Can a carbon tax increase emissions? The backfire effect of carbon tax recycling

Working paper

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Abstract

Recycling the revenues of a carbon tax can mitigate the distributional impacts and lowers the burden on the lowest income deciles. However, a lump-sum rebate to households induces consumption, hence emissions. In this paper, we study the existence of a backfire effect where emissions increase above the pre-tax level because of the recycling of carbon tax revenues. We build a small theoretical model that we extend using microsimulation on French Households Budgets Surveys with long-term elasticities. We estimate that a €158/tCO_2 tax would induce a decrease of 10.9% in emissions, reduced by a uniform lump-sum rebate to a decrease of 5.9% in aggregate emissions. We conclude that the backfire effect is not a sufficient reason to prevent any compensation of the low-income households for the sake of emissions reduction. Indeed, a quarter of households increase their emissions in the face of a lump-sum rebated carbon tax, but the emissions thus emitted represent less than a tenth of the emissions of the 10th (richest) income decile. Recycling only 60% of the carbon tax revenues would reduce the backfire to decrease emissions by almost 8%. Skewing the recycling towards low-income households increases the progressivity of the tax but does not increase emissions. Our study supports the consistency between reducing inequalities and reducing emissions.

1 Introduction

Carbon pricing is a key tool to mitigate greenhouse gas emissions and climate change consequences (Pearce, 1991; Nordhaus, 1993; Stern, 2008). Carbon pricing can be implemented through a carbon tax or an emission trading system. It has proven effective in reducing greenhouse gas emissions (Green, 2021; Leroutier, 2022; Abrell et al., 2018; Andersson, 2019) but it can also be regressive in a number of countries and contexts which is a major concern for the population (Dechezleprêtre et al., 2022).[1] The use of carbon pricing revenues is therefore key to increasing the acceptability of the carbon tax, especially by redistributing all or part of these revenues to households. Recycling the revenues of the carbon tax towards households — through a cash transfer or a tax cut — is a popular option to mitigate distributive concerns. However, the compensation of households will increase consumption, hence emissions.

This paper focuses on whether using the tax revenues to compensate households can limit the effectiveness of the carbon tax in reducing emissions — or even *backfire* and increase emissions. The intuition behind the potential perverse effect of the recycled carbon tax is simple: a carbon tax reduces emissions — to a greater or lesser extent — through the price signal. The objective of

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[1] Meta-analyses show ambiguous results on the regressivity of the carbon tax (Flues and Thomas, 2015; Ohlendorf et al., 2020; Feindt et al., 2021). In the French case, however, Douenne (2020) and Berry (2019) show a clear regressivity. However, it is mainly the perceived regressivity that threatens the social acceptability of the tax (Carattini et al., 2017; Ewald et al., 2022).

most taxes is to redistribute levied revenues through transfers or public services. But for Pigouvian taxes the redistribution is not part of the optimal design of the tax. Redistribution can then trigger an unfortunate effect: whatever the recycling, the excess revenue for households will result in more consumption and hence more emissions compared to a situation in which the tax is levied but not recycled. The reduction of emissions will therefore be lesser than expected. Emissions could even increase above pre-tax level.

Let's take a simple example and consider that all households are dependent on gasoline: their response to the carbon tax is to decrease other consumptions and maintain their gasoline consumption. Low-income households are in the paradoxical situation of energy deprivation while dedicating a large share of their income to gasoline. They will then bear a significant burden from the tax. It is only fair that most of the carbon tax collected should go to them to correct the regressivity of the tax. Low-income households thus receive a larger rebate than the carbon tax they have paid. They might resume all their consumption at the pre-tax level, and use the excess income to purchase more gasoline to increase their mobility. The increase in emissions that follows might more than offset the reduction in emissions of high-income households if they have chosen to reduce low-carbon intensity consumption more than carbon-intensive consumption. In this example, there is a transfer from clean consumption of high-income households to dirty consumption of low-income households, thus creating a backfire effect.[2]

Whether or not there is a backfire stemming from the recycling of carbon pricing revenues to the household is an important question for policymakers. If a fair tax means fully cancelling out the reduction emissions with revenues recycling: then it might be best to renounce the tax or to fully redesign it.

In this paper, we develop a microsimulation model to assess the effects of a carbon tax and a direct lump-sum recycling of the carbon tax towards households. First, we solve a compact theoretical model to illustrate how the different mechanisms allowing for a backfire effect could interact. Importantly, this model shows how heterogeneous carbon intensities and elasticities drive the backfire effect. We use past expenditure surveys to estimate the price and income elasticities by disaggregating goods and households as much as possible. We use these elasticities and the latest French Consumer Expenditures survey to calibrate the microsimulation.

We find no aggregate backfire effect. No matter how we recycle the carbon tax revenues to households, aggregate emissions decrease. We estimate that a €158/tCO_2 tax[3] would bring a decrease of 5.9% if recycled on an equal per-capita basis. The recycling offsets less than half of the carbon tax reduction in emissions (10.9%). Although there is no aggregate backfire effect, with an equal per-capita rebate about 25% of households experience individual backfire effects, i.e. increase their emissions above pre-tax levels. Recycling only part of the revenue from the carbon tax further reduces emissions and limits income effect. Targeting low-income household ensures the progressivity of the tax and compensates a large number of poor households but increases the number of low-income households experiencing individual backfire.

We find that the regressivity of the carbon tax is worsened by lower price elasticities of low and middle-income households for energy goods. Occurrence of individual backfire effects depends more on non-income dimensions — such as the income structure and pre-committed expenditures and age and location (rural, small or big city) — than on income deciles.

This paper contributes to two main strands of literature. First, we contribute to the literature on the distributive impacts of carbon taxes. Most articles concludes that recycling the carbon tax revenues, either in the form of a lump-sum transfer (Budolfson et al., 2021; Cronin et al., 2019; Fremstad and Paul, 2019; Klenert et al., 2018; Beck et al., 2015; Ekins and Dresner, 2004) or to cut labour tax (Pearce, 1991; Parry, 1995; Goulder, 1995; Aubert and Chiroleu-Assouline, 2019)

[2]This kind of perverse effect of taxation is not unique to carbon taxes. Mayeres and Proost (2001) studies a tax aimed at internalising congestion. Paradoxically, the reduction in congestion due to the tax makes car travel more attractive for some people – whom the tax discourages – because the traffic is more fluid than before the tax. There is a feedback effect of the level of externalities on the consumption of the taxed good, i.e. a perverse effect of the tax, which partly cancels out its incentives. This perverse effect stems from the heterogeneity of individuals and diverse time valuations and preferences.

[3]This level of carbon was supposed to be a milestone of carbon taxation in 2025 prior to the freeze that followed the Gilets Jaunes protests.

makes the tax strongly progressive.[4] Although, to the best of our knowledge, there is no literature on the impact of recycling the carbon tax revenues on emissions and the potential "backfire effect".

Two fields are at the frontier of this research gap but do not answer our research question. The closest approach is that of the Environmental Engel Curves (EEC), which allow for the estimation of income elasticities of emissions (Pottier (2022) provides a survey of income elasticities of GHG emissions). Sager (2019) estimates EEC and assesses the increase in emissions due to a reduction in the Gini index representing income inequalities. The second is the study of the well-known "rebound effect" following energy-efficiency measures such as thermal renovation (see for instance Gillingham et al. (2016)). Belaïd et al. (2020) focuses on residential electricity demand and finds that the increase in emission following thermal renovation is sensitive to income. Druckman et al. (2011) coined the term "backfire" when the rebound effects exceed 100% due to economy-wide effects. An even further field studies the risk of carbon leakage due to a carbon tax and thus the potential increase in emissions (Hoel, 1991; Markusen et al., 1995; Copeland and Taylor, 2013). It is outside the scope of this paper as we focus on households rather than on production decisions.

Second, we contribute to the literature on the estimation of elasticities. The most related article is Douenne (2020). It estimates price elasticities for transport and housing energy prices for 50 cells of households (10 income deciles and 5 sizes of urban units) to microsimulate the distributional impact of a carbon tax on fuel in France. Calvet and Marical (2011) also point out the importance of non-income dimension in the estimation of energy elasticities.[5] In contrast to these studies, we do not estimate system elasticities, which allows us to achieve a high level of disaggregation. We test the robustness implication in appendix I.A. We conclude that our estimates of emissions reduction are accurate at 0.1%.

The rest of the paper organises as follows. In section 2, we develop a theoretical framework to derive the conditions of the existence of a backfire effect with increasing heterogeneity between households. In section 2 we present the consumers' expenditures database, the microsimulation model and the estimation framework for elasticities. In section 4, we present the price and income elasticities for 40 classes of households on 14 goods. In section 5, we analyse the microsimulation results. We study the impacts of various carbon price and recycling mechanisms, as well as a sensitivity analysis. Section 6 concludes.

2 A "toy-model" of backfire effects of carbon pricing

In this paper, we aim to quantify the backfire effect in emissions of recycling carbon tax revenues towards households and derive the conditions under which it can happen. It is intuitively simple to understand how a backfire effect can take place. We try to formalise and illustrate it via a theoretical model of consumer demand. We first present a simplified model with limited heterogeneity in households. We then add step-wise heterogeneity with multiple carbon-emitting goods, several households and heterogeneity in the carbon intensities of goods and heterogeneous preferences.

Two mechanisms are put forward that operate through taxation and redistribution: the monetary transfer between households and the transfer between goods within a household basket.

We highlight four different levers influencing a possible backfire effect through the previous two mechanisms:

1. Respectively low and high price and income elasticities for carbon-intensive good;
2. Heterogeneous carbon intensities;
3. Energy-intensive households;

[4] In this paper, we estimate the effect of lump-sum transfer for two reasons. The first one is political: using the carbon tax to lower labour tax would require a complete reshuffle of the tax system, which is less likely to happen than a stand-alone carbon tax and its lump-sum recycling transfer. Sweden has been an exception in that regard. It has greatly contributed to the success of their carbon tax. The second reason is technical: estimating the effect of a double dividend would require a general equilibrium model that would be difficult to calibrate, especially to capture heterogeneity in households, see for instance Rausch et al. (2011); Goulder et al. (2019); Fremstad and Paul (2019); Ravigné et al. (2022).

[5] We can also cite Romero-Jordán et al. (2016), which finds electricity price elasticities in Spain to be U-shaped along income and income elasticities to be N-shaped causing vulnerability of low-income households to the economic crisis and price increase.

4. Revenues recycling favouring the energy-intensive households.

We can add a fifth one, which is heterogeneous price and income elasticities between households. We model an economy where price and income elasticities are pre-determined for households. We do not explicitly consider the utility of households, and do not address utility maximisation for agents or of a benevolent planner. The objective is to assess, given preferences, how the emissions of households subject to a tax and revenue recycling evolve. The productive sector is not modelled either, but it implicitly rests on production functions using only labour, allowing an adjustment of supply and demand.

After each extension of the model, we offer conclusions on the conditions allowing a backfire effect to take place.

2.1 Re-allocating households income

An increase in the price of a specific good — say due to a carbon tax — triggers a reduction in the consumption of this specific good.[6] While when a household receives extra income, it will be distributed across all consumption goods, unless it is earmarked. Hence, a tax and revenue recycling have asymmetric effects on the consumption structure of the household.

Let's consider a single household consuming two goods, a polluting energy good E, and a non-polluting good X. We consider the expenditure in constant euros of each good at time i: E_i and X_i. Respective prices are p_i^E and p_i^X.

A single polluting good The carbon intensity of the energy good per euro spent is $\eta_E > 0$, while $\eta_X = 0$ (this hypothesis will be released in the next sections).[7] Carbon emissions at time 0 are then $\chi_0 = E_0\eta_E$ and at time 1, $\chi_1 = E_1\eta_E$.

The energy good E is taxed with a tax t per ton of carbon. The implementation leads to a price increase: $p_1^E = p_0^E(1+\eta_E t)$. The relative price change of the energy good is then:

$$\frac{p_1^E - p_0^E}{p_0^E} = \eta_E t. \tag{1}$$

The household adjusts its demand to price and income increases with price elasticities, ε_p^E et ε_p^X, and income elasticities ε_r^E et ε_r^X.

The demand for each of these goods between the two periods is governed by the following system, where S is the carbon tax collected:

$$\begin{cases} E_1 = E_0(1+\varepsilon_p^E\eta_E t)\left(1+\varepsilon_r^E\dfrac{S}{E_0+X_0}\right) \\ X_1 = X_0\left(1+\varepsilon_r^X\dfrac{S}{E_0+X_0}\right) \\ S = E_1\eta_E t \end{cases} \tag{2}$$

The solutions of this system are:

$$\begin{cases} X_1 = X_0\dfrac{1-(\varepsilon_r^E-\varepsilon_r^X)\dfrac{E_0}{B_0}\eta_E t(1+\varepsilon_p^E\eta_E t)}{1-\varepsilon_r^E\dfrac{E_0}{B_0}\eta_E t(1+\varepsilon_p^E\eta_E t)} \\ E_1 = E_0\dfrac{\dfrac{E_0}{B_0}(1+\varepsilon_p^E\eta_E t)}{1-\varepsilon_r^E\dfrac{E_0}{B_0}\eta_E t(1+\varepsilon_p^E\eta_E t)} \end{cases} \tag{3}$$

with B_0, the initial budget, $B_0 = X_0 + E_0$.

[6] And triggers a substitution with other goods (note that we have no cross-elasticity in this paper).

[7] It is important to notice that η_E and η_X are expressed as carbon intensities of the expenditures, it explains why we do not express the carbon tax as an excise tax.

We impose that the budget is balanced ($B_1 = B_0$) and that the government redistribute all the carbon tax revenues.

There is a backfire effect if emissions increase, i.e. if emissions at time 1, χ_1, are higher than the pre-tax level χ_0 at time 0 — that is if $\frac{\chi_1}{\chi_0} - 1 > 0$. We can express this growth rate as follows:

$$\frac{\chi_1}{\chi_0} - 1 = \frac{\eta_E t \left(\varepsilon_p^E + \frac{E_0 \varepsilon_r^E}{B_0}(1 + \varepsilon_p^E \eta_E t) \right)}{1 - \frac{\varepsilon_r^E E_0^p \eta_E t}{B_0}(1 + \varepsilon_p^E \eta_E t)}. \tag{4}$$

The growth rate in emissions (4) is always negative (details in appendix G.A). Intuitively, since 100% of the tax is levied on the polluting good while the revenue is spent on the two goods, consumption of energy and thus emissions are reduced. The conclusion is that taxing and giving everything back to the same household does indeed reduce emissions. There can be no backfire effect under these conditions.

We highlight the first lever to have a backfire effect: it needs at least two polluting goods to occur.

Two polluting goods We can find a backfire effect if the second good X is also carbon-emitting. We assume that $0 < \eta_X < \eta_E$. X is then taxed accordingly at the same rate t as the energy good.

The intuitive situation where we can have a backfire effect is the following: very price inelastic demand in energy but high income elasticity. These are typical of a household in energy poverty.

The growth rate in emissions is expressed as follows:[8]

$$\frac{\chi_1}{\chi_0} - 1 = \frac{\left(\varepsilon_p^E \eta_E^2 t E_0 + (1 + \varepsilon_p^E \eta_E t)\chi_0 \frac{\varepsilon_r^E E_0 \eta_E t}{B_0} \right) + \left(\varepsilon_p^X \eta_X^2 t X_0 + (1 + \varepsilon_p^X \eta_X t)\chi_0 \frac{\varepsilon_r^X X_0 \eta_X t}{B_0} \right)}{1 - \frac{\varepsilon_r^E E_0 \eta_E t}{B_0}(1 + \varepsilon_p^E \eta_E t) - \frac{\varepsilon_r^X X_0 \eta_X t}{B_0}(1 + \varepsilon_p^X \eta_X t).} \tag{5}$$

Two conditions must be met to obtain a backfire effect:

1. The consumption of E increases. In other words, the income effect on E is greater than the price effect on E. Since the budget is constant, if E consumption increases, then X consumption decreases.[9] There is a transfer from the clean good to the polluting good. The condition is as follows:

$$\chi_0 t \frac{\varepsilon_r^E}{B_0} E_0 > -\varepsilon_p^E \eta_E t E_0. \tag{7}$$

   That is to say, the increase in E consumption when the sum $\chi_0 t$ is recycled is greater than the decrease in E consumption when subjected to a price increase $\eta_E t$.

2. The carbon intensities must be different so that a transfer of X to E results in an increase in emissions. In the case where both goods are equally emitting, then obviously, a transfer between goods does not change anything. The condition is:

$$E_0 \frac{\varepsilon_r^E}{B_0} \chi_0 \left(1 + X_0 \varepsilon_p^X t \eta_X \frac{(\eta_X - \eta_E)}{\chi_0} \right) + \varepsilon_r^X \frac{\chi_0}{B_0} X_0 \eta_X t (1 + \varepsilon_p^X \eta_X t) - \varepsilon_p^X \eta_X X_0 > 0. \tag{8}$$

   We can understand it as:

$$E_0 \cdot (\text{E income effect}) \left(1 + (\text{X price effect}) \cdot \frac{X_0(\eta_X - \eta_E)}{\chi_0} \right) + X_0 \cdot (\text{X total effect}) > 0$$

[8]Equations and solutions to the demand system are expressed in appendix G.B.

[9]Symmetrically,

$$\chi_0 t \frac{\varepsilon_r^X}{B_0} X_0 < -\varepsilon_p^X \eta_X t X_0. \tag{6}$$

.

If $\eta_X = \eta_E$ then we have a backfire if the income effect on E (increase in consumption of E after recycling) more than compensates for the decrease in consumption of X, i.e. the income elasticity of E is large and also compensates the price effect on E. If on the contrary, we have $\eta_E \gg \eta_X$ then we create a strong multiplier effect on the income effect of E (the price effect on X is totally offset by the income effect on E).

We can therefore translate the condition of a backfire effect as: the dirty good must be significantly dirtier than the clean good. Its income elasticity must be high while its price elasticity is low (or similarly that the price effect of the clean good is high and the income elasticity is low), which implies an increase in the consumption of dirty good E.

This result may seem surprising and violate a number of assumptions about the rationality of agents. It would be irrational to reallocate expenditures when faced with a simultaneous tax and lump-sum transfer. However, in practice, carbon taxation takes place at the same time as consumption, while recycling of carbon tax revenues will likely take place once or twice a year, or could even be redistributed in the form of tax credits (for those paying enough taxes, as a direct cash transfer for the others) as it is the case in British-Columbia, Canada.

We conclude that emissions can decrease — or increase — when the carbon tax collects with one hand and gives it back with the other. We highlight two levers of backfire: the asymmetry between the carbon-intensive low price elasticity and high income elasticity and the difference in carbon content between the two goods.

2.2 Transfers between households

Now let's suppose we have two households: a 'poor' household that consumes (E_0^P, X_0^P) and a rich household that consumes (E_0^R, X_0^R). Without loss of generality, we suppose that the poor household is relatively more energy-intensive than the rich one: $E_0^P/X_0^P > E_0^R/X_0^R$. A fraction x of the total carbon tax revenues collected is given back to the poor household, and the remaining $(1-x)$ to the other household.

One polluting good If we assume that only the good E is carbon-emitting, then there is again no possibility of a backfire effect. Indeed, the within-households effect, from E to X, means a decrease in emissions. In the most extreme case, the total amount collected on E is redistributed to only one of the households ($x = 1$ or $x = 0$) that spends it all on the energy good. The total amount spent on E is the same as the pre-taxed level and the impact on emissions is neutral.

Two polluting goods We shall then consider $0 < \eta_X < \eta_E$.

The program of consumption at time 1 is:

$$\begin{cases} E_1^P = E_0^P(1+\varepsilon_p^E \eta_E t)\left(1+\varepsilon_r^E \dfrac{xS}{E_0^P + X_0^P}\right) \\ X_1^P = X_0(1+\varepsilon_p^X \eta_X t)\left(1+\varepsilon_r^X \dfrac{xS}{E_0^P + X_0^P}\right) \\ E_1^R = E_0^R(1+\varepsilon_p^E \eta_E t)\left(1+\varepsilon_r^E \dfrac{(1-x)S}{E_0^R + X_0^R}\right) \\ X_1^R = X_0^R(1+\varepsilon_p^X \eta_X t)\left(1+\varepsilon_r^X \dfrac{(1-x)S}{E_0^R + X_0^R}\right) \\ S = (E_1^P + E_1^R)\eta_E t + (X_1^P + X_1^R)\eta_X t \end{cases} \tag{9}$$

with $B_0^R = X_0^R + E_0^R$ et $B_0^P = X_0^P + E_0^P$, $\chi_0^E = (E_0^R + E_0^P)$, $\chi_0^X = (X_0^R + X_0^P)$, $B_0^R = (E_0^R + X_0^R)$, $B_0^P = (E_0^P + X_0^P)$.

The expression of $\chi_1/\chi_0 - 1$ is not very telling (see (33) in appendix G.C). Let us instead consider the sensitivity of this expression to x, the recycling key of the carbon tax revenues (see equation (34) in appendix):

$$\frac{\partial\left(\frac{\chi_1}{\chi_0}-1\right)}{\partial x}.$$

The sign of this expression is independent of x. It is positive when the following condition (10) is met:

$$\varepsilon_r^X \eta_X (1+\varepsilon_p^X \eta_X t) < \varepsilon_r^E \eta_E (1+\varepsilon_p^E \eta_E t). \tag{10}$$

We can understand this equation as follows: emissions of E are more sensitive to new income that X. It takes into account the fact that the remaining share of consumption after carbon tax $(1+\varepsilon_p^E \eta_E t)$ and $(1+\varepsilon_p^X \eta_X t)$ might be different between the goods. A huge income elasticity or carbon intensity might no compensate the fact that there is little consumption to grow back. We will hereafter refer to these weighted income elasticities as "carbon income elasticities".

Then one euro recycled towards the energy-intensive household will increase emissions relatively more than if that euro is recycled towards the other household. More precisely, when the income effect for the energy good weighted by the carbon intensity η_E is greater than the income effect in the other good X also weighted by its carbon intensity η_X (10), then the growth rate of emissions reduction grows (positively) with x. That is, if the more the recycling of the carbon tax revenues is focused on the energy-intensive household, the less emissions decrease.

