^+	0.42*	0.58*	0.43*	0.45*	0.47*	0.49**	0.70**	0.54**	0.75**
Hansen test	7.52	0.72	0.80	0.46	0.65	0.74	0.67	0.64	0.78	0.72	0.55
p-value	0.023	0.70	0.67	0.79	0.72	0.69	0.71	0.72	0.67	0.70	0.76
nb obs.	320	32	32	32	32	32	32	32	32	32	32

The first column in Table 6 shows results for an average French consumer. The price coefficient is negative and significant at the 1% level. It seems that consumers find utility in CO_2 emissive cars, but note that this variable also reflects the size and fuel economy of the car. Looking at vintage preferences, compared to new cars, people dislike older products and the effect increases as products get older. The nesting parameter ρ is 0.6 and is significant at the 1% level, meaning that there is, in average, a high correlation of utilities for different cars of the same fuel type. As a result, there will be a larger substitution within the fuel-type nest, hence between EVs of different vintages, than outside the fuel-type nest, hence between gaoline cars and EVs of the same or of different vintages. Concretely, if the price of a new gasoline vehicle increases, substitution should be larger towards older vintages of the dirty product than towards new EVs. Estimating a nested parameter is interesting as it gives a proxy of purely horizontal preferences described in the theoretical model.

The last ten columns in Table 6 show the results for the nested logit model for each income group. Notably, preferences for most product characteristics do not vary linearly with income.

[15]We set $\epsilon = 0.1$ in the estimations.

However, price sensitivity is more pronounced in lower-income groups than in higher-income groups. All things equal, lower-income groups exhibit a higher disutility for used cars compared to higher-income groups. The nesting parameter is larger for high-income groups, suggesting greater resistance to switching from gasoline to electric cars, as well as a lower likelihood of returning to a gasoline cars after owning an EV. These findings calls for targeted measures aimed at middle- and lower-income households, who are more responsive to price changes and potentially less attached to their current fuel type group.

3.4 Simulation approach

We perform several policy counterfactuals using the estimates of each income decile in Table 6 and the equilibrium conditions from the theoretical model. The simulation algorithm finds optimal quantities in each income groups and optimal national prices in equilibrium. It is further described in Appendix 7.2. We define the equilibrium resulting from existing policies as the reference scenario. Using this reference case, we determine the marginal costs and scrapping values that allow to meet the break-even condition.

In the first policy counterfactual, we simulate the implementation of a carbon tax on top of existing policies, considering the 2050 steady-state carbon value from Quinet 2019, which is 776€/tCO_2. In the second set of counterfactuals, we simulate the implementation of different EV subsidy designs.

4 Policy analysis

In the following subsections, we first analyze how environmental policies impact the steady-state fleet. Then, we investigate welfare effects, considering consumer surplus variation, costs and benefits from fleet renewal, and avoided-CO_2 benefits. Finally, we study distributive impacts by focusing on consumer surplus variations across income groups.

Herein, we simulate the policy scenarios and put the resulting market share variations in Table 7.

Table 7: Simulation results: impact of Pigouvian taxation and of different subsidy designs on the steady-state car fleet. Results are relative quantity variations between the reference scenario and the policy counterfactuals. We assume that the potential market is fixed.

Energy	**Vintage**	**Carbon tax**	**Subsidy new cars**	**Sub new and used**
	new	-0.43	-0.12	-0.13
gasoline	1-5	-0.24	-0.0037	-0.0024
	6-10	-0.77	0.037	0.022
	above 10	-0.56	-1	-1
	new	0.30	3.3	2.32
EV	1-5	0.29	-0.71	2.71
	6-10	0.27	-0.65	3.03
	above 10	0.30	-0.81	4.2
Outside good shares		0.75	0.62	0.62

Results are expressed in terms of relative variation, hence the difference between counterfactual and reference quantities divided by the reference quantities. In each scenario, the outside option shares (not renting a car) are also given.