Skewed recycling mechanism The greatest risk of backfire is reached when the full carbon tax revenues is recycled towards the energy-intensive household P. Let us have a look at this situation where $x=1$ and the condition (10) is met.

The sign of growth rate of emissions (see (36) in appendix) depends on (11):

$$\varepsilon_p^E \eta_E t \chi_0^E + \varepsilon_p^X \eta_X t \chi_0^X + \chi_0 \left(\varepsilon_r^X \frac{X_0^P}{B_0^P} \eta_X t (1+\varepsilon_p^X \eta_X t) + \frac{E_0^P}{B_0^P} \varepsilon_r^E \eta_E t (1+\varepsilon_p^E \eta_E t) \right). \tag{11}$$

The two terms of the price effect ($\varepsilon_p^E < 0$, $\varepsilon_p^X < 0$) are negative, and the terms of the income effect are positive. The sign of the expression then depends on which effect prevails over the other, and there can be several combinations.

If we assume that $\varepsilon_r^X \eta_X (1+\varepsilon_p^X \eta_X t) < \varepsilon_r^E \eta_E (1+\varepsilon_p^E \eta_E t)$, it implies that emissions grow with x (note that we have maximised x: $x=1$). Then the relationships between the quantities consumed E_0^P and X_0^P and the price elasticities weighted by the elasticities and emissions at time 0, $\varepsilon_p^E \eta_E \chi_0^E$, and $\varepsilon_p^X \eta_X \chi_0^X$ govern the sign of the expression.

There are many possible combinations. Let us take one for example: if the energy is not very price elastic (less than X), it follows that:

$$\varepsilon_p^E \eta_E > \varepsilon_p^X \eta_X.$$

It means that energy goods (which are essential) are less elastic in emissions than other goods. Then, a backfire effect takes place if:

$$\varepsilon_r^X \eta_X (1+\varepsilon_p^X \eta_X t) \frac{X_0^P}{B_0^P} > -\chi_0^E \varepsilon_p^E \eta_E - \chi_0^X \varepsilon_p^X \eta_X,$$

which implies that the carbon income elasticities of X are greater than the carbon price elasticities of E and X.

We see two intertwined effects (whereas in the section 2.1, we only had one) that is the relationship between price and income elasticities, weighted by consumption — the energy intensity (E_0^P/X_0^P) of the budget of poor households — and aggregate consumption — in fact, aggregate carbon emissions per good (χ_0^E/χ_0^X).

We highlight a third backfire lever: very energy-intensive household consumption will facilitate the occurrence of a backfire effect. It is because the revenues collected are larger, meaning that the effects are potentially larger too. This lever obviously combines with the second, a large difference in carbon content between the two goods.

Conversely, even if the growth rate of emissions is decreasing with x, and we take $x=0$ (i.e. we give the full revenue back to the least energy-intensive household), then we can still have a backfire effect (see (37) in appendix G.C).

General recycling mechanism If we move from $x = 1$ to $\forall x$, then we highlight a fourth lever of the backfire: a recycling mechanism biased towards the most carbon-intensive household.

In the following expression of the growth rate of emissions (12), we can clearly see the four levers that are intertwined: the relations between elasticities, the energy intensity of both households (which drives the total emissions at time 0), and also the value of x. This last lever works through the terms in $x\chi_0$ and $(1-x)\chi_0$.

In all generality, we have:

$$\begin{aligned}
\frac{\chi_1}{\chi_0} - 1 = t\Big[&\chi_0^E \varepsilon_p^E \eta_E^2 + \eta_X^2 \chi_0^X \varepsilon_p^X \\
&+ \chi_0 \varepsilon_r^E \eta_E (1 + \varepsilon_p^E \eta_E t) \left((1-x)\frac{E_0^R}{B_0^R} + x\frac{E_0^P}{B_0^P} \right) \\
&+ \chi_0 \varepsilon_r^X \eta_X (1 + \varepsilon_p^X \eta_X t) \left((1-x)\frac{X_0^R}{B_0^R} + x\frac{X_0^R}{B_0^R} \right) \Big] / \\
&\Big[1 - \left(\frac{E_0^R}{B_0^R}(1-x) + x\frac{E_0^P}{B_0^P} \right) \varepsilon_r^E \eta_E t (1 + \varepsilon_p^E \eta_E t) \\
&- \left(x\frac{X_0^P}{B_0^P} + (1-x)\frac{X_0^R}{B_0^R} \right) \varepsilon_r^X \eta_X t (1 + \varepsilon_p^X \eta_X t)\chi_0 \Big].
\end{aligned} \tag{12}$$

The denominator of this expression is always positive to ensure the balance of the overall budget. The higher the income elasticities are, the closer to zero the denominator will be, and therefore the greater the multiplier effect on the backfire effect.

We can clearly see the four levers in the numerator: the interplay between income elasticities (i) is weighted by the energy (ii) and other goods intensities of each household (iii) and the share of revenues accruing to each of them (iv). This function can be rewritten to highlight the role played by energy intensity and the role of redistribution (13). Even if the income elasticity of E outweighs that of X, then it will still be weighted by the consumption structure of each household, and by the recycling mechanism with x.

$$\begin{aligned}
&t\Big[\chi_0^E \varepsilon_p^E \eta_E^2 + \eta_X^2 \chi_0^X \varepsilon_p^X \\
&+ \chi_0 (1-x) \left(\varepsilon_r^E \eta_E (1 + \varepsilon_p^E \eta_E t)\frac{E_0^R}{B_0^R} + \varepsilon_r^X \eta_X (1 + \varepsilon_p^X \eta_X t)\frac{X_0^R}{B_0^R} \right) \\
&+ \chi_0 x \left(\varepsilon_r^E \eta_E (1 + \varepsilon_p^E \eta_E t)\frac{E_0^P}{B_0^P} + \varepsilon_r^X \eta_X (1 + \varepsilon_p^X \eta_X t)\frac{X_0^P}{B_0^P} \right) \Big].
\end{aligned} \tag{13}$$

2.3 Heterogeneous preferences

Intuitively, and without complex calculations: if households have different elasticities, then we can add two levers favouring a backfire effect: (v) the most energy-intensive households are also the least price elastic and (vi) they are the most income elastic on energy goods.

The term

$$\chi_0 \varepsilon_r^E \eta_E (1 + \varepsilon_p^E \eta_E t) \left((1-x)\frac{E_0^R}{B_0^R} + x\frac{E_0^P}{B_0^P} \right)$$

becomes

$$\chi_0 \left((1-x)\varepsilon_r^{ER} \eta_E (1 + \varepsilon_r^{ER} \eta_E t)\frac{E_0^R}{B_0^R} + x\varepsilon_r^{EP} \eta_E (1 + \varepsilon_p^{EP} \eta_E t)\frac{E_0^P}{B_0^P} \right).$$

This gives even more possibilities for the levers to compensate each other to create a backfire: a high income elasticity or low price elasticity of the energy-intensive household (P) will be able to compensate for a more moderate energy intensity of consumption, or a low difference in carbon-intensities between goods.

Conversely, one can also imagine limiting the backfire effect by playing on the share of carbon tax revenues recycled towards households. If only a portion of the γ was redistributed to households, the terms of the income effect would be linearly weighted by $\gamma < 1$, which would reduce the chances of having a backfire effect.

If we suppose that part of the tax is paid by firms — and not only by households — with a pass-through lower than one, then the price of goods no longer increases by $\eta_E t$ but by $\sigma \eta_E t$ with $0 < \sigma < 1$. It is actually similar to having different carbon intensities but adds a new degree of freedom. Thus, the total amount paid by households and passed on would be lower but the different effects would be the same. However, if the pass-through coefficient were different for the two goods, then we would see yet another lever. If the pass-through coefficient of good X was lower than that of good E, then it would limit the transfer between the two goods, and the amount collected on X would be lower. But this would also increase the carbon intensity differential of consumption of goods X and E for the consumer. This lever would have ambiguous effects on emissions.

The more heterogeneity we add, i.e. more goods, more households with heterogeneous preferences and consumptions, the more we increase the number of combinations of parameters leading to a backfire effect.

From this compact "toy model", we can derive several conditions under which we risk having a backfire effect: the recycling of carbon tax revenues is targeted towards particularly carbon-intensive households. These households are relatively inelastic to the carbon tax on these polluting goods but very elastic on other less carbon-intensive goods, and most of the rebated income is devoted to carbon-intensive expenditure (the income elasticities of carbon-intensive goods are relatively higher than those of other goods).

3 Methods and Data

In this section, we apply the equations of section 2 to a consumer expenditures survey database to perform the microsimulation assessment of the potential backfire effect of a carbon tax and its recycling by lump-sum transfer to households. We first introduce the data (section 3.1) and the microsimulation framework (section 3.2).

We find in section 2 that the interplay of income and price elasticities drive the aggregate reduction in emissions. We will therefore need to estimate the price and income elasticities of households. We detail the methodology in section 3.3 and analyse the elasticities in section 4.

3.1 Data

Budget de Famille We use the French Consumer Expenditures Survey ("Budget de Famille") This survey has been carried out every 5 to 6 years since 1979 by the French public statistical institute INSEE. It contains self-reported data on households: socio-economic characteristics, sources of income and expenditures.

To estimate elasticities, we harmonise the Consumer Expenditures Survey from 1979 to 2010. We use the 2010 version to microsimulate the impacts of the carbon tax and recycling to households.

We build the database from the harmonisation of seven consecutive French Household Expenditures Surveys from 1978 to 2011 (1978-1979, 1984-1985, 1989, 1994-1995, 2000-2001, 2006, 2010-2011). Each survey consists of about 10000 households[10] that report their consumption for 7 days. Expenditures are classified in items compatible with the European nomenclature COICOP (Classification Of Individual Consumption Of Purpose). Households also report income since the 1994-95 survey. They indicate all types of resources: taxable income, social benefits, inter-household transfers, etc. According to socio-economics characteristics, each household is given a weight to ensure the representativeness of the sample by aggregation. We group expenditure items into 14 aggregates,[11] four of which energy products. It answers the objective of the study to describe households' behaviour when facing a carbon tax, particularly on energy consumption. We decide to include construction expenditures as a specific consumption item rather than as an

[10]Number of households per Consumer survey: 9403 (1979); 11 652 (1985); 8829 (1989); 9633 (1995); 10 305 (2001); 10 240 (2006); 10 342 (2010).

[11]Food, Electricity, Gas (natural and biogas), Other residential energy, Construction and construction services, First-hand vehicles, Vehicle fuels and lubricants, Rail and air transport, Road and water transport, Leisure services, Other services, Other consumption/equipment goods, Housing rents, Second-hand vehicles.

investment of the households following (Berry et al., 2016). This nomenclature is consistent over the seven successive surveys.

Prices We follow Clerc and Marcus (2009) and Ruiz and Trannoy (2008) to build individual price index for each household for the 14 goods. For each household, the 14 price indices are calculated by using a geometric mean of the price indices of the items of the INSEE database, weighted by the specific weights of each of these items in the 14 aggregated items.

Vulnerability types We assume that income influences demand through specific elasticities – both income and price – for income deciles, but also that non-income related characteristics such as the location (urban/rural), age, household composition, job, etc., can influence elasticities. Therefore, we divide each cross-section of data between 10 deciles of income (Sun and Ouyang 2016) and 4 types of households describing "economic vulnerability". We classify households from the 2010-2011 consumer survey in 4 vulnerability types using principal component analysis on two types of variables: income structure – in shares of wages, social benefits, capital income and others income – and shares of pre-committed expenditures in their budget (Quinet and Ferrari, 2008; Nadaud, 2021). A detailed analysis of the socio-economic characteristics of the vulnerability classes allows us to establish the following dominant profiles in each class (which does not mean that no other household belongs to the same type):

- Type I: Young working-class households who are tenants in large cities or Paris (medium income deciles);
- Type II: Isolated elderly households with low-income tenants in large cities;
- Type III: Working households with higher standards of living owning their homes in small towns;
- Type IV: Elderly households owning their homes in rural areas (low to medium income deciles).

We estimate for each year of the survey, the vulnerability type of each household (see (Nadaud, 2021) for all details).

Cells For the estimation of elasticities, the database is then composed of 40 household classes — a cell is an income decile crossed with a vulnerability type — at 7 years, which gives 280 cells. For each of these cells we aggregate income, expenses and prices.

Carbon intensity We use the database of Pottier et al. (2020), which estimates the carbon intensity of consumption from the French Household Expenditures Surveys 2010-2011. For each item in our nomenclature, we aggregate the carbon intensities of the goods that compose it with the aggregate structure of household consumption. We obtain carbon intensities (emissions per euro spent) for each of the 14 goods in our nomenclature common to all households (Appendix I.B).[12]

3.2 Microsimulation model

We focus on the distributional impacts of the carbon tax. We assume that the tax is fully passed through to consumers. The full-forward shifting of the tax is a standard assumption in the literature (Devulder and Lisack, 2020; Cronin et al., 2019; Metcalf et al., 2010; Owen and Barrett, 2020), because the relation between a specific market and the pass-through coefficient is ambiguous (Fullerton and Muehlegger, 2019). Newly empirical evidence points to a pass-through on only 70%

[12]The carbon footprint of electricity may seem surprisingly high considering the French energy mix which relies heavily on nuclear plants with low GHG emissions. This may be due to two reasons: some electricity and gas bills are inseparable, the split of Pottier et al. while legit may bias the real consumption; or the investments in electricity production bias the result. We study the impact of high carbon-intensity of electricity in appendix I.B.

of a carbon tax to consumers, reducing the welfare cost for households (Ganapati et al., 2020); nevertheless, they only provide estimates for a couple of industries.

The microsimulation is a 2-step process: the price effect of the carbon tax and the income effect of recycling the carbon tax revenues to households. The introduction of the carbon tax causes a rise in the price of each item j, for each household. Its consumption E_j^1 at time 1 is then to decrease to a level:

$$E_j^1 = E_j^0 \times \left(1 + \varepsilon_p^j \frac{\Delta p_j}{p_j}\right)\left(1 + \frac{\Delta p_j}{p_j}\right), \tag{14}$$

with the increase in price $\Delta p_j / p_j$ being equal to the carbon intensity of the expenditures multiplied by the level of the tax.

The lump-sum transfer S increase consumption at time 2 following:

$$E_j^2 = E_j^1 \times \left(1 + \varepsilon_r^j \frac{S}{\sum_j E_j^0}\right). \tag{15}$$

We assume constant saving rates for each household throughout the simulation. Since we have not computed price elasticities in a system and do not have cross-elasticities, we ensure the closure of the system by allocating surplus and shortfall of consumption on all other budget items using the estimated income elasticities. Our demand system is not far from being balanced and the closure procedure has little bearing on our results (see appendix H.C). It might introduce a small bias to close budget between the price and the income steps, but it is necessary since we then compare the magnitude of the two effects.

The ratio of net surplus S over total consumption is treated as extra-income (whether it is positive or negative). As previously, we iterate the process to ensure the closure of the system (the closure condition is that the aggregate consumption between the original database and the carbon tax budget of households should differ no more than 10^{-7}). To ensure convergence, we remove at each iteration the households with a ratio of net surplus over total consumption higher than 15%. The representativeness of the database is not affected, as these households represent less than 0.3% of the data.

We iterate to ensure the budget is balanced at the end of the 'price effect' step and the 'income effect' step. We finally iterate the whole process — including price and income effects — to ensure the full carbon tax collected it recycled to households. The lump-sum transfer increases household consumption, including that of taxed goods thus increasing the volume of carbon tax revenues. We ensure convergence at the 0.01% threshold (10^{-4}) between the collected and recycled carbon tax. The first two iterations are nested within this one.

3.3 Estimating elasticities

We estimate price and income elasticities for the 14 items defined in our nomenclature using the Linear-Approximate Almost Ideal Demand System – LAIDS (Green and Alston, 1990; Buse, 1994). LAIDS is an approximation of the Almost Ideal Demand System (AIDS) model developed by Deaton and Muellbauer (1980). It is a flexible expression of the Engel curve using the linear Stone price index (16) which allows for harmonious aggregation over consumers (Irfan et al., 2018; Labandeira et al., 2017). LAIDS is widely used for empirical studies, see for instance Armagan and Akbay (2008); Piggott and Marsh (2004) and especially for energy demand (Sommer and Kratena, 2017; Sun and Ouyang, 2016; Ngui et al., 2011; Gundimeda and Köhlin, 2008). We follow Pawlowski and Breuer (2012) to add dimensions beyond price and income in the estimation. Non-income dimensions can represent supply-based opportunities, that is, the more or less difficult access to alternatives and substitution. For example, the price elasticity of gasoline depends on the availability of public transport services, it depends on location and not income.

For each of the 280 cells, we carry out a principal component analysis (PCA) of a certain number of quantitative variables: the type of household, the sex, the age of the reference person in seven groups, the occupation of the reference person, the occupation status of the dwelling, the population stratum of the household's residence, the region (ZEAT, Zone d'Études et d'Aménagement du Territoire), the year of construction of the main residence, the number of vehicles, whether the household is poor and lives below the thresholds of 50% and 60% of the median living standard (income based on the OECD equivalence scale). We perform a PCA for each cell for all variables. We retain the first five principal components as $(\gamma_k)_k$.

The Stone Price index P^* is expressed as

$$\log(P^*) = \sum_{i=1}^{14} w_i \log(P_i), \tag{16}$$

with w_i the budget share of the item i and P_i the price index of item i.

For each of the 280 cells[13] of our database which are the 40 classes of households over 7 surveys, we estimate the following Engel curve (17) which relates budget share w_i to the logarithms aggregated real expenditure of item i of the cell — nominal expenditures E_i deflated by the Stone Price index P^* — the item price P_i. e_i is the regression residual for item i equation. We add five socio-economic characteristics of the cell $(\gamma_k)_k$.

Importantly, we do only include the price of item i in the Engel curve when it is customary to include all the prices to estimate cross-impact. The reason is that the prices of the 14 goods are too correlated. Yet, the imputation of household-specific price indices introduces variability in prices. Moreover, the use of cross-sectional cells over a 30-year period reveals substitution between goods.

$$w_i = a_i + b_i t + c_i \log\left(\frac{E_i}{P^*}\right) + d_i \log(P_i) + \sum_{k=1}^{5} \gamma_k + e_i. \tag{17}$$

We define the price and income elasticities, respectively $e_{E_i X}$ and $e_{E_i P_i}$ for each good i with respect to each cell expenditure E_i, the average household income X and the price of this good P_i.

$$\begin{aligned} e_{E_i P_i} &= \frac{\partial E_i}{\partial P_i}\frac{P_i}{E_i} \\ e_{E_i X} &= \frac{\partial E_i}{\partial X}\frac{X}{E_i} \end{aligned} \tag{18}$$

For each item i, we derive the income and price elasticities as functions of the estimated parameters a_i, b_i, c_i and d_i. In this specification, the coefficients are interpreted as semi-elasticities of the budget share to real expenditure (X/P) and to price. Uncompensated elasticities for income and price are respectively (see appendix H.A):

$$\begin{aligned} e_{E_i P_i} &= \frac{d_i}{w_i} - c_i \\ e_{E_i X} &= 1 + \frac{c_i}{w_i} \end{aligned} \tag{19}$$

Budget shares appear on both sides of the equation (17) within E_i/P^*. We solve this simultaneity issue using instrumental variables and two-stages least square method (Colonescu, 2016). In the first step, we use the real standard of living (income deflated by the number of consumption units of the cell, as per the OECD equivalence scale) as an instrument of the total nominal expenditure of the cell to approach budget shares $\hat{w_i}$. In the second step, we regress the Engel curve equation on $\hat{w_i}$ instead of w_i. As expected, the two variables are closely correlated and the instrumentation is strong for all cells.

We check for collinearity in the estimation model using the variance inflation factors (James et al., 2013) and the Besley, Kuh and Welsh (BKW) condition index test (Belsley, 1980; Silvey, 1969). In case of high collinearity, we drop the socio-economic variable $(\gamma_k)_k$ which adds more collinearity (step-wise selection).

It is not possible to estimate the equation for every 40 cells for the elasticities of domestic fuels - other than natural gas - and rents. The variability between prices and expenses across time is not high enough: we estimate these elasticities on the 10 income deciles.[14]

[13]We cannot call it a pseudo-panel since we do not follow cohorts in time. In pseudo-panels, these cohorts are agents identified by a number of variables stable over time (age, gender, degree) which form cells. The assumption is that one can track the cell in consecutive surveys.

[14]The aggregation on deciles only leads us to divide the size of our sample by 4, from 280 observations (deciles x classes x years) to 70 (deciles x years). The precision of our estimate, which evolves by construction as the square of the sample size, was thus divided by two.

4 Elasticities Estimates

Most of our elasticities are significant at the 1% threshold (Table H.1 in appendix H.B).[15] Income elasticities are generally more significant than price elasticities. Indeed, in budget surveys, expenditures are well observed but not the real prices faced by households; that is why we build price series for each household (see section 3.1). Only three expenditure items are weakly significant at 10%: the price elasticity of second-hand vehicles, the income elasticity of domestic fuels other than gas and that of rents. The price elasticities of domestic fuels other than gas and both the income and price elasticities of transport services are significant at the 20% threshold. We perform an uncertainty analysis in the next section (see section I.A) to assess the validity of the whole set of 1120 elasticities.

Despite not being estimated in systems because we do not estimate cross-elasticities, our estimates of elasticities form a quasi-consistent system (see H.C).

Low long-term price elasticities characterise essential expenditure items. All household classes have a price elasticity between -0.5 and 0 for food, natural gas, gasoline, leisure goods, services, and other goods. Conversely, electricity, transport services (air & rail or water & road) and especially new vehicle purchases are characterised by more variability in price elasticity across households (Figure 1).

For instance, middle-income groups are more dependent on natural gas and gasoline than low and high-income groups: price elasticities are U-shaped across income deciles. Blundell et al. (2012) also finds that price elasticities for gasoline are lower for low- and high-income deciles than for middle-income households. We find that low-income households are dependent on agricultural goods, electricity, other energy, services and rents as price elasticities increase in absolute value towards the richer deciles. That is, poorer households have lower price elasticities for electricity and domestic fuels than richer households. Other expenditure items - construction, new vehicles, leisure or other consumer goods – allows the poorer household to close their budget as they show higher price elasticities than richer households.

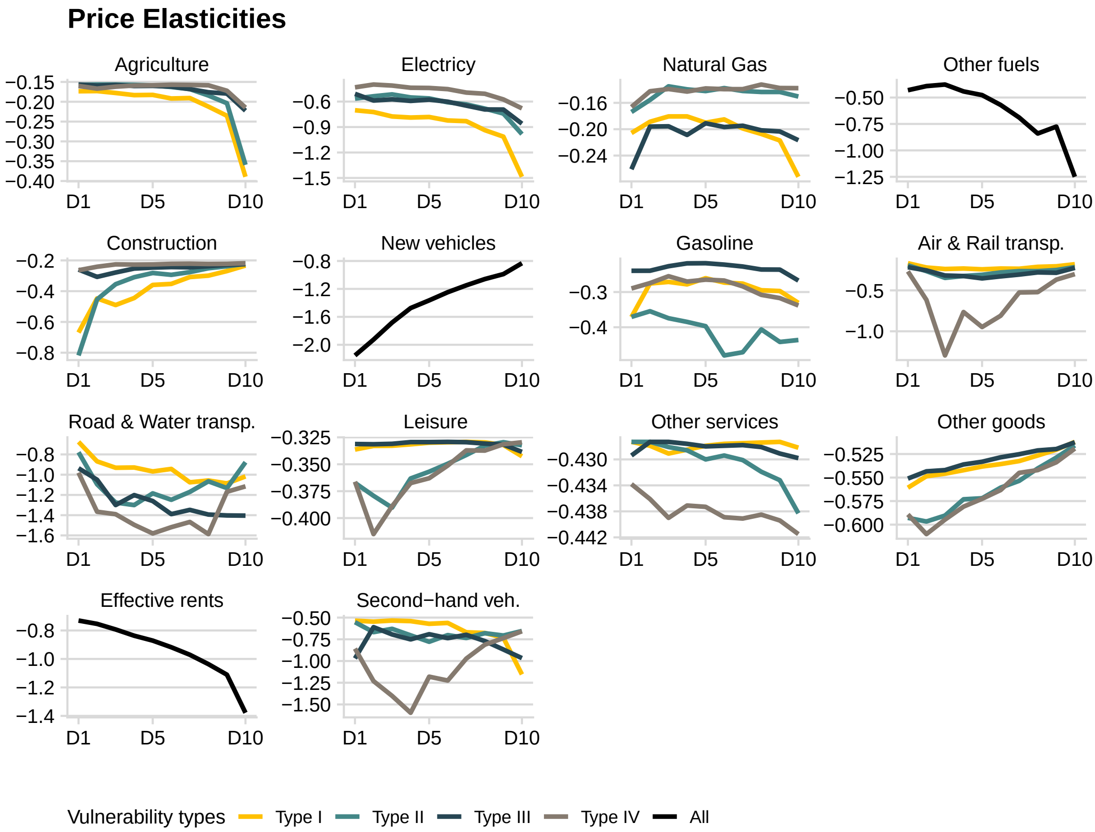
Our estimates concur with those of Gardes (2014) and Gardes and Starzec (2018) on the same database using other methods. The meta-analysis of Labandeira et al. (2017) finds central values to be -0.600 for energy, -0.677 for electricity, -0.614 for natural gas, and -0.720 for gasoline. We have much lower estimates (in absolute values) for gasoline and natural gas, but more negative estimates for electricity. It might be because we estimate long-term elasticities, Deryugina et al. (2020) finds that the price elasticity for electricity is larger in the long run than in the short term.

Price elasticities are in general, not linearly related to income (Figure 1). Their profiles along income illustrate the essential goods for each group. On the contrary, profiles of income elasticities across income are more similar to each other (Figure 2): D1 and D10 have similar values, while there is a decreasing trend from D2 to D9. These results echo the long-term elasticities in Clerc and Marcus (2009).

We find that urban dwellers — mostly represented in vulnerability types I and II — have a more elastic demand for gasoline than rural households. For instance, type I households — mostly young tenants living in large cities — in all income deciles have lower income elasticities than all other classes but also display a more negative price elasticity. Differences between urban and rural households — represented respectively by types I-II and III-IV — are particularly significant for extreme income deciles. Low-income urban dwellers show a higher price elasticity for building than the other two types; similarly, the richest urban dwellers have highly elastic demands for food and electricity. In terms of transport, older urban dwellers type II show, unsurprisingly, less dependence on fuel, with a price elasticity for this good higher than the other types. Rural and elderly (type IV) middle-class households show a high elasticity of demand for transport, second-hand vehicles and services. The poorest (D1-D2) and richest (D9-D10) rural and elderly households (type IV) have average behaviour regarding these items. The divide is not only territorial between urban and rural areas but also generational: older households — mostly represented in types II and IV — show a lesser need for leisure and communication goods, especially among the less well-off (up

[15] Elasticities are computed as a non-linear function of coefficients of the Engel curve and approximated budget share ($\hat{w_i}$). Therefore the standard errors of income and price elasticities are not easily computed. We approximate the variance of the elasticities using the delta method —- that is a Taylor series approximation of the variance of functions of random variables (Casella and Berger, 2002; Colonescu, 2016) — see appendix H.B.

Figure 1: Long-term price elasticities of French households by decile and vulnerability type



to D8), this is also the case for "other consumption goods". Conversely, younger households — types I and III — have more elastic demands for energy but not for services. Studies based on French consumer surveys show that price elasticities vary greatly depending on income (Douenne, 2020) but also on other socio-economic variables (age group, urban or rural location, etc.) (Calvet and Marical, 2011).

We are the first to estimate price and income elasticities on as many goods and households. Our method has advantages and drawbacks. The main advantage is that we differentiate between carbon-intensive and low-carbon goods, and especially between energy goods. It allows for the proposed microsimulation and the estimation of the backfire effect. Two main drawbacks are that we are unable to estimate cross elasticities, and we cannot control for the endogeneity of prices and quantities in time. To estimate reliable elasticities, one needs an exogenous shock, as in Deryugina et al. (2020) that exploits a change in the choice of electricity provider and the negotiation of new contracts (and new prices) town by town in the US. We also do not differentiate between price and tax elasticity. It might have importance, as Andersson (2019) finds carbon tax elasticity of gasoline is three times larger than the price elasticity of gasoline in Sweden.

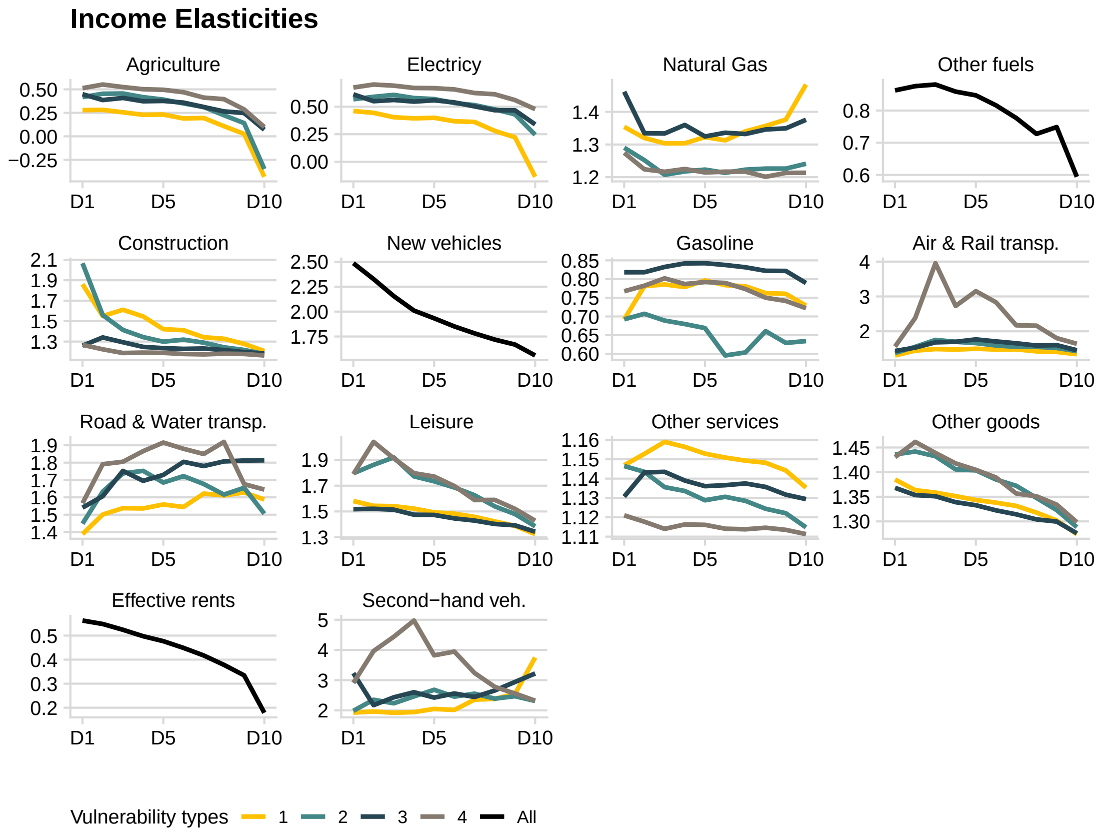
5 Microsimulation and application to the French carbon tax

5.1 Price signal: distribution of the decrease in emissions

A 158€/tCO_2 carbon tax[16] — covering both direct and indirect emissions — decreases aggregate households' emissions by 10.9%. It plays on three levers: the decrease in consumption of carbon-intensive goods (the so-called sufficiency), the substitution of other goods to carbon-intensive

[16] Level of carbon tax in 2025, since abandoned.

Figure 2: Long-term income elasticities of French households by decile and vulnerability type



goods,[17] and energy efficiency since the long-term elasticities encapsulate the past trends in energy efficiency when energy prices have risen.[18] Since we do not have a general equilibrium model, we neglect the use of revenues collected by the government outside of direct revenue recycling to households in the form of lump-sum transfers. In this section 5.1 we assume that the use of the revenues levied are not carbon-emitting.

Prior to any compensation mechanism, carbon pricing is regressive when applied on both direct and indirect emissions of households: it weights disproportionally on poorest households as they dedicate a more important share or income to carbon-intensive items (Figure 3). The first income decile D1 — the bottom 10% of the income distribution according to the OECD equivalence scale[19] — dedicates 9.2% of their income to carbon tax, and 5.7% of their total expenditures whereas the top income income decile D10 dedicates 3.0% of their income and 4.7% of their expenditures to carbon tax.

We show that regressivity is clear when carbon tax is compared against income: the share of income dedicated to carbon tax decreases with each income decile. When compared against total expenditures, the carbon tax is only regressive from D5 to D10 since the first half of the income distribution dedicates between 5.7 and 5.9% of their total expenditures to carbon tax. As Pottier (2022) explains, we know that the saving rate increases with income. Hence, an increase

[17] Although we do not have cross-elasticities in our model, the historical trends provided by the use of several consumer expenditures survey encapsulate some of the substitutions.

[18] Long-term elasticities capture a number of effects, including fuel-efficiency trends or behavioural change. A small increase in gasoline prices over time may be characterised by a high gasoline elasticity, which reflects the continued improvement in vehicle consumption. But households have also increased their mobility needs over the same period which may counteract the previous overestimation of elasticity. Calvet and Marical (2011) estimates gasoline elasticities, taking into account the improvement in vehicle consumption over 20 years. They use the price of the fuel required to drive 100km and not the price per litre.

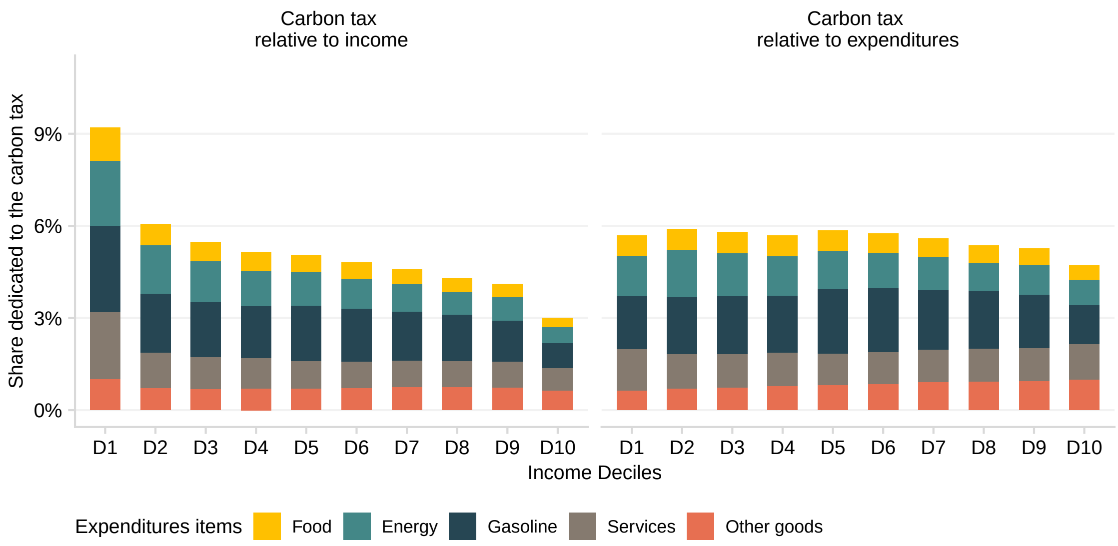
[19] It OECD scale represents the number of consumption units of the households: one share for the first adult, half a share for each subsequent adult, 0.3 per child.

in income triggers a lesser increase in expenditure and thus in carbon footprint. We can conclude that the carbon tax burdens more the low-income households relative to both their income and total expenditures.

Feindt et al. (2021) finds that the carbon tax may be slightly progressive in a number of countries when considering the full carbon footprint of households. In the US Metcalf (2019); Cronin et al. (2019); Hassett et al. (2009) find the carbon tax to be progressive. Fremstad and Paul (2019) find that the carbon tax without recycling is regressive when compared against both income and expenditures.

The heterogeneity in preferences increases the regressivity of the carbon tax since low-income households have lower price elasticities for the most polluting goods (except natural gas, but the gradient across deciles is small) compared to higher income households.

Figure 3: Relative weight of carbon pricing for households



Note: In the left-hand panel the aggregate volume of carbon tax paid by each income decile is compared to the aggregate disposable income, in the right-hand panel the volume of carbon tax is compared to the volume of total consumption. The difference is savings or debt.

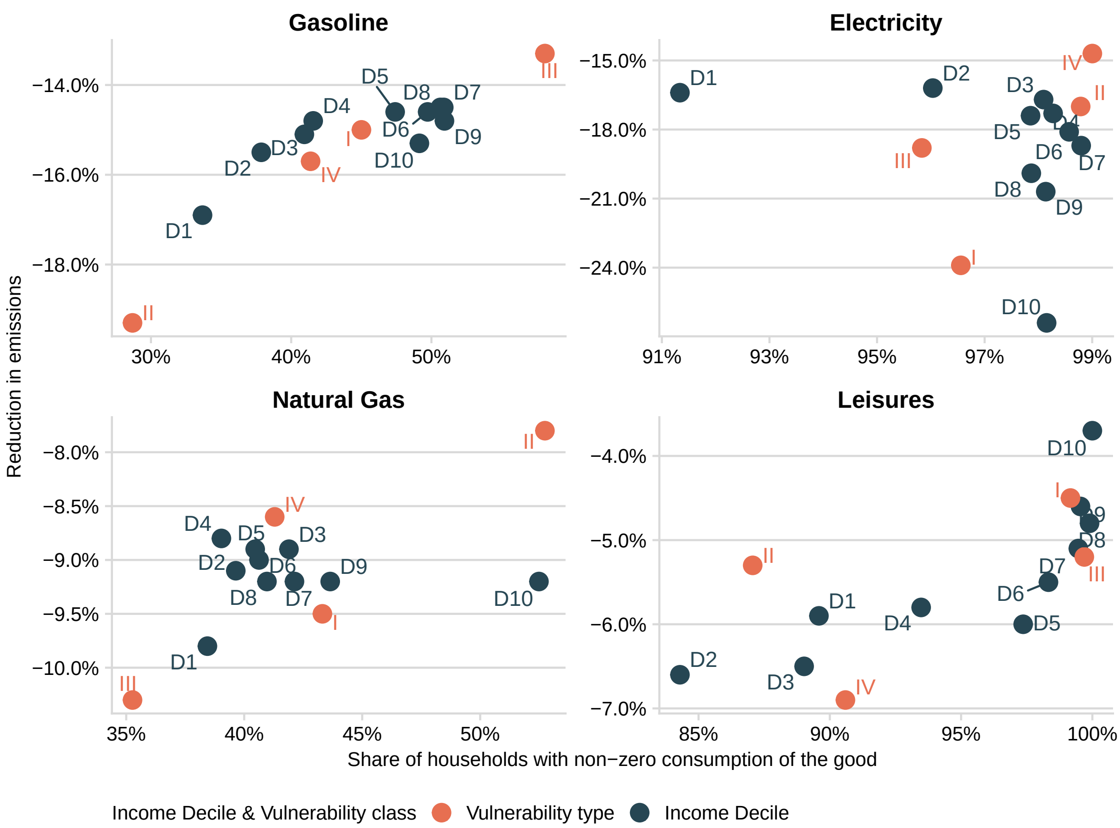
The main share of carbon tax comes from fuel and energy bills for all income deciles. But the weight of these two items and of food decreases with income. This drives the regressivity of carbon pricing. We demonstrate the assumption in section 2 that low-income households are also the most energy-intensive. It will therefore be necessary to compensate the poorest households (which we translated with x close to 1 in the theoretical model, section 2), which increases the risk of backfire. These are the largest emissions items, but they are also the ones on which households are making the greatest effort, reducing their fuel-related emissions by 14% to 17% (compared to an average of 10.9%).

The effort to reduce emissions is not homogeneous between households. Figure 4 plots the decrease in emissions for an item due to the carbon pricing against the share of households with non-zero expenses for that item. Zero fuel expenditure may indicate that a household does not own a car (this is the case for 19% of households on average, but 41.1% of D1, and only 8.8% of D9 and 10.6% of D10) or that they did not fill their tanks during the survey expenditure collection period.[20] D1 households have paradoxically the lowest number of gasoline consumers and are the

[20]Respondents typically complete their shopping diaries over one or two weeks depending on the goods. For some goods this may lead to some variability if purchases are made less frequently than the response period. For summing up the expenditure this does not have so much impact as it averages the expenditure over large categories, overestimating the consumption of one household and overestimating that of the other. On a large enough sample the average consumption is quite correct. If a household consumes about €50 of fuel every week but only refills every fortnight, then a one-week survey will give a correct estimate of the aggregate consumption per week, i.e.

most impacted in terms of budget share[21] and consumption reduction. Middle-income classes (D2-D8) are more fuel dependent than extreme deciles, hence a smaller reduction in real consumption of gasoline. Unsurprisingly, they were dominant in the Yellow Vests events in France in 2018 (Delpirou, 2018). Conversely, D1 electricity demand is relatively inelastic in price compared to high-income deciles - price elasticity is -1.032 for D10 against -0.56 for D1 and D2. Consumption of natural gas is more homogeneous. Unsurprisingly, as with gasoline, low-income households (D1-D3) already consume less leisure than other households (only 85-90% report leisure expenditure compared to 100% for households D7-D10) and would make a reduction of nearly 6% in this item of expenditure due to the carbon tax (although leisure goods are by far the least carbon intensive of all).

Figure 4: Vertical and horizontal heterogeneity of emission reduction and user distribution



Note: The four vulnerability types are used in the estimation of elasticities. We have highlighted the most represented characteristics profile for each type: Type I: Young working class households tenants in large cities or in Paris (medium income deciles); Type II: isolated elderly households with low-income tenants in large cities; Type III: Working households with higher standards of living owning their homes in small towns; Type IV: elderly households owning their home in rural areas (low to medium income deciles).

€100. If we want to estimate the share of households experiencing backfire or being compensated for the carbon tax paid then we risk overestimating the backfire if both households are given the same lump-sum transfer. The first household, which is heavily taxed because it is a large consumer, will nevertheless reduce its consumption, but this will not be compensated by the lump-sum. Conversely, we consider that the second household does not consume any petrol and that part of the cash transfer will be spent on fuel. So we will consider that 50% of the sample will increase the emissions linked to fuel whereas, compared to their actual weekly consumption, it is possible that either they both increase their fuel emissions or they both decrease it. To reassure ourselves that our estimate is nonetheless accurate we need more assumptions: the frequency of purchase of carbon-intensive goods is higher than the duration of the survey, an average can be made on other carbon purchases, the behaviour of the poorest will be lower and more regular purchases. For electricity and gas consumption, annual or monthly bills are collected during the survey.

[21] 9.8% of expenditures for D1 household with non-zero fuel bills and 5.4% for D1 households owning a vehicle.

Our analysis highlights the impact of the carbon tax across households' characteristics that are not income. Variability between types of vulnerability — created as an artefact of elasticities estimation (see section 2.2) —- is greater than the variability between income deciles. As expected, type III households (dominated by urban working households) show high dependency on gasoline but large reduction in natural gas consumption. Conversely, type II households (low-income urban elderly households) favour heating over mobility and leisure, which translates in low reduction in natural gas and electricity but high reduction in gasoline.

Long-term price and income elasticities approximate the reaction of households to carbon price. Adaptation can be of three kinds: i) a reduction in consumption by reducing waste, ii) investment in more energy-efficient appliances or dwellings, iii) or deprivation resulting in a loss of comfort. Similar studies undergone on French population at the same date (2010-2011) show that low-income households are already in a situation of deprivation of energy for space heating (Cayla et al., 2010). Low-income households are found among those most willing to reduce energy consumption but declare that they cannot invest in energy-efficient equipment that would allow them to decrease energy bills (Cayla et al., 2011; Bartiaux, 2006). Poorest households are particularly constrained in their access to capital, which is economically translated as high discount rate for energy efficient investment (Jaffe and Stavins, 1994). Therefore, it seems reasonable to conclude that the significant decrease in real energy consumption undergone by the first income deciles is mainly deprivation rather than investment in energy-efficient appliances.