In the presence of a carbon tax (first column), the volume of gasoline cars decreases for all vintages, with relative variations going from 24% for the 1-5 vintage group (which is also the largest group) to 56% for the old car group. There is an increase of about 30% in all EVs. The largest increase is for the outside option that goes from 0.49 in the reference situation to 0.75 in case of a carbon tax. This means that the decrease in gasoline cars is not compensated by an increase in EVs and results in demotorization.

Intead, in the first subsidy design (second column), we put a 2,000€ subsidy on new EVs. In the second design, we implement a subsidy starting from 2,000€ for new cars and slightly increasing as vehicles age[16].

Putting a subsidy on new EVs only increases the quantity of new cars (+330%) and decreases the shares of all other cars. Appart from the old gasoline cars that exit the fleet, the largest losses in market shares are for used EVs (65% to 81% decrease). This can be explained by the large nesting parameter that leads to larger subsitution within the nest than outside. The outside option size also increases, reaching 0.62, due to the removal of used gasoline cars.

On the other hand, putting a subsidy on both new and used EVs (last column) increases the market shares of all clean vehicles by 232% to 402%. The effect on the outside option is similar to the new car subsidy scenario. The decrease in new gasoline cars market shares is larger.

4.1 Welfare calculation

We focus on steady-state welfare. Consider T as the vintage at which cars are scrapped.

$$W^S = -\sum_i c^i q_0^i + \sum_i \delta v^i (\gamma_{T-1}^i q_{T-1}^i - q_T^i) + \sum_a \sum_i CS_a^i - \sum_a h_a q_a^B \tag{13}$$

The first term is the cost of new gasoline and EVs entering the fleet. $\gamma_{T-1}^i q_{T-1}^i - q_T^i$ is the fraction of vintage T vehicles scrapped and CS_a^i is the consumer surplus of all individuals renting i_a vehicles. q_a^B is the number of gasoline vehicles of vintage a rented in that period.

In the nested logit model, individual consumer surplus is the expected utility of each consumer's best car choice (Train 2009). The variation of consumer surplus from the counterfactual compared to the reference scenario is:

$$\Delta \mathbf{E}(CS^d)) = \frac{1}{-\alpha^d} \Big(ln(\sum_{k=1}^{J_1} \exp(\frac{\delta_k^1}{1-\rho^d})) - ln(\sum_{k=1}^{J_0} \exp(\frac{\delta_k^0}{1-\rho^d})) \Big) \tag{14}$$

With CS^d the mean consumer surplus, α^d the price sensitivity and ρ^d the nested parameter

[16] We put a 2,000€ subsidy for new EVs and increase the subsidy by 100€ for each older vintage

in demographic group d. The indices 0 and 1 represent respectively the reference scenario and a counterfactual. We calculate total consumer surplus weighting each income group by its population N^d times the probability to by a car in a given scenario.

$$\Delta CS = \sum_d \Delta \mathbf{E}(CS^d))N^d \sum_j s_j^d$$

We report total consumer surplus variation benefits from avoiding CO_2 emissions, and fleet renewal benefits for each counterfactual specification, compared to the reference scenario in Table 8, .

Table 8: Welfare per consumer under different policy counterfactuals. All results are taken against the reference scenario, where CO_2 is not taxed and are expressed in 2019B€.

Counterfactual	ΔCS* (2019 B€)	CO2 benefits* (2019 B€)	Fleet renewal (2019 B€)	ΔW^S (2019 B€)
1: Carbon tax				
776€/tCO2	-31.5	11.4	80.3	60.3
2 and 3: EV subsidies				
New cars	2.19	3.58	0.23	6.00
New+used cars	2.12	3.70	8.7	14.5

As shown in Table 8, a national carbon tax results in substantial consumer surplus losses, totaling 32 billion euros. This effect is partly due to consumers shifting to the outside option (where surplus is normalized to zero) and the sharp increase in prices of gasoline vehicles, which remain popular with consumers. The tax yields the highest CO_2 reduction benefits, valued at 11.4 billion euros, and leads to significant gains for dealers, reaching 80.3 billion euros—mainly driven by a reduction in new gasoline vehicles entering the market. Altogether, the policy produces a substantial welfare gain of 60 billion euros compared to the reference scenario.