From this section, we may draw two conclusions. Firstly, we conclude that carbon taxation is regressive in France. Despite limitations in our microsimulation — namely the absence of input-output model to compute the prices taking into account the production sector structure — it appears essential to couple carbon taxation with an appropriate redistribution policy. Secondly, the heterogeneity of carbon-intensive consumption will make the targeting of the carbon tax revenues recycling mechanism all the more important. If policymakers want to compensate each and every household in the first income decile, they would have to over-compensate the non-gasoline consumer in order to compensate the burdened households. It would likely trigger a large backfire effect for these households.

5.2 Between income and backfire effects

In this section, we present the consequences of the recycling of carbon tax revenues in the form of an equal per capita lump-sum transfer.[22] The overall reduction in emissions is of 5.9%, to be compared to the fall of 10.9% when we supposed the absence of recycling. We conclude that there is no full backfire effect, in the sense that a lump-sum rebated carbon tax still allows for a decrease in emissions.

We detail how households use this additional income. We test alternative recycling mechanisms and the robustness of this result in the next section.

5.2.1 Distribution of the income effect

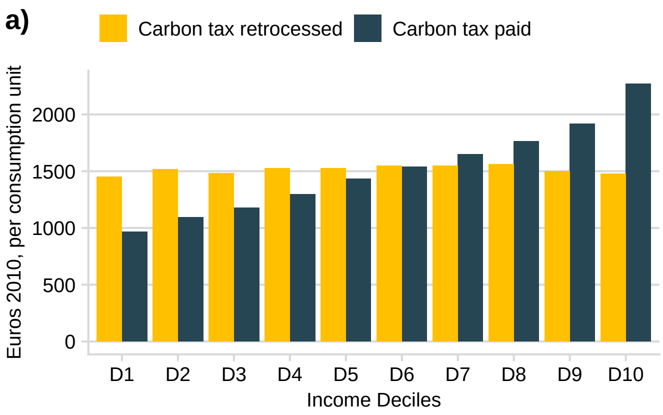
The carbon tax is made strongly progressive by an equal per capita lump-sum transfer since it benefits more the poorest households in proportion to their income. Because income inequalities are greater than inequalities in emissions, the transfer offsets the regressivity of the carbon tax. The lump-sum per capita of the carbon tax of 158€/tCO_2 amounts to 985€ per consumption unit (constant 2010 euros), i.e. an average extra income of 3.1%. It represents an extra-income of 10.2% for the D1 and 1.3% for the D10. On average, the carbon tax benefits households below the median wage (D1-D5) who are compensated more than they pay in carbon tax. Again, the situation is heterogeneous, with the lump-sum compensating only 72% of D1-D5 households, ranging from 82.4% of D1 to 62.2% of D5 (Figure 5).[23]

Figure 6 shows how the increase and decrease of emissions (and therefore real consumption) are distributed among goods. All households mainly use the revenue from the carbon tax to buy back

[22] It is more precisely per consumption unit lump-sum transfer, adapted with the OECD equivalence scale to take into account the size of the household, but we call hereafter per-capita transfer.

[23] We shall bear in mind that the 18% of D1 households who pay more carbon tax than the rebate may be households that have made a large expenditure of carbon goods (e.g. a significant refuel of gasoline) in the data collection period).

Figure 5: Distribution of rebates among households



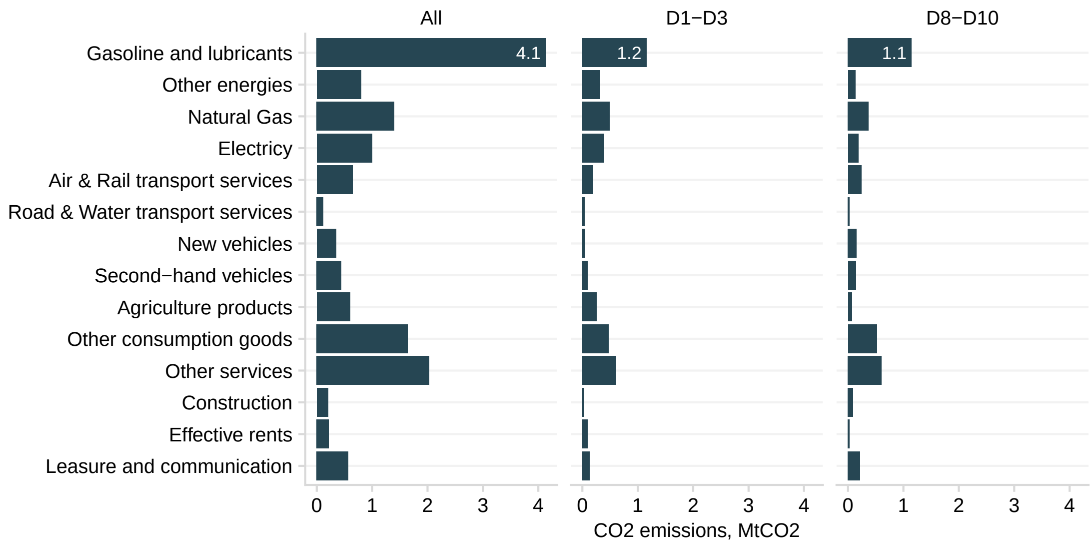
b)

Income Decile	Overcompensated households
1	82.4%
2	77.9%
3	72.6%
4	69.9%
5	62.2%
6	56.8%
7	51.7%
8	50.8%
9	39.1%
10	29%

Note: (a) Carbon tax rebate and carbon tax bills aggregated per income decile and (b) the share or households for which the rebate compensates at least the carbon tax they are paying, which mean they are "over-compensated".

some of the gasoline they renounced because of the tax. The poorest households, D1-D3, use the lump-sum rebate to increase their energy consumption, including electricity. Their consumption of natural gas even exceeds the pre-tax level. They also increase their spending on food, leisure and other goods and services (composite goods). In contrast, wealthier households, D8-D10, spend less of their lump-sum rebate on food and energy (and almost none on electricity). However, they also increase their consumptions of leisure and other goods and services. All households increase their consumptions of rail and air transport services (these expenditures are aggregated, which is a limitation of the nomenclature because their carbon footprints are very different although they are quite similar in purpose). These results reflect quite directly the profile of income elasticities presented in section 4: income elasticities for food and electricity fall for high incomes, and are relatively stable and high for composite goods, recreation, travel and gasoline.

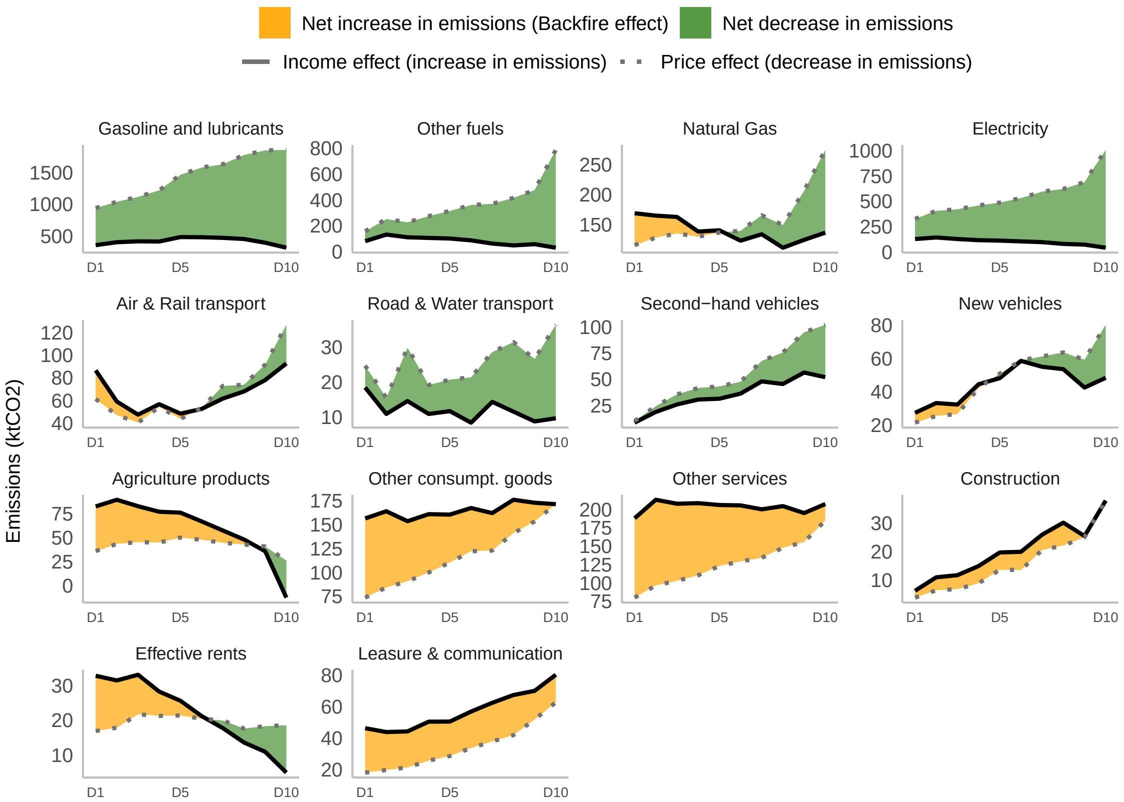
Figure 6: Distribution of the lump-sum transfer per item



5.2.2 Backfire effect

Aggregate emissions are reduced by the tax even when accounting for the income effect of recycling carbon tax revenues. The allocation of a large share of the recycling revenues to gasoline does not fully offset the impact of the price signal. Figure 7 compares the price and the income effects for all items and income deciles. A backfire — i.e. a volume of emissions that exceeds the pre-tax level — arises when the income effect offsets the price effect (yellow area). With the exception of natural gas, whose consumption increases for the first half of the income distribution, the items for which there is a backfire are the least carbon-intensive items. The backfire magnitude decreases with income, it disappears at D5 for air and rail transport, new vehicles, food and rent.

Figure 7: Price and income effects per item and income decile



The reduction of aggregate emissions is largely borne by high income deciles, both in volume (Figure 7) and relative to pre-tax emissions (Figure 8). Figure 8 represents the reduction in emissions due to the signal against the increase due to the income effect for the 14 goods of 40 classes of households (income deciles × vulnerability type). Any point higher than the black diagonal line indicates a backfire effect for a specific item. Adding horizontal heterogeneity of preferences, we find a stronger backfire effect for low- and middle-income households. However, the main message remains: the backfire is mostly located on low carbon-intensive goods and for households below the median income. D8-D10 households reduce their gasoline consumptions by almost 40% while the income effect is only about 3%. The level of consumption of the high-income — even the urban rich — is high enough that the income effect is insufficient to create a backfire on the most polluting goods.

Aggregate emissions decrease by 5.9% but D1 only reduces its emissions by 3.0% and D10 by 8.2%. About half (54%) of the D1 households experience a backfire effect and increase their emissions relative to pre-tax levels, when it is only the case for 10.3% of D9 and 3.5% of D10 households (Figure 9). The latter households are mostly city dwellers and single households.[24]

[24] A possible explanation for D10 households with emissions low enough that they experience a backfire would be

Figure 8: Price and income effects of consumption over the 40 cells of households (income deciles × vulnerability types) for the 14 goods and services of the frameworks represented by their carbon intensity

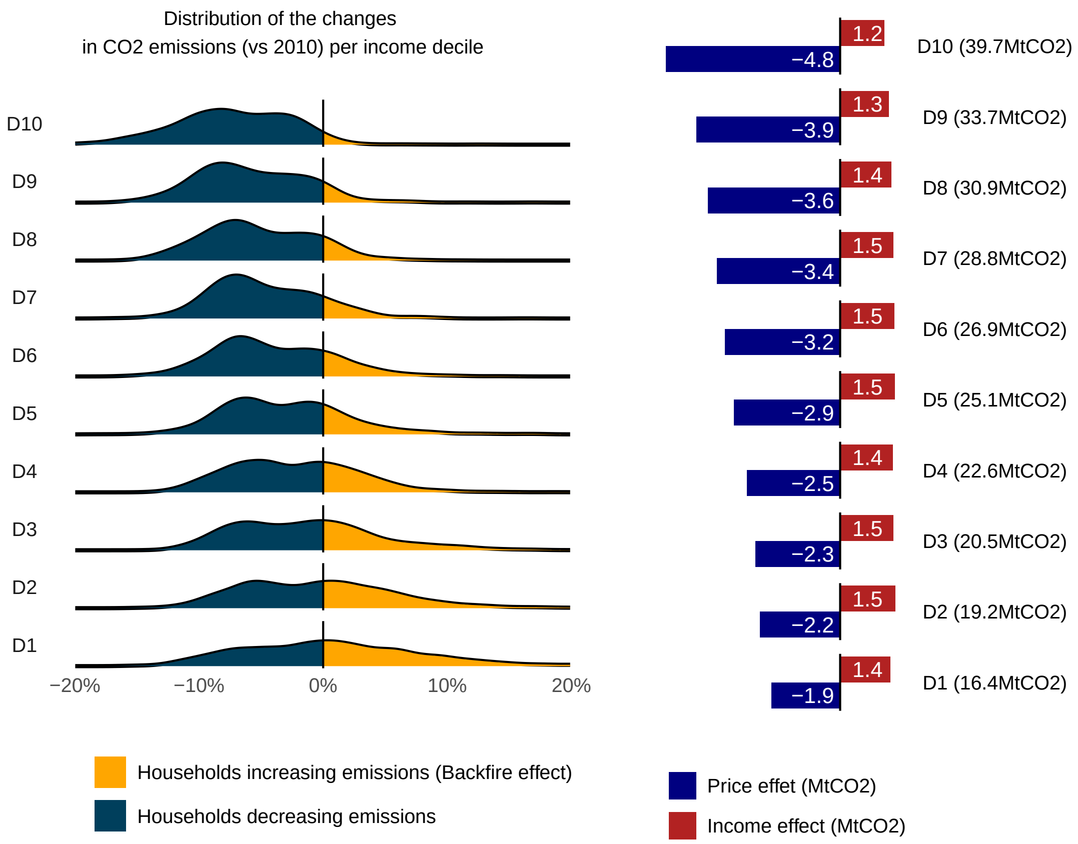
Note: For each of 14 goods, the decrease in real consumption due to the carbon tax ("Price effect") is compared to the increase in consumption following the lump-sum transfer. Both variations are vis-à-vis no-policy consumption. Hence, a backfire effect exactly compensating the price effect would be situated in the black line. All points above this line are increased consumption due to the carbon tax and its recycling. Size of point indicates the carbon intensity of the particular good.

Overall, about 25% of households increase their emissions after the tax and its recycling, mainly in D1-D5 households. Income effect for D1 represents 1.4MtCO_2 (Figure 9), which amounts to 3.5% of D10 emissions after tax and recycling. The whole D1-D3 income effect (4.4 MtCO_2) only weighs 11% of D10 emissions. We already have the intuition — before testing it in the next section — that the way to increase the effectiveness of the tax without compromising fairness is not to reduce the income effect of the poorest but to increase the effort of the richest.

Figure 10 crosses income with other horizontal dimensions and shows for each cell the share of households experiencing a backfire effect. Households whose emissions increase compared to pre-tax levels, beyond the key dimension of income, are always the most urban and the oldest. This makes them the most fuel elastic as they have access to better public transport and in the case of retired households have little forced mobility because they escape daily commuting. The influence of vulnerability type varies with income. Type II (urban elderly) contains significantly more backfire households for D3-D8 than other types. It is not the case for extreme income deciles. Similarly, single households stand out from D3 onwards, while they compare with single-parent families and old couples for D1-D2.

that these households have only *seasonally* low emissions. BDF addresses the seasonality issue by conducting its survey in 6 waves spread over 12 months. Backfire households are not significantly more present in any of the 6 survey waves. See Figure I.5, appendix I.C.

Figure 9: Carbon tax and recycling: backfire of CO_2 emissions per income decile



Source: Authors calculations. Reading: Almost half of the households in D1 increase their emissions after the introduction of the tax and its recycling by equal per capita lump-sum transfer: there is a backfire effect. But for D1 the increase in emissions due to the recycling amounts to 1.4 $MtCO_2$, that is, 3.5% of the emissions of D10. The optimal solution is to focus the recycling on the first deciles. Comments: The first panel represents the distributional density of household emissions increases or decreases relative to 2010 broken down by income deciles. The densities are adjusted to the number of households represented. The second panel represents the change in aggregate emissions of the decile due to the price signal of the tax and the income effect of the recycling of the carbon tax revenues.

5.3 Extensions

In this section, we extend the previous work in several directions and test for more policy designs.

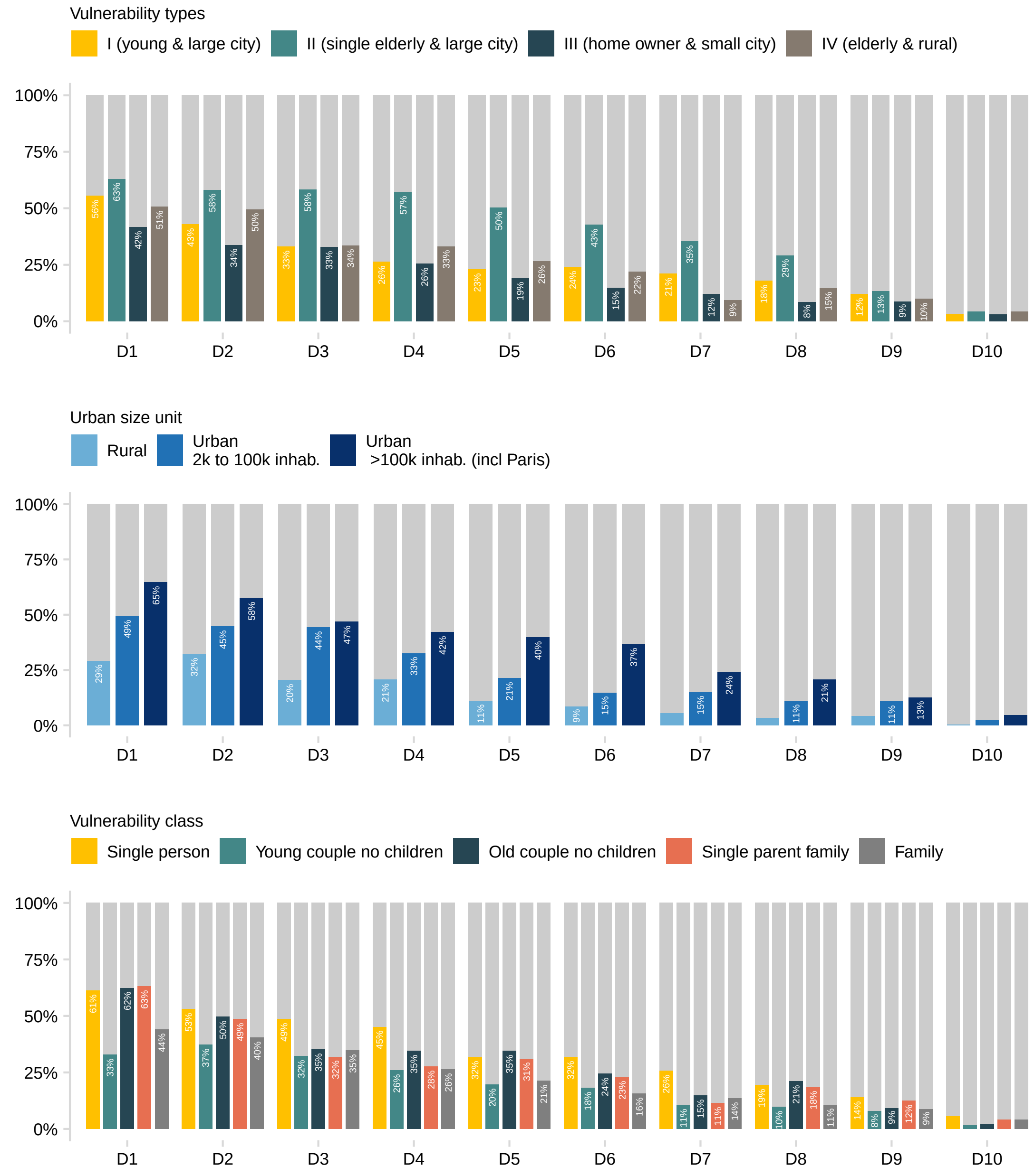
5.3.1 Increasing the carbon price

We compute the reduction in emissions for several values of the carbon tax. Final emission reductions versus 2010 — including the recycling of carbon tax revenues on an equal per capita lump-sum transfer — are almost linearly related to the value of the carbon tax. Nevertheless, the magnitude of the backfire effect decreases as the carbon tax increases (Table 1). At 158€/tCO_2 a little less than half of the decrease in emissions due to the price signal is offset by the income effect. The proportion is only 25% for a 1000€/tCO_2 tax. The ratio of emissions reduction after and before the rebate increases with the price of carbon. It means that the full taxation & recycling mechanism is more and more effective as the policy is more ambitious.

5.3.2 Homogenising preferences

We run several simulations where we assume greater homogeneity of preferences of households. We test for the absence of vertical heterogeneity, by allowing all households to react using the

Figure 10: Share of households experiencing a backfire effect in emissions per income decile and another horizontal dimension



Note: Share of households with a backfire effect. Values below 6% do not appear on the graph.

elasticities of the D10, according to their vulnerability type, *as if they were rich*. The overall reduction in emissions would then be -8.2%, that is 2.3pts lower than the simulation with full heterogeneity of preferences. Table 2 summarises the reduction if each income deciles preferences were to be applied to all households. Without surprise, D10 preferences are those allowing the largest emissions reduction due to high price elasticities. The behaviour of the low- and middle-income deciles drive emissions up compared to the baseline.