For EV subsidies, consumer surplus outcomes are similar between the two subsidy designs, both producing an overall gain of about 2 billion euros. CO_2 emissions reductions are slightly higher when subsidies also cover used EVs (3.7 billion euros compared to 3.58 billion euros). The main difference remains in the fleet renewal term, driven by a larger reduction of new gasoline cars entering the market in the second subsidy design. A subsidy targeting only new EVs achieves 10% of the welfare gains of the first-best outcome, while a combined subsidy on both new and used EVs achieves approximately one-fourth of the first-best gains, which is still far from the first-best outcome but brings substantial improvements.

4.2 Distributive effects

Our preliminary results show that the carbon tax is the only policy that has a positive effect on the poorest income group. The subsidies benefit the richest groups more as they are the ones renting EVs. This could also be because, subsidies lead to the removal from the fleet of

Table 9: Consumer surplus variation by income decile in € per capita, from the poorest (decile 1) to the richest (decile 10)

Income decile	**Carbon tax**	**New subsidy**	**New & used subsidy**
Decile 1	53.7	-6.61	-13.1
Decile 2	-146	10.3	6.85
Decile 3	- 766	60.8	61.3
Decile 4	-332	23.7	22.6
Decile 5	-400	27.5	26.8
Decile 6	-473	31.8	31.6
Decile 7	-519	33.7	33.4
Decile 8	-1560	124	127
Decile 9	-492	29.9	29.0
Decile 10	-735	43.0	40.3

old polluting vehicles, which are often owned by lower-income households, but these vehicles are not systematically replaced by an EV and lead to demotorotization of the poorest.

5 Concluding remarks

So far, we have build a theoretical model of vertical and horizontal preferences that we have described and estimated using a simple choice model where cars are segmented by "EV" and "gasoline" fuel types as well as according to their vintage group.

The theoretical development of including vertical and horizontal preferences proves to be a crucial contribution since it breaks the equivalence between Pigouvian taxes and subsidies. Our main finding in this regard is that a subsidy on second-hand EVs must be implemented in the transition to net-zero emissions. This is the case because subsidies to new and used EVs work as complements in the implementation of the optimal policy.

To quantify the importance of the previous result, the estimation has used the 2019 fleet data for an average French consumer and can be replicated for different socio-demographic groups. When we implement a carbon tax at the 2050 carbon value level, the individual loss in consumer surplus is not compensated by the important CO2 benefits, but the fleet renewal benefits allow to reach large and positive welfare gains. When we only put a subsidy on new EVs, we see a large increase in new EVs and a large decrease in the closest substitutes, hence of used EVs. To increase the size of the EV fleet, one option is to put an additional subsidy on used EVs. Yet, for both subsidy designs, the welfare improvements are far from the first-best results, 10% for the new car subsidy and 1/4 of the first best when we add a substantial used-car subsidy.

6 Theoretical Appendix

This appendix contains proofs of propositions and lemmas.

6.1 Proof of Proposition 1

to be completed

The proof is divided in three parts.

Part (i). We first show that there are no welfare gains of adjusting either tax away from its Pigouvian level by a marginal amount. With the aid of Figure 4, note that the net benefit of marginal increasing τ_0 by an arbitrarily small amount equal to $\varepsilon \approx 0$ is given by (after neglecting second-order effects)

$$\begin{aligned}\Delta W_{\tau_0} = & \frac{\varepsilon}{2t}\left(1-\theta_{EV}\right)h_0 - \frac{\varepsilon}{2t}\left(1-\theta_{EV}\right)t(1-2\eta_0') \\ & - \frac{\varepsilon}{2t}\int_{\theta_G'}^{\theta_{EV}} \theta\Delta s d\theta - \frac{\varepsilon}{2t}\int_{\theta_G'}^{\theta_{EV}} t(1-2\tilde{\eta}(\theta))d\theta + \frac{\varepsilon}{2t}(\theta_{EV}-\theta_G')(c+h_0) \\ & - \frac{\varepsilon}{\Delta s}\eta_1'\theta_G'\Delta s - \frac{\varepsilon}{\Delta s}\eta_1'(h_1-h_0) + \frac{\varepsilon}{\Delta s}\eta_1' c\end{aligned} \tag{15}$$

where $\tilde{\eta}(\theta) = (t+\theta\Delta s - c - \tau_0)/2t$ connects the horizontal and vertical preferences of individuals indifferent between a new gasoline gasoline car and a second-hand EV.

Each line captures gains and losses associated to three different groups of individuals. The first line corresponds to individuals located on the vertical line that intersects the horizontal axis at $\eta_0' = 1/2 - \tau_0/2$ and with vertical preferences that go from $\theta = \theta_{EV} = c/\Delta s$ to $\theta = 1$. By switching from new gasoline cars to new EVs, these individuals contribute with pollution gains equal to h_0 each (the first term in the first line). These individuals also suffer horizontal losses by moving further away from their preferred (no-intervention) choice (the second term in the first line). In fact, an individual located at $\eta \leq 1/2$ incurs a disutility of $t\eta$ when buying a new gasoline car and $t(1-\eta)$ when buying a new EV. Hence, switching to the latter entails an extra utility loss of $t(1-2\eta)$. There is an additional effect not reflected in the first line: the extra costs from additional new EVs entering the market are exactly offset by the savings from fewer new gasoline cars being sold.

The second line captures the costs and benefits associated with individuals located along the diagonal, extending from $\eta_1' = 1/2 - \tau_1/2t$ to η_0', and from $\theta_G' = (c - \tau_1 + \tau_0)/\Delta s$ to θ_{EV}, who switch from new gasoline cars to second-hand EVs in response to the marginal increase in τ_0. The first two terms of the line are losses from the vertical downgrade (from moving from a new to a second-hand car) and additional horizontal disutility, respectively. These private losses contrast with the social gains—captured in the last term of the line—from fewer new gasoline cars entering the market and reduced pollution. Finally, the third line includes welfare changes associated with individuals with vertical preferences θ_G' and horizontal preferences extending from $\eta = 0$ to $\eta = \eta_1'$. These changes include losses from vertical downgrades and more pollution (first and second terms of the line, respectively), and gains from fewer new gasoline cars entering the market (last term of the line).

Similarly, the net benefit of marginal increasing τ_1 by an arbitrarily small amount equal to

$\varepsilon \approx 0$ is given by

$$\Delta W_{\tau_1} = \frac{\varepsilon}{\Delta s}\eta_1'\theta_G'\Delta s + \frac{\varepsilon}{\Delta s}\eta_1'(h_1 - h_0) - \frac{\varepsilon}{\Delta s}\eta_1' c + \frac{\varepsilon}{2t}\theta_G' h_1 - \frac{\varepsilon}{2t}\int_0^{\theta_G'} t(1-2\eta_1')d\theta \tag{16}$$

The first line includes welfare changes associated with individuals with vertical preferences θ_G' and horizontal preferences extending from $\eta = 0$ to $\eta = \eta_1'$ who switch from second-hand to new gasoline cars in response to the marginal increase in τ_1. These changes include vertical upgrades (first term of the line), less pollution (second term), and extra costs from more new gasoline cars (last term). And the second line includes wlefare changes associated with individuals located on the vertical line that intersects the horizontal axis at η_1' and with vertical preferences that go from $\theta = 0$ to $\theta = \theta_G'$. These changes include less pollution (first term of the line) and horizontal disutilities (second term). Collecting terms in expressions (15) and (16) and rearranging yields expressions (5) and (6) in the text. Making $\tau_0 = h_0$ and $\tau_1 = h_1$ in (15) and (16) solves the system $\Delta W_{\tau_0} = \Delta W_{\tau_1} = 0$.