If everyone acted like a D1 household, there would be little difference on aggregate emissions because two mechanisms would compensate each other: the middle classes (D2-D7) which have lower price elasticities in absolute terms would reduce their emissions more, but the richest, who

Table 1: Impact of the carbon price on the reduction of emissions

Carbon price (€/tCO2)	Price signal (emissions vs 2010) (A)	Price & income effects (emissions vs 2010) (B)	Partial backfire (ratio of the two effects) (B/A-1)
10	-0.7%	-0.4%	-47.1%
50	-3.7%	-1.9%	-47.0%
100	-7.1%	-3.8%	-46.6%
150	-10.4%	-5.6%	-46.2%
200	-13.6%	-7.4%	-45.7%
300	-19.5%	-10.8%	-44.6%
400	-25.0%	-14.3%	-43.0%
500	-30.2%	-17.8%	-41.0%
750	-42.0%	-27.5%	-34.6%
1000	-53.0%	-39.0%	-26.4%

Table 2: Reduction in aggregate emissions without vertical heterogeneity of preferences

Decile preference generalised to total population	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10
Aggregate emissions (vs 2010)	-5.75%	-5.36%	-5.32%	-5.61%	-5.38%	-5.75%	-5.92%	-6.32%	-6.44%	-8.22%

Reading: If all households were to behave as D1 households aggregate reduction in emissions would be -5.75%.

are normally more elastic, would therefore reduce their emissions less (by 1.8 pts: D10 with D1 elasticities cut their emissions by 6.4% instead of 8.2% with their own elasticities).

Likewise, if we suppose horizontal homogeneity, emissions will decrease more if all households are type I and II (resp. -6.79% and -7.41% in emissions versus 2010). These types are dominated by urban households which are much less dependent on gasoline and thus exhibit higher price elasticities.

We may conclude that heterogeneity of preferences may either boost or slow down emissions reduction. Differentiating the behaviour of low-income deciles and rural households is key to avoiding overestimating the reduction of emissions.

5.3.3 Focusing the recycling mechanism

The equal per capita lump-sum allows the carbon tax to be progressive across income deciles. Surveys show that public support for the carbon tax is highest when the recycling of its revenues is earmarked for green investments or recycled and targeted at low-income households (Dechezleprêtre et al., 2022).[25]

To target low-income households, we exclude the richest households from the recycling mechanism. The full carbon tax revenues are then given back in the form of a larger equal per capita lump-sum transfer to the first income deciles. Whatever the households benefiting from this targeted mechanism, the emission reduction is almost the same (Table 3). We conclude that to reduce emissions further, we need to downsize the share of carbon tax revenues redistributed to households. This would kill one bird with two stones and free up revenue that could be earmarked for investments in low-carbon technologies or subsidies directed to households for thermal renovation or electric vehicles, for instance.

Emissions are further reduced if the mechanism excludes the top income deciles without increasing the rebate for the rest of the population (Table 4). If 50% of the carbon tax revenues is recycled towards the bottom half of the income distribution (with a similar 985€ per consumption unit), aggregate emissions are reduced by 8.4%. Cutting the recycling for the top 40% means

[25]Ewald et al. (2022) finds that recycling the carbon revenues to households, either to the low-income or to all, is not popular in Sweden, unlike using the revenues to invest in clean energy and research on climate change.

Table 3: Emissions reduction with targeted recycling of the full carbon tax revenues on the first income deciles

D1-D10	D1-D9	D1-D8	D1-D7	D1-D6	D1-D5	D1-D4	D1-D3	D1-D2	D1
-5.90%	-5.82%	-5.77%	-5.71%	-5.69%	-5.66%	-5.68%	-5.63%	-5.67%	-5.76%

Reading: Carbon tax 158€/tCO_2 . The full carbon tax is recycled towards the households indicated in the form of an equal per capita lump-sum transfer. Recycling the 41 billion euros to the first income brings an emissions reduction of 5.76%.

Table 4: Emissions reduction with equal per capita lump-sum recycling restricted to the first income deciles

D1-D10	D1-D9	D1-D8	D1-D7	D1-D6	D1-D5	D1-D4	D1-D3	D1-D2	D1
-5.90%	-6.35%	-6.84%	-7.36%	-7.89%	-8.42%	-8.95%	-9.46%	-9.97%	-10.48%

Reading: Carbon tax 158€/tCO_2 . The rebate per consumption unit is 985€ in all the recycling mechanisms. Only the indicated income deciles actually perceived the rebate. The remaining carbon tax revenues is earmarked for green investments that we suppose not carbon-emitting. Restricting the carbon tax revenues to the first 9 income deciles, excluding the top 10%, means a reduction in aggregate emission of 6.35% compared to -5.90% if the D10 is included.

improving the effectiveness of the tax by 2 points, to -7.9% on emissions. There is therefore a trade-off between reducing emissions further and offsetting as many households as possible.

Policymakers can then try to achieve a certain emission reduction target. If we assume that the objective is that the income effect should not offset more than 25% of the emission reduction due to the price signal (arbitrary example), from the Table 4 we infer that only 60% of the amount of the tax should be recycled. Indeed, we have seen that it is the amount of tax recycled that influences emissions more than its distribution (Table 3)

Figure 11 illustrates the trade-off between the emission target and progressivity. Two mechanisms are compared: i) an equal per capita lump-sum spread over D1-D6, D1-D8 or D1-D10, and ii) a mechanism skewing the redistribution towards low-income households. If n deciles are included in the recycling, then a household in D1 will receive n times more per capita than a household in Dn; a household in D2, $n-1$ times more, etc. This mechanism may not be optimal but it illustrates how a recycling mechanism can focus on the lowest incomes.

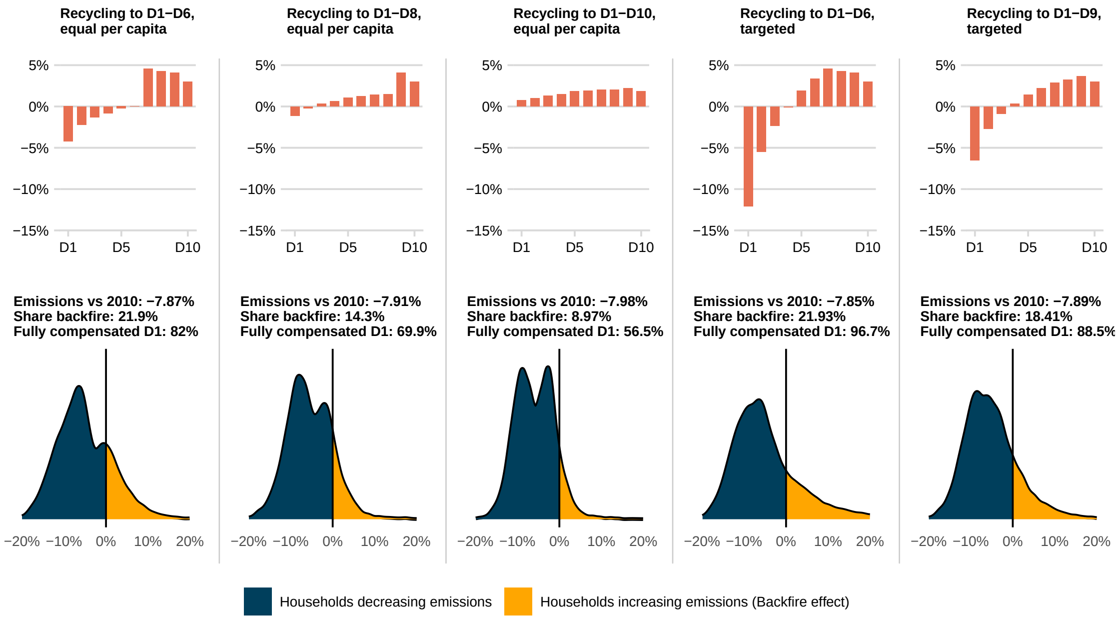
The reduction in emissions is comparable between all mechanisms. What changes is the progressivity of the net carbon tax, the share of D1 households fully compensated of their carbon tax bill and the share of households that increase their emissions (experiencing a backfire). We should then focus on the distributional aspects.

First, recycling 60% of the tax revenue on an equal per capita basis to all households makes the tax progressive but does not fully compensate the top deciles on average. A mechanism that excludes the top deciles creates a large increase in the weight of carbon tax relative to income for the last income deciles. It risks threatening acceptability.

Mechanisms favouring low-income households allow for better progressivity, by slightly compensating the richest. The trade-off is between 3 dimensions: progressivity, the protection of D1 households and the share of individual backfire effects.

These mechanisms increase the share of D1 households that are at least compensated for their carbon bill. If recycling is targeted and limited to D1-D6, 99.7% of D1 is at least compensated, compared to 88.5% if D1-D9 are compensated (targeted), and only 69.9% with an equal per-capita on D1-D8. In a targeted mechanism, however, households in D4-D5 are not compensated on average (the distribution is too skewed towards low-income households). If the share of fully compensated D1 households and the share of backfire households are correlated, the equal per capita lump-sum transfers to D1-D6 (column 1) and the targeted recycling towards D1-D6 (column 4) allow about 22% of households to increase their emissions, but fully compensate respectively 82 and 96% of D1 households.

Figure 11: Equity versus effectiveness with recycling 60% of the carbon tax revenues to households



Note: Each column corresponds to a recycling mechanism of the carbon tax revenues. In all mechanisms, only 60% of the total amount of carbon tax revenues is redistributed to households. The figure compares a recycling mechanism on the progressivity of the tax, emissions reduction, the share of individual backfires and the share of fully compensated D1 households. The so-called "targeted" mechanisms recycle over n income deciles (D1Dn) and are biased in favour of the poorest, giving n times more to D1 than to Dn. A negative net tax indicates that the decile's recycling revenue is higher than its tax payments The lower graph plots the density of the emission reduction among all households. One part of the households (yellow) increases its emissions above the pre-tax level, another part (navy blue) reduces its emissions.

6 Conclusion

This paper assesses the long-term reduction in emissions induced by a carbon tax whose revenues are recycled to households. We find that a backfire effect — an increase of aggregate emission above the pre-tax level — can theoretically take place but that in France, the recycling of carbon tax revenues only offsets about half of the emissions reduction.

We used a partial equilibrium set-up to derive the conditions for the carbon tax and lump-sum recycling to decrease aggregated emissions. We estimated price and income elasticities for 14 expenditure items for 40 classes of households using 1979-2010 French Household Budget surveys. We developed a microsimulation model to assess emissions reductions and distributional impacts of the carbon tax and its revenue recycling mechanism.

We show with a simple model that there is a risk of backfire due to recycling carbon tax revenues. In France, the most energy-intensive households are the low-income ones. The recycling mechanisms will therefore compensate these households and transfer the carbon tax revenues from the richest to the poorest. Low-income households are also the least price elastic for natural gas and electricity, and the most income elastic for these same goods. Conversely, middle-income households rather than low-income ones are the most dependent on fuel. We show that horizontal heterogeneity has a large impact on the elasticities of energy goods: rural households are less price elastic on gasoline, while older households are less price elastic on natural gas and electricity for heating.

Overall, a carbon tax of 158€/tCO_2 — which was the level of carbon tax planned in France for 2025 before the freeze that followed the *Gilets Jaunes* protests — recycled at 100% to households in the form of an equal per capita (on an equivalence scale) lump-sum transfer reduces aggregate emissions by 5.9%. Recycling 60% of the carbon tax revenues only leads to emissions reduction of about 8%: the income effect is only a quarter of the price effect. Depending on the recycling mechanism, more or less targeted towards low-income, the reform backfires for 9% to 22% of households, who increase their emissions above the pre-tax level depending on their location (urban or rural), their age and the type of dwelling they live in.

We conclude that although it is a valid concern that the recycling of the carbon tax revenues partially offsets the tax-induced reduction in emissions, the limited backfire effect is not sufficient to prevent any compensation for the low-income households in the name of emissions reduction. If the recycling is partial and targeted towards the lower income groups (for instance, excluding the richest 20% of households D9-D10 and skewed towards the first income deciles), it makes the tax progressive. It is then up to policymakers to fine-tune the recycling mechanism to maximise social acceptability according to citizens' preferences for a progressive tax, protection of the poorest or more equitable distribution of the emission reduction effort.

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G Theoretical model

G.A A single household with a single polluting good

Program

$$\begin{cases} E_1 = E_0(1+\varepsilon_p^E \eta_E t)\left(1+\varepsilon_r^E \dfrac{S}{E_0+X_0}\right) \\ X_1 = X_0\left(1+\varepsilon_r^X \dfrac{S}{E_0+X_0}\right) \\ S = E_1 \eta_E t \end{cases} \tag{20}$$

The solutions of this system are:

$$\begin{cases} X_1 = X_0 \dfrac{1-(\varepsilon_r^E - \varepsilon_r^X)\dfrac{E_0}{B_0}\eta_E t(1+\varepsilon_p^E \eta_E t)}{1-\varepsilon_r^E \dfrac{E_0}{B_0}\eta_E t(1+\varepsilon_p^E \eta_E t)} \\ E_1 = E_0 \dfrac{\dfrac{E_0}{B_0}(1+\varepsilon_p^E \eta_E t)}{1-\varepsilon_r^E \dfrac{E_0}{B_0}\eta_E t(1+\varepsilon_p^E \eta_E t)} \end{cases} \tag{21}$$

with $B_0 = X_0 + E_0$.

Hypotheses We assume throughout this exercise that price and income elasticities allow for balanced household budgets by keeping savings constant (see discussion of our elasticities in section 3):

$$X_0 + E_0 = E_1 + X_1 \tag{22}$$

The fact that we do not derive situation-specific elasticities prevents us from imposing that the elasticities sum to 1 for each item i:

$$\begin{cases} 1 = \sum_i w_0^i \left(1+\varepsilon_p^i \dfrac{\Delta p^i}{p_0^i}\right) \\ 1 = \sum_i w_0^i \varepsilon_r^i \end{cases}$$

Ensuring these conditions are always met while solving (20) would mean that consumers define their preferences (i.e. their elasticities) at the same time as their consumption, which is absurd and moreover violates the utility maximisation at the basis of demand systems. We derive elasticities from a budget-constrained household utility maximisation programme, which assumes consumption-independent elasticities. Therefore, in the microsimulation part of this paper, we ensure that budgets are balanced by iteration.

We ensure the budget is balanced ex-post, $B_1 = B_0$. Which is the same as writing:

$$E_0\sigma\eta_E t\left(\varepsilon_p^E + (1+\varepsilon_p^E\sigma\eta_E t)\left(\varepsilon_r^E\frac{E_0^p}{E_0^p + X_0^p} + \varepsilon_r^X\frac{X_0^p}{E_0^p + X_0^p}\right)\right) = 0 \tag{23}$$

The first term, $E_0\sigma\eta_E t\varepsilon_p^E$, indicates how much the energy budget has decreased and the second term the increase following the rebate.

We also impose that even in the absence of recycling, expenditure remains positive, i.e.

$$1 + \varepsilon_p^E\eta_E t > 0 \tag{24}$$

Emissions reduction The growth rate of emissions is:

$$\frac{\chi_1}{\chi_0} - 1 = \frac{\eta_E t\left(\varepsilon_p^E + \frac{E_0\varepsilon_r^E}{B_0}(1+\varepsilon_p^E\eta_E t)\right)}{1 - \frac{\varepsilon_r^E E_0^p\eta_E t}{B_0}(1+\varepsilon_p^E\eta_E t)}, \tag{25}$$

with $\chi_0 = E_0\eta_E$ et $\chi_1 = E_1\eta_E$.

The denominator of this equation is always positive, otherwise no matter how much S is recycled, the carbon tax generated by this extra revenue would be greater than S: we would have an infinite cycle.

It can also be seen as:

$$\text{If } 1 - \frac{\varepsilon_r^E E_0^p\eta_E t}{B_0}(1+\varepsilon_p^E\eta_E t) < 0,$$

then

$$\forall S > 0,\ \frac{W\varepsilon_r^E E_0^p\eta_E t}{B_0}(1+\varepsilon_p^E\eta_E t) > S,$$

and since

$$S = \eta_E t E_0(1+\varepsilon_p^E\eta_E t) + \eta_E t E_0(1+\varepsilon_p^E\eta_E t)\left(\varepsilon_r^E\frac{S}{E_0 + X_0}\right),$$

then if the second term is greater than S, the first term must be negative to balance, which is impossible since all of the components of the first term are positive.

The sign of the growth rate of emissions is therefore driven by the numerator of the expression. Intuitively, this ratio is positive when the income effect is weaker than the price effect. Mathematically, it means that:

$$\varepsilon_p^E + \frac{E_0\varepsilon_r^E}{B_0}(1+\varepsilon_p^E\eta_E t) < 0. \tag{26}$$

Given that

$$\varepsilon_p^E + (1+\varepsilon_p^E\eta_E t)\left(\varepsilon_r^E\frac{E_0}{B_0}\right) + (1+\varepsilon_p^E\eta_E t)\left(\varepsilon_r^X\frac{X_0}{E_0 + X_0}\right), \tag{27}$$

it would mean that we have the following:

$$(1+\varepsilon_p^E\eta_E t)\left(\varepsilon_r^X\frac{X_0}{B_0}.\right) < 0 \tag{28}$$

Equation (28) is impossible to achieve since the price effect cannot be greater than 100%, hence:

$$(1+\varepsilon_p^E\sigma\eta_E t) \geq 0$$

and of course:

$$\varepsilon_r^X\frac{X_0}{B_0} \geq 0.$$

The conclusion is that we always have a decrease in emissions given these hypotheses.

G.B A single household with two polluting goods

Program

$$\begin{cases} E_1 = E_0(1+\varepsilon_p^E \eta_E t)\left(1+\varepsilon_r^E \dfrac{S}{E_0+X_0}\right) \\ X_1 = X_0(1+\varepsilon_p^X \eta_X t)\left(1+\varepsilon_r^X \dfrac{S}{E_0+X_0}\right) \\ S = E_1\eta_E t + X_1 \eta_X t \end{cases} \tag{29}$$

The solutions of this system are:

$$\begin{cases} X_1 = X_0 \dfrac{(1+\varepsilon_p^X\eta_X t)(-1+(\varepsilon_r^E-\varepsilon_r^X)\dfrac{E_0}{B_0}\eta_E t(1+\varepsilon_p^E\eta_E t)}{1-\varepsilon_r^E\dfrac{E_0}{B_0}\eta_E t(1+\varepsilon_p^E\eta_E t)-\varepsilon_r^X\dfrac{X_0}{B_0}\eta_X t(1+\varepsilon_p^X\eta_X t)} \\ E_1 = E_0 \dfrac{(1+\varepsilon_p^E\eta_E t)(1+(\varepsilon_r^E-\varepsilon_r^X)\dfrac{X_0}{B_0}\eta_X t(1+\varepsilon_p^X\eta_X t)}{1-\varepsilon_r^E\dfrac{E_0}{B_0}\eta_E t(1+\varepsilon_p^E\eta_E t)-\varepsilon_r^X\dfrac{X_0}{B_0}\eta_X t(1+\varepsilon_p^X\eta_X t)} \end{cases} \tag{30}$$

with $B_0 = X_0 + E_0$.

Emissions growth rate

$$\frac{\chi_1}{\chi_0}-1 = \frac{\left(\varepsilon_p^E\eta_E^2 tE_0 + (1+\varepsilon_p^E\eta_E t)\chi_0\dfrac{\varepsilon_r^E E_0\eta_E t}{B_0}\right) + \left(\varepsilon_p^X\eta_X^2 tX_0 + (1+\varepsilon_p^X\eta_X t)\chi_0\dfrac{\varepsilon_r^X X_0\eta_X t}{B_0}\right)}{1-\dfrac{\varepsilon_r^E E_0\eta_E t}{B_0}(1+\varepsilon_p^E\eta_E t)-\dfrac{\varepsilon_r^X X_0\eta_X t}{B_0}(1+\varepsilon_p^X\eta_X t).} \tag{31}$$

The effects add up linearly to the case where $\eta_X = 0$, but unlike section G.A, the solutions are symmetrical in X and E.

G.C Transfers between households

Program The program of consumption at time 1 is:

$$\begin{cases} E_1^P = E_0^P(1+\varepsilon_p^E\eta_E t)\left(1+\varepsilon_r^E\dfrac{xS}{E_0^P+X_0^P}\right) \\ X_1^P = X_0(1+\varepsilon_p^X\eta_X t)\left(1+\varepsilon_r^X\dfrac{xS}{E_0^P+X_0^P}\right) \\ E_1^R = E_0^R(1+\varepsilon_p^E\eta_E t)\left(1+\varepsilon_r^E\dfrac{(1-x)S}{E_0^R+X_0^R}\right) \\ X_1^R = X_0^R(1+\varepsilon_p^X\eta_X t)\left(1+\varepsilon_r^X\dfrac{(1-x)S}{E_0^R+X_0^R}\right) \\ S = (E_1^P+E_1^R)\eta_E t + (X_1^P+X_1^R)\eta_X t \end{cases} \tag{32}$$

NB: solutions to this system are not digest and add little to the understanding of the problem at hand.

Emissions growth rate

$$\begin{aligned} \frac{\chi_1}{\chi_0}-1 = \Bigg[&\chi_0^E\eta_E\varepsilon_p^E\eta_E t + \chi_0^X\eta_X\varepsilon_p^X\eta_X t + \chi_0\varepsilon_r^E\eta_E t(1+\varepsilon_p^E\eta_E t)\left(x\frac{E_0^P}{B_0^P}+(1-x)\frac{E_0^R}{B_0^R}\right) \\ &+ \chi_0\varepsilon_r^X\eta_X t(1+\varepsilon_p^X\eta_X t)\left(x\frac{X_0^P}{B_0^P}+(1-x)\frac{X_0^R}{B_0^R}\right)\Bigg] / \\ &\left[1-\varepsilon_r^E\eta_E t(1+\varepsilon_p^E\eta_E t)\left(x\frac{E_0^P}{B_0^P}+(1-x)\frac{E_0^R}{B_0^R}\right)-\varepsilon_r^X\eta_X t(1+\varepsilon_p^X\eta_X t)\left(x\frac{X_0^P}{B_0^P}+(1-x)\frac{X_0^R}{B_0^R}\right)\right] \end{aligned} \tag{33}$$

As in appendix G.A, the denominator of the expression (33) is always positive because the budget is balanced.