Part (ii). Since any arbitrary allocation of cars in Figure 4 requires three price interventions, we now show that the social planner cannot do better with a third price instrument, such as a tax (which could be negative) on either new or second-hand EVs. Consider the former. The net benefit of adding an arbitrarily small tax $\varepsilon \approx 0$ on new EVs is given by

$$\begin{aligned}\Delta W_{\tau_0^{EV}} \quad = \quad & -\frac{\varepsilon}{2t}(1-\theta_{EV})\,h_0 + \frac{\varepsilon}{2t}(1-\theta_{EV})\,t(1-2\eta_0') \\ & + \frac{\varepsilon}{\Delta s}(1-\eta_0')c - \frac{\varepsilon}{\Delta s}(1-\eta_0')\theta_{EV}\Delta s\end{aligned}$$

where $\eta_0' = 1/2 - \tau_0/2$ (with $\tau_0 = h_0$) and $\theta_{EV} = c/\Delta s$. It is easy to see that $\Delta W_{\tau_0^{EV}} = 0$. The same holds if we consider an arbitrarily small tax on second-hand EVs, confirming that the planner can reach the first-best by relying exclusively on taxes on polluting vehicles.

Part (iii) To be written

6.2 Proof of Proposition 2

to be written

6.3 Proof of Lemma 1

By contradiction. Suppose that $\sigma_0^* = \sigma_1^*$. If so, $\Delta W_{\sigma_0} = 0$ in (7) leads to $\sigma_0^* = h_0$, but $\Delta W_{\sigma_1} = 0$ in (8) leads to $\sigma_1^* = h_1$; a contradiction since $h_1 > h_0$. Suppose then that $\sigma_0^* > \sigma_1^*$. If so, $\Delta W_{\sigma_0} = 0$ implies that $\sigma_0^* < h_0$ (recall that $\Delta s > c + \sigma_1 - \sigma_0$), but $\Delta W_{\sigma_1} = 0$ implies that $\sigma_1^* > h_1$ (recall that $h_0 < t$); again, a contradiction since $h_1 > h_0$. Therefore, it must hold that $\sigma_0^* < \sigma_1^*$. This and $\Delta W_{\sigma_0} = 0$ imply that $\sigma_0^* > h_0$. On the other hand, $\sigma_0^* < \sigma_1^*$ and $\Delta W_{\sigma_1} = 0$ imply that $\sigma_1^* < h_1$, which concludes the proof.

6.4 Proof of Proposition 3

to be written

6.5 Proof of Proposition 4

Let $\sigma_0^{**}(h_0)$ and $\sigma_0^*(h_0)$ be the optimal subsidies for new electric cars during the transition and in steady state, respectively, as a function of $h_0 \leq h_1$. Visual inspection of their first-order conditions suggests both functions to be strictly concave.[17] So, the idea of the proof is to show that $\sigma_0^*(h_0)$ crosses $\sigma_0^{**}(h_0)$ from below and only once, at $h_0 = h_1$. Showing that $\sigma_0^{**}(h_0)$ crosses $\sigma_0^*(h_0)$ at $h_0 = h_1$ is immediate from looking at (10) and the system of equations (7) and (8) for $\Delta W_{\sigma_0} = \Delta W_{\sigma_1} = 0$. The unique solution when $h_0 = h_1$ is $\sigma_0^{**} = \sigma_0^* = \sigma_1^* = h_1 = h_0$.