Derivative of the growth rate of emissions relative to x, the carbon tax revenues allocation

$$\frac{\partial\left(\frac{\chi_1}{\chi_0}-1\right)}{\partial x} = \left[\left(\varepsilon_r^E\eta_E t(1+\varepsilon_p^E\eta_E t) - \varepsilon_r^X\eta_X t(1+\varepsilon_p^X\eta_X t)\right)\left(E_0^P X_0^R - E_0^R X_0^P\right)\left(\chi_0^E(1+\varepsilon_p^E\eta_E t) + \chi_0^X(1+\varepsilon_p^X\eta_X t)\right)\right] / \left[\chi_0\left(1-\varepsilon_r^E\eta_E t(1+\varepsilon_p^E\eta_E t)\left(x\frac{E_0^P}{B_0^P}+(1-x)\frac{E_0^R}{B_0^R}\right)-\varepsilon_r^X\eta_X t(1+\varepsilon_p^X\eta_X t)\left(x\frac{X_0^P}{B_0^P}+(1-x)\frac{X_0^R}{B_0^R}\right)\right)^2\right] \tag{34}$$

The denominator of the fraction is always positive. We have imposed the following hypotheses,

1. $(1+\varepsilon_p^E\eta_E t) > 0$,
2. $(1+\varepsilon_p^X\eta_X t) > 0$, and
3. $\frac{E_0^P}{X_0^P} > \frac{E_0^R}{X_0^R}$, hence $E_0^P X_0^R - E_0^R X_0^P > 0$.

It stems that the sign of the numerator depends on the central term and on the following condition:

$$\varepsilon_r^X\eta_X(1+\varepsilon_p^X\eta_X t) < \varepsilon_r^E\eta_E(1+\varepsilon_p^E\eta_E t) \tag{35}$$

Growth rate of emissions when the full carbon tax revenues is recycled towards the energy-intensive household P: $x=1$ The evolution of total emissions is given by:

$$\left(\frac{\chi_1}{\chi_0}-1\right) = \frac{\varepsilon_p^E\eta_E t\chi_0^E + \varepsilon_p^X\eta_X t\chi_0^X + \left(\varepsilon_r^X\frac{X_0^P}{B_0^P}\eta_X t(1+\varepsilon_p^X\eta_X t) + \frac{E_0^P}{B_0^P}\varepsilon_r^E\eta_E t(1+\varepsilon_p^E\eta_E t)\right)\chi_0}{\left(1-\frac{X_0^P}{B_0^P}\varepsilon_r^X\eta_X(1+\varepsilon_p^X\eta_X t) - \frac{E_0^P}{B_0^P}\varepsilon_r^E\eta_E(1+\varepsilon_p^E\eta_E t\right)\chi_0} \tag{36}$$

The denominator of this function is always positive to ensure a balanced budget (see appendix G.A). The sign of this expression depends on the sign of the numerator: the two price effect terms ($\varepsilon_p^E < 0$, $\varepsilon_p^X < 0$) are negative, and the income effect terms are positive. It all depends on which effect prevails over the other, and there are multiple combinations.

Growth rate of emissions when the full carbon tax revenues is recycled towards the least energy-intensive household R: $x=0$

$$\frac{\chi_1}{\chi_0}-1 = \frac{\chi_0^E\varepsilon_p^E\eta_E t + \chi_0^X\varepsilon_p^X\eta_X t + \chi_0\left(\varepsilon_r^E\eta_E t(1+\varepsilon_p^E\eta_E t)\left(\frac{E_0^R}{B_0^R}\right) + \varepsilon_r^X\eta_X t(1+\varepsilon_p^X\eta_X t)\left(\frac{X_0^R}{B_0^R}\right)\right)}{\left(1-\left(\frac{E_0^R}{B_0^R}\right)\varepsilon_r^E\eta_E t(1+\varepsilon_p^E\eta_E t) - \left(\frac{X_0^R}{B_0^R}\right)\varepsilon_r^X\eta_X t(1+\varepsilon_p^X\eta_X t\right)\chi_0} \tag{37}$$

H Elasticities estimates

H.A Computation of elasticities

We present here the detailed calculations of the estimated elasticities on the 14 consumption items.

The computations of elasticities from the coefficients draw heavily on the article by Pawlowski and Breuer (2012) from which the following computations are derived with the results of Green and Alston (1990) for the popular LA-AIDS model.

Equation (17) above, relates the budget shares to the logarithms of real expenditure and the item price. In this specification, the coefficients are interpreted as budget share elasticities, and we wish to calculate the income and price elasticities of total expenditure.

In the case of equation (17), the elasticities are respectively for price and income:

$$\begin{aligned} e_{E_i P_i} &= \frac{\partial E_i}{\partial P_i}\frac{P_i}{E_i} = \frac{d_i}{w_i} - c_i \\ e_{E_i X} &= \frac{\partial E_i}{\partial X}\frac{X}{E_i} = 1 + \frac{c_i}{w_i} \end{aligned} \tag{38}$$

For each good i, the simplified expression of the Engel curve is:

$$w_i = a_i + c_i \log\left(\frac{X}{P^*}\right) + d_i \log(P_i) + e_i \tag{39}$$

We voluntarily omit time t and the coefficients of the principal components without loss of generality. The coefficients are interpreted as semi-elasticities of the budget share to real expenditure (X/P^*) and to price P_i (Deaton and Muellbauer, 1980). Therefore, we need to find the expressions of the price and income elasticities of expenditure for each item as functions of the regression coefficients on price and income.

Consider the total expenditure:

$$X = \sum_{i=1}^{14} E_i \tag{40}$$

from which the budget shares are calculated:

$$w_i = \frac{E_i}{X} = \frac{E_i}{\sum_{i=1}^{14} E_i}. \tag{41}$$

The calculus trick consists mainly in using Engel's equation (39), noticing that

$$E_i = X \cdot w_i,$$

so that:

$$E_i = Xw_i = Xa_i + Xc_i \log\left(\frac{X}{P^*}\right) + Xd_i \log(P_i) \tag{42}$$

That is,

$$E_i = Xa_i + Xc_i \log(X) - Xc_i \log(P^*) + Xd_i \log(P_i) \tag{43}$$

A difficulty with equation (39) is that the Stone index P^*, is a function of individual prices P_i, which causes a simultaneity bias that makes the OLS estimator inconsistent. The model must therefore be estimated using instrumental variables but, above all, this relationship between the expenditure deflator and elasticities must be taken into account.

Consider the expression of the Stone index:

$$\log(P^*) = \sum_{i=1}^{14} w_i \log(P_i) \tag{44}$$

The derivative for any individual price i is:

$$\frac{\partial \log(P)}{\partial P_i} = \frac{w_i}{P_i} \tag{45}$$

We can now calculate the expression of $\partial E_i/\partial X$, i.e.:

$$\frac{\partial E_i}{\partial X} = a_i + c_i \log(X) - c_i \log(P^*) + d_i \log(P_i) + \frac{Xc_i}{w_i} \tag{46}$$

Likewise, since we have $w_i = E_i/X$, it follows immediately that: $X/E_i = 1/w_i$. This allows us to deduce the expression of the income elasticity of the expenditure of item i:

$$\frac{\partial E_i}{\partial X} = w_i + c_i. \tag{47}$$

Hence, the income elasticity is:

$$e_{E_i X} = \frac{\partial E_i}{\partial X}\frac{X}{E_i} = (w_i + c_i)\frac{1}{w_i} = 1 + \frac{c_i}{w_i}. \tag{48}$$

For the price elasticity of expenditure of product i under consideration, the computation is similar although somewhat more complicated. Starting from equation (43), we compute the price elasticity for item i:

$$\frac{\partial E_i}{\partial P_i} = -Xc_i\frac{\partial \log(P^*)}{\partial P_i} + \frac{Xd_i}{P_i}. \tag{49}$$

Now, we recall the expression (45) and introduce it in (49):

$$\frac{\partial E_i}{\partial P_i} = -Xc_i\frac{w_i}{P_i} + \frac{Xd_i}{P_i}. \tag{50}$$

Let us now calculate the second member of the price elasticity expression,

$$\begin{aligned} e_{E_i P_i} = \frac{\partial E_i}{\partial P_i} &= \left(\frac{Xd_i}{P_i} - Xc_i\frac{w_i}{P_i}\right)\frac{P_i}{Xw_i} \\ &= \frac{Xd_i}{P_i} \times \frac{P_i}{Xw_i} - \frac{Xw_i c_i}{Xw_i} \\ &= \frac{d_i}{w_i} - c_i \end{aligned} \tag{51}$$

Notice that if Engel's equation was more general using all prices or if we used a different deflator than the Stone index given by equation (44), the expressions of the elasticities would be different.

H.B Standard Errors

We compute the standard errors of the elasticities with the delta method (Greene, 2003; Colonescu, 2016). The delta method is a method of approximating the standard deviations of a function of estimated coefficients. In this paper, the equations giving the price and income elasticities of the expenditure items considered are used. Let $h(x)$ be the function of the estimated coefficients, then the variance of the function $h(x)$ is given by

$$V(h(x)) = th'(x)V(x)h'(x), \tag{52}$$

with $V(x)$ the variance-covariance matrix of the estimated coefficients x, $h'(x)$ the first derivative of the function $h(x)$ and t, the transposition operator of a vector.

All values and significance are indicated in Table H.1. Aggregated values and t-Student values are available in Table H.5. Disaggregated significance of price and income elasticities are available in Tables H.7 and H.6. Please refer to Table I.8 for the nomenclature explicitation.

H.C Quasi-balanced demand system

A system of demand should verify the following equations for each cell of households and the aggregated population:

$$\begin{cases} 1 = \sum_i w_0^i \left(1 + \varepsilon_p^i \frac{\Delta p_i}{p_i^0}\right)\left(1 + \frac{\Delta p_i}{p_i^0}\right) \\ 1 = \sum_i w_0^i \varepsilon_r^i \end{cases} \tag{53}$$

Table H.5: Aggregated price and income elasticities and average Student's t per expenditures items

	Income Elasticity	t-Student	Price Elasticity	t-Student
Food	0.3	5.10 ***	-0.17	-3.20**
Electricity	0.49	10.75***	-0.67	-12.50***
Gas (natural and biogas)	1.3	26.02***	-0.16	-3.19**
Other residential energy	0.8	1.8°	-0.62	-1.47
Construction and construction services	1.33	4.44 ***	-0.26	-2.40*
First-hand vehicles	1.95	11.88***	-1.39	-3.37***
Vehicle fuels and lubricants	0.77	5.80***	-0.27	-4.56***
Rail and air transport	1.78	5.80***	-0.35	-1.47
Road and water transport	1.69	4.13***	-1.19	-1.39
Leisure services	1.57	41.49***	-0.2	-2.38*
Other services	1.13	44.61***	-0.22	-7.59***
Other consumption/equipment goods	1.36	36.85***	-0.39	-5.03***
Housing rents	0.44	1.81°	-0.97	-1.94*
Second-hand vehicles	2.74	3.63***	-0.71	-1.67°

Significance:°10% = 1.6 ; * 5% = 1.96; ** 1% = 2.58; *** 0.1% = 3.29. Yellow: significant at 10%, orange, not significant

Using the 158€/tCO_2 carbon tax, the weighted sum of elasticities is equal to 0.9997697 for income elasticities and to 1.03 for price elasticities. For all 40 cells, the median value for the weighted sum of income elasticities is 0.990 and 1.03 for price elasticities (Figure H.2 and H.3). It is therefore reasonable to use these elasticities as a quasi-system and to close the budget in the microsimulation by reallocating surpluses or shortfalls to the budget using the income elasticities (see section 3.2).

I Robustness analysis

I.A Uncertainty on elasticities

We assess the propagation of uncertainty from the estimated coefficients of the Engel curves using a Monte-Carlo simulation on all elasticities. Income and price elasticities are non-linear functions of estimated coefficients (see section 2.3). Therefore, we cannot compute covariance matrices between elasticities. We approximate uncertainty propagation with the assumption of full independence of all elasticities even if it obviously overestimates the dispersion of results. The outcome of Monte-Carlo is the emissions of each income decile following the introduction of carbon tax (price effect) and the lump-sum transfer (income effect) as modelled in section 4. We launch 26,000 runs of the model, each of the 1125 elasticities following a specific gaussian distribution (see figures 1 and 2 for the mean and appendix H.B to discuss the computation of standard errors). We plot the distribution of the aggregate level of emissions and the distribution of each income deciles emissions.

We show in Figure I.4 that the distribution of uncertainty is almost gaussian for each income decile emissions distribution and aggregated emissions. The outcome obtained using mean expectations as per in section 3.3 is within the 99.9% interval of confidence. Uncertainty is obviously higher for richer households as their larger emissions are more sensitive to changes in elasticities.

I.B Alternative carbon intensity for electricity

Carbon footprint The quantity of CO_2 emitted per euro spent is about 1662gCO_2 /€, which means about 200gCO_2 /MWh (using 119€/MWh, the average price of a MWh of electricity from table 2.9 in De Lauretis (2017)). The current carbon footprint of electricity production on the French national territory in 2022 is about 60gCO_2 /MWh.

The carbon intensity of electricity appears to be high (Table I.8) when electricity is supposed to be decarbonised in France. We attempt to explain this figure and then test the robustness of

Table H.6: Significance of income elasticities

Income decile	Vulnerability type	A01	A02	A03	A04	A05	A06	A07	A08	A09	A10	A11	A12	A13	A14
D1	I	***	***	***	*	*	***	***	***	***	***	***	***	**	***
D1	II	***	***	***	*	°	***	***	***	***	***	***	***	**	***
D1	III	***	***	***	*	***	***	***	***	***	***	***	***	**	**
D1	IV	***	***	***	*	***	***	***	***	***	***	***	***	**	***
D2	I	***	***	***	**	**	***	***	***	***	***	***	***	**	***
D2	II	***	***	***	**	*	***	***	***	***	***	***	***	**	***
D2	III	***	***	***	**	***	***	***	***	***	***	***	***	**	***
D2	IV	***	***	***	**	***	***	***	***	***	***	***	***	**	**
D3	I	***	***	***	**	*	***	***	***	***	***	***	***	*	***
D3	II	***	***	***	**	**	***	***	***	***	***	***	***	*	***
D3	III	***	***	***	**	***	***	***	***	***	***	***	***	*	***
D3	IV	***	***	***	**	***	***	***	**	***	***	***	***	*	**
D4	I	**	***	***	*	**	***	***	***	***	***	***	***	*	***
D4	II	***	***	***	*	***	***	***	***	***	***	***	***	*	***
D4	III	***	***	***	*	***	***	***	***	***	***	***	***	*	***
D4	IV	***	***	***	*	***	***	***	***	***	***	***	***	*	**
D5	I	**	***	***	*	**	***	***	***	***	***	***	***	*	***
D5	II	***	***	***	*	***	***	**	***	***	***	***	***	*	***
D5	III	***	***	***	*	***	***	***	***	***	***	***	***	*	***
D5	IV	***	***	***	*	***	***	***	**	***	***	***	***	*	**
D6	I	*	***	***	°	**	***	***	***	***	***	***	***	°	***
D6	II	***	***	***	°	***	***	*	***	***	***	***	***	°	***
D6	III	***	***	***	°	***	***	***	***	***	***	***	***	°	***
D6	IV	***	***	***	°	***	***	***	***	***	***	***	***	°	**
D7	I	*	***	***	0.2	***	***	***	***	***	***	***	***	0.2	***
D7	II	***	***	***	0.2	***	***	*	***	***	***	***	***	0.2	***
D7	III	***	***	***	0.2	***	***	***	***	***	***	***	***	0.2	***
D7	IV	***	***	***	0.2	***	***	***	***	***	***	***	***	0.2	**
D8	I	0.3	***	***	0.4	***	***	***	***	***	***	***	***	0.2	***
D8	II	**	***	***	0.4	***	***	**	***	***	***	***	***	0.2	***
D8	III	***	***	***	0.4	***	***	***	***	***	***	***	***	0.2	***
D8	IV	***	***	***	0.4	***	***	***	***	***	***	***	***	0.2	***
D9	I		**	***	0.3	***	***	***	***	***	***	***	***	0.3	***
D9	II	0.2	***	***	0.3	***	***	**	***	***	***	***	***	0.3	***
D9	III	**	***	***	0.3	***	***	***	***	***	***	***	***	0.3	***
D9	IV	***	***	***	0.3	***	***	***	***	***	***	***	***	0.3	***
D10	I	**	0.3	***		***	***	***	***	***	***	***	***		**
D10	II	*	**	***		***	***	**	***	***	***	***	***		***
D10	III	0.5	***	***		***	***	***	***	***	***	***	***		**
D10	IV	0.3	***	***		***	***	***	***	***	***	***	***		***

Significance: °10% = 1.6 ; * 5% = 1.96; ** 1% = 2.58; *** 0.1% = 3.29. Other low significance levels are indicated in the table.

Table H.7: Significance of price elasticities

Income decile	Vulnerability type	A01	A02	A03	A04	A05	A06	A07	A08	A09	A10	A11	A12	A13	A14
D1	I	***	***	***	0.2	*	***	***	0.2	0.2	*	***	***	°	°
D1	II	**	***	***	0.2	*	***	***	0.2	0.2	*	***	***	°	°
D1	III	**	***	***	0.2	*	***	***	0.2	0.2	*	***	***	°	0.2
D1	IV	*	***	***	0.2	*	***	***	0.2	0.2	*	***	***	°	0.2
D2	I	***	***	**	0.2	*	***	***	0.2	0.2	*	***	***	°	°
D2	II	**	***	**	0.2	*	***	***	0.2	0.2	*	***	***	°	°
D2	III	**	***	***	0.2	*	***	***	0.2	0.2	*	***	***	°	°
D2	IV	°	***	***	0.2	*	***	***	0.2	0.2	*	***	***	°	0.2
D3	I	***	***	**	0.2	*	***	***	0.2	0.2	*	***	***	°	°
D3	II	**	***	**	0.2	*	***	***	0.2	0.2	*	***	***	°	°
D3	III	**	***	***	0.2	*	***	***	0.2	0.2	*	***	***	°	°
D3	IV	*	***	***	0.2	*	***	***	0.2	0.2	*	***	***	°	0.2
D4	I	***	***	**	0.2	*	***	***	0.2	0.2	*	***	***	°	°
D4	II	**	***	**	0.2	*	***	***	0.2	0.2	*	***	***	°	°
D4	III	**	***	***	0.2	*	***	***	0.2	0.2	*	***	***	°	°
D4	IV	*	***	***	0.2	*	***	***	0.2	0.2	*	***	***	°	0.2
D5	I	***	***	**	0.2	*	***	***	0.2	0.2	*	***	***	°	°
D5	II	**	***	**	0.2	*	***	***	0.2	0.2	*	***	***	°	°
D5	III	**	***	***	0.2	*	***	***	0.2	0.2	*	***	***	°	°
D5	IV	*	***	***	0.2	*	***	***	0.2	0.2	*	***	***	°	0.2
D6	I	***	***	**	0.2	*	***	***	0.2	0.2	*	***	***	°	°
D6	II	**	***	*	0.2	*	***	***	0.2	0.2	*	***	***	°	°
D6	III	**	***	***	0.2	*	***	***	0.2	0.2	*	***	***	°	°
D6	IV	*	***	***	0.2	*	***	***	0.2	0.2	*	***	***	°	0.2
D7	I	***	***	**	0.2	*	***	***	0.2	0.2	*	***	***	°	°
D7	II	***	***	*	0.2	*	***	***	0.2	0.2	*	***	***	°	°
D7	III	***	***	***	0.2	*	***	***	0.2	0.2	*	***	***	°	°
D7	IV	**	***	**	0.2	*	***	***	0.2	0.2	*	***	***	°	0.2
D8	I	***	***	**	0.2	*	***	***	0.2	0.2	*	***	***	°	°
D8	II	***	***	*	0.2	*	***	***	0.2	0.2	*	***	***	°	°
D8	III	***	***	***	0.2	*	***	***	0.2	0.2	**	***	***	°	°
D8	IV	**	***	**	0.2	*	***	***	0.2	0.2	*	***	***	°	0.2
D9	I	***	***	*	0.2	*	***	***	0.2	0.2	**	***	***	°	°
D9	II	***	***	*	0.2	*	***	***	0.2	0.2	*	***	***	°	°
D9	III	***	***	***	0.2	*	***	***	0.2	0.2	**	***	***	°	0.2
D9	IV	***	***	*	0.2	*	***	***	0.2	0.2	*	***	***	°	°
D10	I							***	0.2	0.2	**	***	***	*	0.2
D10	II							***	0.2	0.2	**	***	***	*	°
D10	III							***	0.2	0.2	**	***	***	*	0.2
D10	IV							***	0.2	0.2	*	***	***	*	°

Significance: °10% = 1.6 ; * 5% = 1.96; ** 1% = 2.58; *** 0.1% = 3.29. Other low significance levels are indicated in the table.

Table I.8: Expenditures Nomenclature and carbon intensity of consumption

Code	Description	Carbon intensity (gCO_2 per euro spent)
A01	Food	185.2
A02	Electricity	1662.8
A03	Gas (natural and biogas)	1835.5
A04	Other residential energy	2024.8
A05	Construction and construction services	138.1
A06	First-hand vehicles	257.6
A07	Vehicle fuels and lubricants	2722.9
A08	Rail and air transport	773.0
A09	Road and water transport	773.0
A10	Leisure services	93.0
A11	Other services	164.4
A12	Other consumption/equipment goods	176.6
A13	Housing rents	121.9
A14	Second-hand vehicles	257.6

Note: Carbon intensities are from Pottier et al. (2020). Carbon intensities are expressed in gCO_2 par euro spent (constant € 2010), they include direct and indirect emissions. See Nadaud (2020) for detailed aggregation from the Classification of Individual Consumption by Purpose (COICOP).

our simulations if we adopt a lower figure.

One reason is that part of the household energy bills in BDF are joint gas and electricity bills. Pottier (2022) following De Lauretis (2017) allocates the bills to electricity and natural gas using the same pattern as households using the same heating system and separable bills between gas and electricity. This correction is doubtlessly the best one can do but suffers from several biases. The first is that the main heating system is a weak variable as hot water and heating system can be different, most households who benefit from urban heating do not know it, etc. Second, the quality of heating systems can vary widely between an efficient global electric heater to multiple "toaster-like" small electric heaters. Some households in collective housing also benefit from shared heating systems where heating bills are included in the service charge (with other utilities).

Another reason is that the costs and emissions of investment in production have been included in the sector's emissions and therefore increase them.

Robustness test We have run robustness tests using a smaller carbon footprint of electricity. 60gCO_2 /MWh translates into 500gCO_2 /€ in 2010. Using this value, we estimate the carbon tax and recycling to reduce emissions by 5.5% (versus 5.9% in the main scenario), and without recycling the carbon tax revenues, the reduction would be of 9.8% (versus 10.9% in the main scenario). All of our conclusions and analysis stand.

The reduction is somewhat smaller because the price elasticity of electricity is larger in absolute terms than other goods (natural gas or gasoline for instance) with lower income elasticities. The magnitude of the backfire effect (35% of households increase their emissions) is higher than in the previous exercise: the high price elasticity on electricity can no longer offset the income effects on other items.

The carbon tax is still regressive with respect to income on D1-D10, but only regressive on D7-D10 with respect to total consumption (compared to D5-D10 with the emission coefficients of (Pottier et al., 2020))

I.C Wave influence on the backfire effect

It does not appear that the wave of the consumer expenditures influences the share of household increasing their emissions above the pre-tax level. The exception being the first income decile where the variation in the share of backfire households decrease with the wave.

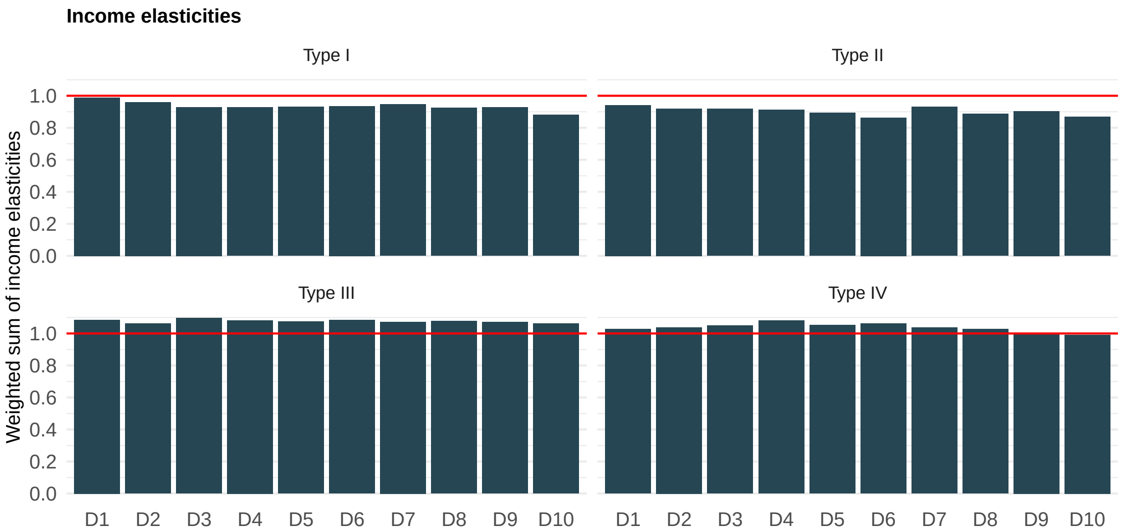
Figure H.1: Long-term price and income elasticities of French households by decile and vulnerability type

		A01	Agriculture	A02	Electricité	A03	Gaz	A04	Autres comb	A05	BTP	A06	Véhicules ne	A07	Carburants
decile	typo4	Income	Price	Income	Price	Income	Price	Income	Price	Income	Price	Income	Price	Income	Price
		0.279***	-0.179***	0.099	-0.257***	1.354***	-0.193***	0.863*	-0.423	1.861*	-0.65*	2.486***	-2.153***	0.692***	-0.362***
D01	1	(3.86)	(-3.43)	(1.09)	(-3.93)	(23.82)	(-3.42)	(2.39)	(-1.47)	(1.99)	(-2.29)	(9.25)	(-3.33)	(3.66)	(-4.61)
		0.417***	-0.12**	0.46***	-0.708***	1.29***	-0.159***	0.863*	-0.423	2.067°	-0.802*	2.486***	-2.153***	0.692***	-0.361***
D01	2	(7.14)	(-2.83)	(8.1)	(-12.53)	(28.3)	(-3.51)	(2.39)	(-1.47)	(1.79)	(-2.28)	(9.25)	(-3.33)	(3.66)	(-4.61)
		0.448***	-0.106**	0.567***	-0.566***	1.462***	-0.251***	0.863*	-0.423	1.26***	-0.205*	2.486***	-2.153***	0.818***	-0.21***
D01	3	(8.1)	(-2.66)	(12.44)	(-12.48)	(35.76)	(-6.17)	(2.39)	(-1.47)	(4.47)	(-2.4)	(9.25)	(-3.33)	(7.32)	(-4.53)
		0.513***	-0.079*	0.612***	-0.506***	1.274***	-0.151***	0.863*	-0.423	1.268***	-0.211*	2.486***	-2.153***	0.767***	-0.271***
D01	4	(10.48)	(-2.22)	(14.97)	(-12.45)	(37.05)	(-4.41)	(2.39)	(-1.47)	(4.37)	(-2.4)	(9.25)	(-3.33)	(5.37)	(-4.57)
		0.282***	-0.178***	0.674***	-0.424***	1.32***	-0.175**	0.876**	-0.382	1.55**	-0.42*	2.327***	-1.926***	0.781***	-0.254***
D02	1	(3.91)	(-3.42)	(19.58)	(-12.39)	(22.54)	(-3.01)	(2.68)	(-1.47)	(2.6)	(-2.32)	(9.7)	(-3.34)	(5.81)	(-4.56)
		0.453***	-0.104**	0.444***	-0.73***	1.252***	-0.139**	0.876**	-0.382	1.559*	-0.427*	2.327***	-1.926***	0.707***	-0.344***
D02	2	(8.27)	(-2.63)	(7.58)	(-12.53)	(28.94)	(-3.22)	(2.68)	(-1.47)	(2.57)	(-2.32)	(9.7)	(-3.34)	(3.93)	(-4.6)
		0.386***	-0.133**	0.589***	-0.536***	1.335***	-0.183***	0.876**	-0.382	1.341***	-0.265*	2.327***	-1.926***	0.818***	-0.21***
D02	3	(6.27)	(-2.99)	(13.62)	(-12.46)	(28.12)	(-3.87)	(2.68)	(-1.47)	(3.63)	(-2.36)	(9.7)	(-3.34)	(7.33)	(-4.53)
		0.551***	-0.062°	0.549***	-0.589***	1.224***	-0.124***	0.876**	-0.382	1.224***	-0.179*	2.327***	-1.926***	0.782***	-0.253***
D02	4	(12.25)	(-1.9)	(11.58)	(-12.49)	(38.82)	(-3.95)	(2.68)	(-1.47)	(5.04)	(-2.42)	(9.7)	(-3.34)	(5.85)	(-4.56)
		0.256***	-0.19***	0.701***	-0.387***	1.304***	-0.166**	0.881**	-0.367	1.611*	-0.465*	2.156***	-1.682***	0.786***	-0.249***
D03	1	(3.42)	(-3.51)	(22.23)	(-12.36)	(20.76)	(-2.66)	(2.81)	(-1.47)	(2.43)	(-2.31)	(10.32)	(-3.35)	(5.96)	(-4.56)
		0.456***	-0.103**	0.404***	-0.783***	1.207***	-0.115**	0.881**	-0.367	1.414**	-0.319*	2.156***	-1.682***	0.689***	-0.365***
D03	2	(8.35)	(-2.61)	(6.43)	(-12.55)	(29.14)	(-2.79)	(2.81)	(-1.47)	(3.15)	(-2.34)	(10.32)	(-3.35)	(3.6)	(-4.61)
		0.409***	-0.124**	0.607***	-0.513***	1.334***	-0.182***	0.881**	-0.367	1.294***	-0.23*	2.156***	-1.682***	0.832***	-0.193***
D03	3	(6.88)	(-2.88)	(14.65)	(-12.45)	(28.81)	(-3.96)	(2.81)	(-1.47)	(4.07)	(-2.38)	(10.32)	(-3.35)	(8.08)	(-4.51)
		0.525***	-0.073*	0.561***	-0.574***	1.217***	-0.12***	0.881**	-0.367	1.188***	-0.152*	2.156***	-1.682***	0.802***	-0.229***
D03	4	(11)	(-2.13)	(12.11)	(-12.48)	(37.32)	(-3.69)	(2.81)	(-1.47)	(5.83)	(-2.46)	(10.32)	(-3.35)	(6.59)	(-4.55)
		0.229**	-0.201***	0.691***	-0.401***	1.304***	-0.166**	0.859*	-0.435	1.546**	-0.417*	2.01***	-1.475***	0.779***	-0.257***
D04	1	(2.96)	(-3.59)	(21.18)	(-12.37)	(20.43)	(-2.62)	(2.31)	(-1.47)	(2.61)	(-2.32)	(11.01)	(-3.36)	(5.72)	(-4.56)
		0.417***	-0.12**	0.394***	-0.796***	1.218***	-0.12**	0.859*	-0.435	1.344***	-0.268*	2.01***	-1.475***	0.68***	-0.376***
D04	2	(7.13)	(-2.83)	(6.18)	(-12.55)	(27.41)	(-2.72)	(2.31)	(-1.47)	(3.61)	(-2.36)	(11.01)	(-3.36)	(3.45)	(-4.61)
		0.373***	-0.139**	0.578***	-0.551***	1.36***	-0.196***	0.859*	-0.435	1.248***	-0.197*	2.01***	-1.475***	0.842***	-0.181***
D04	3	(5.93)	(-3.05)	(13.02)	(-12.47)	(28.42)	(-4.13)	(2.31)	(-1.47)	(4.64)	(-2.41)	(11.01)	(-3.36)	(8.66)	(-4.5)
		0.502***	-0.083*	0.546***	-0.594***	1.225***	-0.124***	0.859*	-0.435	1.192***	-0.155*	2.01***	-1.475***	0.787***	-0.248***
D04	4	(10.03)	(-2.3)	(11.41)	(-12.49)	(35.21)	(-3.59)	(2.31)	(-1.47)	(5.73)	(-2.45)	(11.01)	(-3.36)	(6)	(-4.56)
		0.232**	-0.2***	0.67***	-0.429***	1.323***	-0.177**	0.847*	-0.471	1.421**	-0.325*	1.933***	-1.364***	0.796***	-0.236***
D05	1	(3.01)	(-3.58)	(19.25)	(-12.4)	(20.89)	(-2.81)	(2.11)	(-1.47)	(3.11)	(-2.34)	(11.46)	(-3.36)	(6.36)	(-4.55)
		0.391***	-0.131**	0.399***	-0.79***	1.223***	-0.123**	0.847*	-0.471	1.299***	-0.234*	1.933***	-1.364***	0.669**	-0.39***
D05	2	(6.41)	(-2.96)	(6.3)	(-12.55)	(26.95)	(-2.73)	(2.11)	(-1.47)	(4.01)	(-2.38)	(11.46)	(-3.36)	(3.29)	(-4.62)
		0.377***	-0.137**	0.569***	-0.563***	1.325***	-0.178***	0.847*	-0.471	1.236***	-0.188*	1.933***	-1.364***	0.842***	-0.181***
D05	3	(6.02)	(-3.03)	(12.54)	(-12.48)	(28.43)	(-3.83)	(2.11)	(-1.47)	(4.84)	(-2.42)	(11.46)	(-3.36)	(8.69)	(-4.5)
		0.496***	-0.086*	0.558***	-0.578***	1.214***	-0.119***	0.847*	-0.471	1.19***	-0.153*	1.933***	-1.364***	0.792***	-0.241***
D05	4	(9.79)	(-2.35)	(11.97)	(-12.48)	(34.69)	(-3.41)	(2.11)	(-1.47)	(5.79)	(-2.46)	(11.46)	(-3.36)	(6.19)	(-4.55)
		0.19*	-0.218***	0.668***	-0.431***	1.313***	-0.171**	0.816°	-0.567	1.411**	-0.317*	1.851***	-1.247***	0.784***	-0.251***
D06	1	(2.34)	(-3.7)	(19.07)	(-12.4)	(19.71)	(-2.58)	(1.69)	(-1.48)	(3.17)	(-2.34)	(12.03)	(-3.37)	(5.89)	(-4.56)
		0.35***	-0.149**	0.368***	-0.832***	1.213***	-0.118*	0.816°	-0.567	1.319***	-0.249*	1.851***	-1.247***	0.596*	-0.478***
D06	2	(5.37)	(-3.15)	(5.52)	(-12.56)	(24.68)	(-2.41)	(1.69)	(-1.48)	(3.82)	(-2.37)	(12.03)	(-3.37)	(2.4)	(-4.64)
		0.359***	-0.145**	0.533***	-0.611***	1.336***	-0.184***	0.816°	-0.567	1.229***	-0.182*	1.851***	-1.247***	0.838***	-0.186***
D06	3	(5.58)	(-3.11)	(10.85)	(-12.5)	(27.49)	(-3.8)	(1.69)	(-1.48)	(4.96)	(-2.42)	(12.03)	(-3.37)	(8.4)	(-4.51)
		0.47***	-0.097*	0.539***	-0.603***	1.217***	-0.12**	0.816°	-0.567	1.178***	-0.145*	1.851***	-1.247***	0.79***	-0.244***
D06	4	(8.83)	(-2.52)	(11.09)	(-12.49)	(33.62)	(-3.33)	(1.69)	(-1.48)	(6.1)	(-2.47)	(12.03)	(-3.37)	(6.1)	(-4.56)
		0.195*	-0.216***	0.656***	-0.447***	1.34***	-0.186**	0.777	-0.689	1.342***	-0.266*	1.782***	-1.148***	0.781***	-0.255***
D07	1	(2.42)	(-3.69)	(18.13)	(-12.41)	(19.92)	(-2.78)	(1.32)	(-1.48)	(3.62)	(-2.36)	(12.61)	(-3.38)	(5.8)	(-4.56)
		0.312***	-0.165***	0.361***	-0.84***	1.223***	-0.123*	0.777	-0.689	1.29***	-0.227*	1.782***	-1.148***	0.604*	-0.468***
D07	2	(4.52)	(-3.31)	(5.37)	(-12.56)	(23.89)	(-2.42)	(1.32)	(-1.48)	(4.11)	(-2.38)	(12.61)	(-3.38)	(2.48)	(-4.64)
		0.312***	-0.165***	0.514***	-0.636***	1.332***	-0.182***	0.777	-0.689	1.232***	-0.185*	1.782***	-1.148***	0.832***	-0.194***
D07	3	(4.52)	(-3.31)	(10.04)	(-12.51)	(25.41)	(-3.48)	(1.32)	(-1.48)	(4.9)	(-2.42)	(12.61)	(-3.38)	(8.03)	(-4.51)
		0.412***	-0.122**	0.502***	-0.652***	1.217***	-0.12**	0.777	-0.689	1.175***	-0.142*	1.782***	-1.148***	0.773***	-0.264***
D07	4	(6.99)	(-2.86)	(9.59)	(-12.51)	(30.71)	(-3.04)	(1.32)	(-1.48)	(6.2)	(-2.48)	(12.61)	(-3.38)	(5.55)	(-4.57)
		0.108	-0.253***	0.624***	-0.49***	1.357***	-0.195**	0.727	-0.842	1.328***	-0.256*	1.719***	-1.059***	0.763***	-0.277***
D08	1	(1.21)	(-3.91)	(15.74)	(-12.44)	(17.9)	(-2.58)	(1.01)	(-1.48)	(3.74)	(-2.37)	(13.23)	(-3.39)	(5.22)	(-4.58)
		0.224**	-0.203***	0.28***	-0.948***	1.226***	-0.125*	0.727	-0.842	1.244***	-0.194*	1.719***	-1.059***	0.661**	-0.399***
D08	2	(2.88)	(-3.61)	(3.7)	(-12.58)	(22.19)	(-2.27)	(1.01)	(-1.48)	(4.7)	(-2.41)	(13.23)	(-3.39)	(3.17)	(-4.62)
		0.265***	-0.185***	0.475***	-0.688***	1.346***	-0.189***	0.727	-0.842	1.217***	-0.174*	1.719***	-1.059***	0.822***	-0.205***
D08	3	(3.6)	(-3.47)	(8.6)	(-12.52)	(24)	(-3.39)	(1.01)	(-1.48)	(5.17)	(-2.43)	(13.23)	(-3.39)	(7.52)	(-4.52)
		0.396***	-0.129**	0.468***	-0.698***	1.201***	-0.112**	0.727	-0.842	1.182***	-0.148*	1.719***	-1.059***	0.75***	-0.292***
D08	4	(6.53)	(-2.94)	(8.34)	(-12.53)	(29.43)	(-2.75)	(1.01)	(-1.48)	(6)	(-2.47)	(13.23)	(-3.39)	(4.88)	(-4.58)
		0.026	-0.289***	0.613***	-0.505***	1.376***	-0.205*	0.749	-0.776	1.277***	-0.218*	1.669***	-0.988***	0.761***	-0.279***
D09	1	(0.26)	(-4.08)	(15.01)	(-12.45)	(16.8)	(-2.52)	(1.13)	(-1.48)	(4.25)	(-2.39)	(13.8)	(-3.39)	(5.17)	(-4.58)
		0.141	-0.239***	0.222**	-1.025***	1.226***	-0.125*	0.749	-0.776	1.218***	-0.174*	1.669***	-0.988***	0.629**	-0.437***
D09	2	(1.64)	(-3.83)	(2.71)	(-12.59)	(20.43)	(-2.09)	(1.13)	(-1.48)	(5.16)	(-2.43)	(13.8)	(-3.39)	(2.76)	(-4.63)
		0.248***	-0.193***	0.43***	-0.748***	1.349***	-0.191***	0.749	-0.776	1.197***	-0.159*	1.669***	-0.988***	0.822***	-0.206***
D09	3	(3.29)	(-3.53)	(7.17)	(-12.54)	(24.02)	(-3.42)	(1.13)	(-1.48)	(5.61)	(-2.45)	(13.8)	(-3.39)	(7.5)	(-4.53)
		0.286***	-0.176***	0.467***	-0.699***	1.213***	-0.118*	0.749	-0.776	1.179***	-0.145*	1.669***	-0.988***	0.742***	-0.302***
D09	4	(4)	(-3.4)	(8.31)	(-12.53)	(26.15)	(-2.56)	(1.13)	(-1.48)	(6.09)	(-2.47)	(13.8)	(-3.39)	(4.67)	(-4.59)
		-0.431**	-0.486***	0.56***	-0.576***	1.484***	-0.263*	0.594	-1.254	1.208***	-0.167*	1.56***	-0.832***	0.729***	-0.317***
D10	1	(-3)	(-4.68)	(12.06)	(-12.48)	(12.4)	(-2.21)	(0.56)	(-1.48)	(5.37)	(-2.44)	(15.42)	(-3.42)	(4.37)	(-4.59)
		-0.348*	-0.45***	-0.136	-1.503***	1.241***	-0.133°	0.594	-1.254	1.178***	-0.145*	1.56***	-0.832***	0.634**	-0.431***
D10	2	(-2.57)	(-4.6)	(-1.14)	(-12.64)	(15.6)	(-1.68)	(0.56)	(-1.48)	(6.1)	(-2.47)	(15.42)	(-3.42)	(2.82)	(-4.63)
		0.07	-0.27***	0.245**	-0.996***	1.376***	-0.205**	0.594	-1.254	1.184***	-0.149*	1.56***	-0.832***	0.789***	-0.244***
D10	3	(0.75)	(-3.99)	(3.08)	(-12.59)	(19.75)	(-2.96)	(0.56)	(-1.48)	(5.95)	(-2.46)	(15.42)	(-3.42)	(6.1)	(-4.56)
		0.478***	-0.685***	0.339***	-0.87***	1.214***	-0.118*	0.594	-1.254	1.164***	-0.135*	1.56***	-0.832***	0.722***	-0.326***
D10	4	(8.68)	(-12.52)	(4.87)	(-12.57)	(22.05)	(-2.16)	(0.56)	(-1.48)	(6.54)	(-2.49)	(15.42)	(-3.42)	(4.23)	(-4.6)