On the other hand, single crossing from below requires (i) $\partial\sigma_0^{**}(h_0 = h_1)/\partial h_0 < \partial\sigma_0^*(h_0 = h_1)/\partial h_0$; and (ii) $\partial^2\sigma_0^{**}(h_0 = h_1)/\partial h_0^2 < \partial^2\sigma_0^*(h_0 = h_1)/\partial h_0^2 < 0$ for all $h_0 \leq h_1$. To show (i), allow h_0 in both (10) and (7) to marginally drop from h_1 to $h_1 - \varepsilon_h$, with ε_h arbitrarily small, and ask what would be the marginal changes in σ_0 for the first-order conditions to continue holding, that is, (10) and $\Delta W_{\sigma_0} = 0$ in (7). Denote these marginal changes by ε'_{σ_0} and ε''_{σ_0}, respectively. It turns out, after simple manipulation, that

$$\varepsilon'_{\sigma_0} = \varepsilon''_{\sigma_0} = \frac{\Delta s - c}{\Delta s - c + t + h_1}\varepsilon_h$$

indicating that both σ_0^{**} and σ_0^* adjust downward by the same amount (recall that $\Delta s > c$). But this is only the direct adjustment. In the case of σ_0^*, there is also an indirect adjustment, as the drop ε_h has also a downward impact on σ_1^*. Given the complementarity of (optimal) subsidies established in Proposition 3, this indirect adjustment shows that σ_0^* must necessarily fall more than σ_0^{**} (to find the actual drop of σ_0^* requires solving the system of first-order conditions for σ_0^* and σ_1^*). Finally, showing (ii) demands a tedious algebraic manipulation and is therefore omitted.

7 Empirical Appendix

This appendix contains details on the estimation model validity in subsection 7.1, and a description of the simulation algorithm in subsection 7.2.

7.1 Validity of the demand model

We face several da difficulties with this demand model. First, since products are very aggregated (J=32), we have a small number of observations, resulting in few degrees of freedom and frequent instrument collinearity issues. We use the variables that avoid instrument collinearity, that result in a nesting parameter σ between zero and one, and that pass the Hansen test. The

[17] In fact, plugging the parameters values following the proposition yield $\sigma_0^{**}(h_0) = \sqrt{3}\sqrt{59 + 64h_0}/8 - 13/8$ and $\sigma_0^*(h_0) = h_0/2 + 3\sqrt{3 + 4h_0}/8 - 5/8$

objective of the test is to assess the validity of the additional restrictions imposed by the overidentified model. The null hypothesis H_0 is that the instruments are valid. The alternative hypothesis H_1 is that the additional restrictions due to overidentification, do not hold, indicating model misspecifications. To validate the specified model, the test needs to have a test statistic close to zero and a large p-value. In all specifications presented in Table 6, I fail to reject H_1, which validates the models. The full model has a higher test statistic and lower p-value, suggesting that the reduced model is more appropriate. For the counterfactual analyses, we will therefore use the reduced model.

7.2 Simulation Algorithm

In the outer loop, we look for the number of new cars to add to the fleet alongside the vector of product prices so that the break-even, fleet, and scrapping conditions are met. This is similar to what is done in Barahona, Gallego, and Montero 2020 but differs slightly because there are two sets of equilibrium conditions - one for each fuel type - to meet simultaneously instead of one. Each equilibrium condition is a squared difference. Barahona, Gallego, and Montero 2020 minimizes an objective function that is the sum of squares to obtain simultaneously the different equilibrium conditions. Here, we need to minimize two objective functions at the same time. This brings difficulties because of the small number of EVs. As few EVs are in the 2019 fleet, fleet parameters calibrated with 2019 fleet data might not reflect the dynamics of EV sales in the future. The solution so far has been to minimize the Mahalanobis distance between the two objectives and to put a lower weight on the EV objective.

In the inner loop, we choose a policy scenario (no intervention, Pigouvian taxes, new and used electric car subsidies) that determines an initial price vector. Keeping preferences and other fleet parameters fixed, we calculate predicted quantities in each income groups using the structure of the nested logit model. Then we sum over the income groups to get the total volume for each product and compute the counterfactual market shares.

Table 10: Optimal marginal costs and scrapping values in the no intervention equilibrium (in 10,000€)

	gasoline	EV
c	3.45	2.90
v	0.0250	0.0990