		A08	Transp air+ra	A09	Transp_rout	A10	Loisirs	A11	Autres servi	A12	Autres produ	A13	Loyers	A14	Véhicules d'	A14	Véhicules d'
decile	typo4	Income	Price	Income	Price	Income	Price	Income	Price	Income	Price	Income	Price	Income	Price	Income	Price
		1.307***	-0.14	1.388***	-0.671	1.581***	-0.204*	1.147***	-0.238***	1.385***	-0.419***	0.563**	-0.745°	1.926***	-0.412°	1.926***	-0.412°
D01	1	(9.21)	(-1.51)	(5.89)	(-1.39)	(38.8)	(-2.32)	(40.84)	(-7.49)	(34.32)	(-4.97)	(2.79)	(-1.92)	(4.54)	(-1.79)	(4.54)	(-1.79)
		1.377***	-0.171	1.448***	-0.774	1.796***	-0.26*	1.147***	-0.237***	1.436***	-0.467***	0.563**	-0.745°	1.985***	-0.434°	1.985***	-0.434°
D01	2	(7.9)	(-1.49)	(5.32)	(-1.39)	(32.16)	(-2.15)	(40.94)	(-7.49)	(31.42)	(-4.89)	(2.79)	(-1.92)	(4.39)	(-1.77)	(4.39)	(-1.77)
		1.435***	-0.196	1.541***	-0.934	1.518***	-0.188*	1.131***	-0.215***	1.368***	-0.403***	0.563**	-0.745°	3.232**	-0.892	3.232**	-0.892
D01	3	(7.13)	(-1.48)	(4.69)	(-1.39)	(41.78)	(-2.39)	(45.24)	(-7.6)	(35.46)	(-5)	(2.79)	(-1.92)	(3.16)	(-1.6)	(3.16)	(-1.6)
		1.562***	-0.251	1.566***	-0.977	1.79***	-0.259*	1.121***	-0.201***	1.431***	-0.462***	0.563**	-0.745°	2.909***	-0.774	2.909***	-0.774
D01	4	(6.01)	(-1.47)	(4.55)	(-1.39)	(32.3)	(-2.16)	(48.44)	(-7.69)	(31.7)	(-4.9)	(2.79)	(-1.92)	(3.32)	(-1.63)	(3.32)	(-1.63)
		1.445***	-0.2	1.501***	-0.865	1.544***	-0.195*	1.153***	-0.246***	1.363***	-0.398***	0.548**	-0.771°	1.963***	-0.426°	1.963***	-0.426°
D02	1	(7.02)	(-1.48)	(4.93)	(-1.39)	(40.46)	(-2.36)	(39.47)	(-7.45)	(35.8)	(-5.01)	(2.63)	(-1.93)	(4.44)	(-1.77)	(4.44)	(-1.77)
		1.555***	-0.248	1.633***	-1.093	1.862***	-0.278*	1.144***	-0.233***	1.442***	-0.472***	0.548**	-0.771°	2.352***	-0.569°	2.352***	-0.569°
D02	2	(6.06)	(-1.47)	(4.25)	(-1.39)	(30.79)	(-2.12)	(41.67)	(-7.51)	(31.13)	(-4.89)	(2.63)	(-1.93)	(3.79)	(-1.69)	(3.79)	(-1.69)
		1.533***	-0.238	1.607***	-1.047	1.521***	-0.189*	1.143***	-0.233***	1.354***	-0.389***	0.548**	-0.771°	2.173***	-0.503°	2.173***	-0.503°
D02	3	(6.22)	(-1.47)	(4.36)	(-1.39)	(41.62)	(-2.39)	(41.76)	(-7.51)	(36.53)	(-5.03)	(2.63)	(-1.93)	(4.04)	(-1.72)	(4.04)	(-1.72)
		2.384***	-0.607	1.791***	-1.365	2.04***	-0.324*	1.118***	-0.196***	1.461***	-0.491***	0.548**	-0.771°	3.964**	-1.161	3.964**	-1.161
D02	4	(3.73)	(-1.45)	(3.73)	(-1.39)	(27.96)	(-2.05)	(49.68)	(-7.72)	(30.22)	(-4.86)	(2.63)	(-1.93)	(2.92)	(-1.57)	(2.92)	(-1.57)
		1.49***	-0.22	1.538***	-0.929	1.541***	-0.194*	1.159***	-0.255***	1.358***	-0.393***	0.524*	-0.813°	1.92***	-0.41°	1.92***	-0.41°
D03	1	(6.57)	(-1.48)	(4.71)	(-1.39)	(40.59)	(-2.36)	(38.12)	(-7.42)	(36.16)	(-5.02)	(2.39)	(-1.93)	(4.55)	(-1.79)	(4.55)	(-1.79)
		1.754***	-0.334	1.738***	-1.274	1.919***	-0.292*	1.136***	-0.222***	1.432***	-0.463***	0.524*	-0.813°	2.234***	-0.525°	2.234***	-0.525°
D03	2	(5.03)	(-1.46)	(3.87)	(-1.39)	(29.76)	(-2.09)	(43.81)	(-7.57)	(31.61)	(-4.9)	(2.39)	(-1.93)	(3.95)	(-1.71)	(3.95)	(-1.71)
		1.683***	-0.304	1.753***	-1.298	1.514***	-0.187*	1.144***	-0.233***	1.351***	-0.386***	0.524*	-0.813°	2.431***	-0.598°	2.431***	-0.598°
D03	3	(5.33)	(-1.46)	(3.83)	(-1.39)	(41.99)	(-2.4)	(41.67)	(-7.51)	(36.72)	(-5.03)	(2.39)	(-1.93)	(3.7)	(-1.68)	(3.7)	(-1.68)
		3.954**	-1.289	1.805***	-1.389	1.912***	-0.291*	1.114***	-0.191***	1.439***	-0.47***	0.524*	-0.813°	4.436**	-1.335	4.436**	-1.335
D03	4	(2.9)	(-1.44)	(3.69)	(-1.39)	(29.88)	(-2.1)	(51.11)	(-7.76)	(31.28)	(-4.89)	(2.39)	(-1.93)	(2.82)	(-1.56)	(2.82)	(-1.56)
		1.476***	-0.214	1.536***	-0.926	1.522***	-0.189*	1.156***	-0.251***	1.351***	-0.387***	0.498*	-0.861°	1.943***	-0.419°	1.943***	-0.419°
D04	1	(6.71)	(-1.48)	(4.71)	(-1.39)	(41.53)	(-2.38)	(38.67)	(-7.43)	(36.71)	(-5.03)	(2.14)	(-1.93)	(4.49)	(-1.78)	(4.49)	(-1.78)
		1.698***	-0.31	1.753***	-1.299	1.772***	-0.254*	1.134***	-0.219***	1.406***	-0.438***	0.498*	-0.861°	2.462***	-0.609°	2.462***	-0.609°
D04	2	(5.26)	(-1.46)	(3.83)	(-1.39)	(32.71)	(-2.17)	(44.37)	(-7.58)	(33.07)	(-4.94)	(2.14)	(-1.93)	(3.67)	(-1.67)	(3.67)	(-1.67)
		1.699***	-0.311	1.695***	-1.199	1.475***	-0.177*	1.139***	-0.227***	1.339***	-0.375***	0.498*	-0.861°	2.601***	-0.661°	2.601***	-0.661°
D04	3	(5.26)	(-1.46)	(4.01)	(-1.39)	(44.27)	(-2.45)	(42.87)	(-7.54)	(37.69)	(-5.06)	(2.14)	(-1.93)	(3.54)	(-1.65)	(3.54)	(-1.65)
		2.727***	-0.757	1.866***	-1.494	1.797***	-0.261*	1.116***	-0.194***	1.418***	-0.45***	0.498*	-0.861°	4.974**	-1.533	4.974**	-1.533
D04	4	(3.42)	(-1.44)	(3.55)	(-1.39)	(32.13)	(-2.15)	(50.21)	(-7.73)	(32.38)	(-4.92)	(2.14)	(-1.93)	(2.73)	(-1.55)	(2.73)	(-1.55)
		1.5***	-0.224	1.559***	-0.965	1.493***	-0.182*	1.153***	-0.246***	1.343***	-0.379***	0.477*	-0.897°	2.048***	-0.457°	2.048***	-0.457°
D05	1	(6.49)	(-1.48)	(4.59)	(-1.39)	(43.17)	(-2.42)	(39.44)	(-7.45)	(37.32)	(-5.05)	(1.97)	(-1.94)	(4.26)	(-1.75)	(4.26)	(-1.75)
		1.662***	-0.295	1.685***	-1.182	1.734***	-0.244*	1.129***	-0.212***	1.404***	-0.436***	0.477*	-0.897°	2.682***	-0.69	2.682***	-0.69
D05	2	(5.43)	(-1.46)	(4.05)	(-1.39)	(33.67)	(-2.19)	(45.83)	(-7.62)	(33.17)	(-4.94)	(1.97)	(-1.94)	(3.48)	(-1.65)	(3.48)	(-1.65)
		1.768***	-0.34	1.729***	-1.258	1.473***	-0.177*	1.136***	-0.223***	1.333***	-0.369***	0.477*	-0.897°	2.423***	-0.595°	2.423***	-0.595°
D05	3	(4.98)	(-1.46)	(3.9)	(-1.39)	(44.38)	(-2.45)	(43.65)	(-7.56)	(38.21)	(-5.07)	(1.97)	(-1.94)	(3.71)	(-1.68)	(3.71)	(-1.68)
		3.151**	-0.94	1.916***	-1.579	1.771***	-0.254*	1.116***	-0.194***	1.405***	-0.437***	0.477*	-0.897°	3.822**	-1.109	3.822**	-1.109
D05	4	(3.17)	(-1.44)	(3.44)	(-1.39)	(32.74)	(-2.17)	(50.29)	(-7.74)	(33.12)	(-4.94)	(1.97)	(-1.94)	(2.95)	(-1.58)	(2.95)	(-1.58)
		1.477***	-0.214	1.545***	-0.94	1.483***	-0.179*	1.151***	-0.243***	1.338***	-0.374***	0.449°	-0.947°	2.015***	-0.445°	2.015***	-0.445°
D06	1	(6.7)	(-1.48)	(4.67)	(-1.39)	(43.77)	(-2.44)	(39.89)	(-7.46)	(37.75)	(-5.06)	(1.76)	(-1.94)	(4.33)	(-1.76)	(4.33)	(-1.76)
		1.594***	-0.265	1.722***	-1.246	1.686***	-0.232*	1.131***	-0.215***	1.385***	-0.418***	0.449°	-0.947°	2.454***	-0.606°	2.454***	-0.606°
D06	2	(5.81)	(-1.47)	(3.92)	(-1.39)	(35.03)	(-2.22)	(45.28)	(-7.6)	(34.33)	(-4.97)	(1.76)	(-1.94)	(3.68)	(-1.67)	(3.68)	(-1.67)
		1.709***	-0.315	1.805***	-1.388	1.446***	-0.17*	1.137***	-0.223***	1.322***	-0.359***	0.449°	-0.947°	2.559***	-0.645°	2.559***	-0.645°
D06	3	(5.21)	(-1.46)	(3.69)	(-1.39)	(46.2)	(-2.5)	(43.51)	(-7.56)	(39.13)	(-5.09)	(1.76)	(-1.94)	(3.58)	(-1.66)	(3.58)	(-1.66)
		2.832***	-0.802	1.88***	-1.518	1.697***	-0.235*	1.114***	-0.191***	1.389***	-0.423***	0.449°	-0.947°	3.946**	-1.155	3.946**	-1.155
D06	4	(3.34)	(-1.44)	(3.52)	(-1.39)	(34.69)	(-2.22)	(51.08)	(-7.76)	(34.05)	(-4.96)	(1.76)	(-1.94)	(2.92)	(-1.57)	(2.92)	(-1.57)
		1.482***	-0.217	1.622***	-1.073	1.458***	-0.173*	1.149***	-0.241***	1.331***	-0.368***	0.417	-1.003°	2.356***	-0.57°	2.356***	-0.57°
D07	1	(6.65)	(-1.48)	(4.29)	(-1.39)	(45.36)	(-2.48)	(40.27)	(-7.47)	(38.33)	(-5.07)	(1.55)	(-1.94)	(3.79)	(-1.69)	(3.79)	(-1.69)
		1.554***	-0.247	1.677***	-1.168	1.626***	-0.216*	1.129***	-0.212***	1.372***	-0.407***	0.417	-1.003°	2.554***	-0.643°	2.554***	-0.643°
D07	2	(6.07)	(-1.47)	(4.08)	(-1.39)	(37.02)	(-2.27)	(45.92)	(-7.62)	(35.17)	(-4.99)	(1.55)	(-1.94)	(3.58)	(-1.66)	(3.58)	(-1.66)
		1.657***	-0.292	1.78***	-1.346	1.429***	-0.165*	1.138***	-0.224***	1.314***	-0.352***	0.417	-1.003°	2.443***	-0.602°	2.443***	-0.602°
D07	3	(5.46)	(-1.47)	(3.75)	(-1.39)	(47.45)	(-2.53)	(43.27)	(-7.55)	(39.89)	(-5.11)	(1.55)	(-1.94)	(3.69)	(-1.67)	(3.69)	(-1.67)
		2.172***	-0.516	1.85***	-1.466	1.589***	-0.207*	1.114***	-0.191***	1.357***	-0.392***	0.417	-1.003°	3.238**	-0.894	3.238**	-0.894
D07	4	(4.01)	(-1.45)	(3.58)	(-1.39)	(38.47)	(-2.31)	(51.17)	(-7.76)	(36.29)	(-5.02)	(1.55)	(-1.94)	(3.15)	(-1.6)	(3.15)	(-1.6)
		1.425***	-0.192	1.611***	-1.055	1.423***	-0.164*	1.148***	-0.24***	1.318***	-0.355***	0.378	-1.072°	2.38***	-0.579°	2.38***	-0.579°
D08	1	(7.25)	(-1.48)	(4.34)	(-1.39)	(47.95)	(-2.54)	(40.52)	(-7.48)	(39.55)	(-5.1)	(1.32)	(-1.95)	(3.76)	(-1.68)	(3.76)	(-1.68)
		1.555***	-0.248	1.616***	-1.063	1.54***	-0.194*	1.124***	-0.206***	1.348***	-0.383***	0.378	-1.072°	2.388***	-0.582°	2.388***	-0.582°
D08	2	(6.06)	(-1.47)	(4.32)	(-1.39)	(40.67)	(-2.36)	(47.26)	(-7.66)	(36.99)	(-5.04)	(1.32)	(-1.95)	(3.75)	(-1.68)	(3.75)	(-1.68)
		1.592***	-0.264	1.807***	-1.393	1.403***	-0.158**	1.136***	-0.222***	1.304***	-0.342***	0.378	-1.072°	2.659***	-0.682	2.659***	-0.682
D08	3	(5.82)	(-1.47)	(3.68)	(-1.39)	(49.61)	(-2.58)	(43.77)	(-7.56)	(40.91)	(-5.14)	(1.32)	(-1.95)	(3.5)	(-1.65)	(3.5)	(-1.65)
		2.162***	-0.511	1.92***	-1.586	1.59***	-0.207*	1.115***	-0.192***	1.351***	-0.386***	0.378	-1.072°	2.779***	-0.726	2.779***	-0.726
D08	4	(4.02)	(-1.45)	(3.43)	(-1.39)	(38.42)	(-2.31)	(50.88)	(-7.75)	(36.72)	(-5.03)	(1.32)	(-1.95)	(3.41)	(-1.64)	(3.41)	(-1.64)
		1.408***	-0.184	1.628***	-1.084	1.388***	-0.154**	1.144***	-0.234***	1.302***	-0.34***	0.335	-1.149°	2.548***	-0.641°	2.548***	-0.641°
D09	1	(7.46)	(-1.49)	(4.27)	(-1.39)	(50.96)	(-2.62)	(41.51)	(-7.51)	(41.14)	(-5.14)	(1.09)	(-1.95)	(3.59)	(-1.66)	(3.59)	(-1.66)
		1.522***	-0.234	1.655***	-1.13	1.48***	-0.178*	1.122***	-0.203***	1.323***	-0.36***	0.335	-1.149°	2.469***	-0.612°	2.469***	-0.612°
D09	2	(6.31)	(-1.47)	(4.16)	(-1.39)	(43.94)	(-2.44)	(48.08)	(-7.68)	(39.08)	(-5.09)	(1.09)	(-1.95)	(3.67)	(-1.67)	(3.67)	(-1.67)
		1.604***	-0.269	1.812***	-1.401	1.392***	-0.156**	1.132***	-0.216***	1.3***	-0.338***	0.335	-1.149°	2.94***	-0.785	2.94***	-0.785
D09	3	(5.75)	(-1.47)	(3.67)	(-1.39)	(50.57)	(-2.61)	(44.95)	(-7.6)	(41.37)	(-5.15)	(1.09)	(-1.95)	(3.3)	(-1.62)	(3.3)	(-1.62)
		1.804***	-0.356	1.676***	-1.167	1.52***	-0.189*	1.114***	-0.19***	1.334***	-0.37***	0.335	-1.149°	2.559***	-0.645°	2.559***	-0.645°
D09	4	(4.85)	(-1.46)	(4.08)	(-1.39)	(41.63)	(-2.39)	(51.31)	(-7.76)	(38.09)	(-5.07)	(1.09)	(-1.95)	(3.58)	(-1.66)	(3.58)	(-1.66)
		1.342***	-0.156	1.588***	-1.014	1.324***	-0.138**	1.135***	-0.221***	1.274***	-0.314***	0.179	-1.426*	3.75**	-1.083	3.75**	-1.083
D10	1	(8.49)	(-1.5)	(4.45)	(-1.39)	(58.2)	(-2.8)	(43.88)	(-7.57)	(44.34)	(-5.23)	(0.47)	(-1.96)	(2.97)	(-1.58)	(2.97)	(-1.58)
		1.433***	-0.195	1.506***	-0.874	1.385***	-0.154**	1.115***	-0.192***	1.288***	-0.327***	0.179	-1.426*	2.311***	-0.554°	2.311***	-0.554°
D10	2	(7.16)	(-1.48)	(4.9)	(-1.39)	(51.26)	(-2.63)	(50.81)	(-7.75)	(42.63)	(-5.18)	(0.47)	(-1.96)	(3.84)	(-1.69)	(3.84)	(-1.69)
		1.457***	-0.205	1.813***	-1.403	1.343***	-0.143**	1.129***	-0.213***	1.276***	-0.315***	0.179	-1.426*	3.222**	-0.889	3.222**	-0.889
D10	3	(6.9)	(-1.48)	(3.67)	(-1.39)	(55.8)	(-2.74)	(45.66)	(-7.61)	(44.11)	(-5.22)	(0.47)	(-1.96)	(3.16)	(-1.6)	(3.16)	(-1.6)
		1.642***	-0.286	1.645***	-1.113	1.428***	-0.165*	1.111***	-0.187***	1.298***	-0.337***	0.179	-1.426*	2.321***	-0.557°	2.321***	-0.557°
D10	4	(5.53)	(-1.47)	(4.2)	(-1.39)	(47.52)	(-2.53)	(52.23)	(-7.79)	(41.51)	(-5.15)	(0.47)	(-1.96)	(3.83)	(-1.69)	(3.83)	(-1.69)

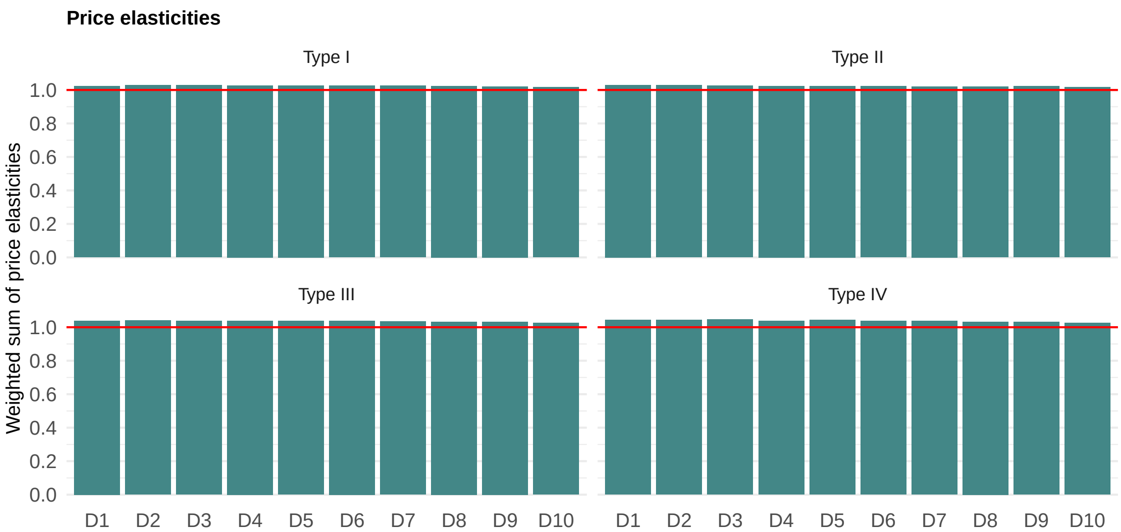
Source: Authors calculations. Reading: households in decile 1, type I, have income and price elasticities of 0.28 and -0.18 for agricultural products; 0.46 and -0.70 for electricity; etc. We estimated the shaded elasticities without distinction of class (A04; A06; A13). Significance thresholds: * 5% = 1.96 ; ** 1% = 2.58 ; *** 0.1% = 3.29. In brackets we indicate the values of the Student's t-test.

Figure H.2: Weighted sum of income elasticities by budget share



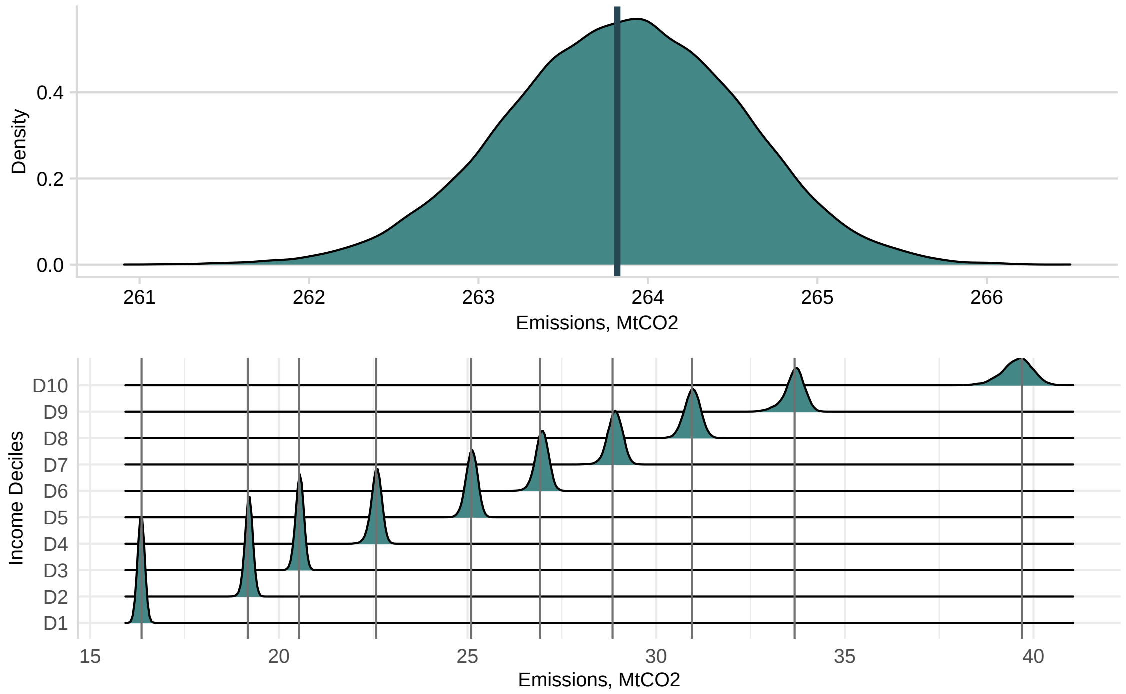
Source: Authors calculations. Note: The value of the carbon tax is 158€/tCO_2 .

Figure H.3: Weighted sum of price elasticities by budget share



Source: Authors calculations. Note: The value of the carbon tax is 158€/tCO_2 .

Figure I.4: Distribution of final emissions of households, using Monte-Carlo simulations on price and income elasticities



Note: For each of the 26,000 simulations, we independently draw each of the elasticities in a Gaussian distribution. The vertical lines indicate the volume of emissions using the mean expectations. The value of the carbon tax is 158€/tCO_2 .

Figure I.5: Share of household experiencing a backfire per wave of survey