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Evidence from a Natural Experiment on Cross-border Fuel Sales

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Abstract

We report a natural experiment on the border between Spain and Portugal, in which we analyze the potential effects of carbon pricing instruments on fuel tourism and the associated risk of carbon leakage. We exploit a fuel tax increase in Portugal to identify and quantify its effect on fuel sales in the Spanish border regions. Our results from applying a difference-in-difference strategy and a synthetic control methodology robustly show that while cross-border tax changes do not affect gasoline sales they have a significant impact on diesel sales, increasing the latter on average by 10% in the border provinces. Synthetic control estimates further show that this effect is mainly driven by routes carrying the highest volumes of heavy-duty vehicles. This **novel** differential effect by fuel type is attributable to the massive tanks of heavy goods vehicles that run on diesel. We estimate a carbon leakage equivalent to 29% of Portugal's annual mitigation commitment for road transport emissions. The central contribution and policy implication of this paper, which might equally be transferred to other developed countries of a federal or quasi-federal nature, is that fuel tourism driven by heavy goods vehicles confounds the potential mitigation effects and revenue gains of climate policy.

Keywords: Carbon leakage; fuel tourism; carbon price; fuel tax; road transportation; climate policy

JEL codes: Q58, R48, H23, H26

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1. Introduction

As climate-related crises worsen, policy makers are increasingly turning their attention to the mitigation of greenhouse gas (GHG) emissions from the transport sector, especially those generated by road transport. Transport is the only sector in which current GHG emissions are still above 1990 levels –33% higher in the EU (EEA, 2022)– and it has actually become the largest GHG contributor in many countries, including the US (EPA, 2023). Moreover, population and income growth project further increases in miles traveled, car ownership rates and demand for freight transport globally, which, given current policies and technologies, will result in higher GHG emissions (IEA, 2022).

Against this backdrop, many countries are ramping up their climate policies on road transportation. This includes the EU, which in recent years has adopted more ambitious climate targets[1] by proposing, inter alia, a revision of the Energy Taxation Directive (ETF) and the coverage of road transport emissions by a new emissions trading system that will become operative as of 2027. In this regard, pricing instruments –including carbon pricing and energy taxes– are considered a cost-effective approach to reducing emissions (Gago et al., 2014). Yet, despite the efforts of EU legislation to harmonize energy taxation across the Union, differences in fuel prices between neighboring countries can jeopardize potential gains from these policies by becoming a source of carbon leakage and revenue loss. Here, we examine how so-called 'fuel tourism' –that is, the optimizing behavior of drivers who cross a border to fill up their vehicles at a lower price– is interacting with climate policies in the road transportation sector.

Fuel tourism has been well documented in many territories, including Europe (Banfi et al., 2005; Jansen & Jonker, 2018; Leal et al., 2009; Morton et al., 2018) and the US (Manuszak & Moul, 2009). In this paper, we analyze the role that this strategic behavior plays in the current context of climate policies, especially, that of increasing fuel prices via taxes or carbon pricing. Significantly, drivers have been found to react more to changes in fuel prices resulting from taxes or carbon pricing than to the same price change derived from market forces (Antweiler & Gulati, 2016; Li et al., 2014; Scott, 2012; Tiezzi & Verde, 2016). This reaction is explained in terms of the salience or persistence of the tax versus market price oscillations. Hence, based on the assumption that drivers fill up their tanks in the

[1] In July 2021, the EU Commission published its "fit-for-55" package, committing itself to reduce GHG emissions by 55% (compared to 1990 levels) as a step to achieving climate neutrality by 2050.

low-price country when the latter is considered close enough –i.e. choose to engage in fuel tourism, this paper explores whether a tax-motivated price change further increases fuel tourism. In short, we seek to determine the elasticity of fuel tourism to cross-border changes in energy taxes or similar climate policies.

To do so, we exploit the plausibly exogenous change in the fuel tax in Portugal, the *Imposto sobre os Produtos Petrolíferos* (ISP), to analyze fuel consumption –both of gasoline and diesel– in Spain at the province level (NUTS 3). Spain and Portugal share the longest uninterrupted border in the EU (1,214km), characterized by numerous crossing points, while gasoline and diesel prices have traditionally been much lower in Spain, an ideal mix to ensure fuel tourism is an everyday reality. In February 2016, Portugal raised its fuel tax by six cents of a euro, making fuel tourism, in theory, even more appealing. Here we identify, and quantify, the effect that this tax increase had on fuel consumption and emission rates and discuss its implications in terms of climate mitigation policies.

In our identification strategy we use Spain's non-border provinces and, as such, those not exposed to the tax change in Portugal, as a control group for the seven treated provinces that do share a border with Portugal. We employ two seminal quasi-experimental methods: a two-way fixed effects difference-in-difference estimator and a synthetic control approach (Abadie, 2021). In so doing, we use monthly data, spanning January 2011–December 2019, of both gasoline and diesel consumption at the province level, controlling for a range of potential confounders including fuel prices and the number of filling stations as well as income and demographic characteristics. We show that our main key assumptions are met for both identification strategies, hence yielding credible causal results.

The main result to emerge from the difference-in-difference estimation is the significantly different outcomes presented by gasoline, on the one hand, and diesel, on the other. While consumption of the former shows no significant response to the cross-border tax increase – indicating that fuel tourism follows a 'business-as-usual' pattern, diesel consumption increases by around 10% in the border provinces. These results are consistent across different specifications and matching procedures, including propensity score and entropy balance matchings (Abadie & Imbens, 2011; Hainmueller, 2012). Moreover, this result cannot be attributed to a potentially endogenous distribution of filling stations. We estimate a cross elasticity of fuel sales in Spain with respect to Portuguese tax changes of

1.9 for diesel and 0.2 for gasoline. This difference can be explained by the fact that heavy goods vehicles – run almost exclusively on diesel and with huge fuel tanks – constitute the main source of the cross-border response to the change in tax.

To better control for potential time-varying unobserved heterogeneity, we construct synthetic provinces for each of the seven border (treated) provinces, which provides additional confirmation of our outcomes –namely, a marked impact on diesel consumption but no effect on that of gasoline. The synthetic control procedure provides additional insights into the local distribution of this particular effect. 2. Although a positive effect on diesel consumption remains for most border provinces, only three of them –Badajoz up 7%, Huelva up 17%, Zamora up 20%– show a statistically significant increase at the standard levels of confidence. These three provinces lie on routes carrying the highest volumes of heavy-duty vehicles between Portugal and Spain (OTEP 2020).

The main implication of our findings is that heavy goods vehicles are channeling the carbon leakage attributable to pricing instruments in the road transportation sector. This result is relevant not only for cross-country trade but also for trade in federal or quasi-federal countries where taxation policies might differ. Emission reduction is likely to be confounded by emission leakage to neighboring countries in conjunction with a loss in revenue. Here, the tax change introduced in Portugal results in an annual carbon leakage of 115,000 tCO_2, equivalent to 29% of the country's annual CO_2 mitigation commitment for road transport for 2030 (NECP-Portugal, 2019). These emissions, however, far from being mitigated, are added to Spain's annual emissions, while Portugal must face the corresponding foregone revenue from its diesel tax.

We contribute to the broader literature on fuel taxation, fuel tourism and, more generally, horizontal tax externalities by factoring in the issue of carbon leakage in the current context of mitigation policies. Hence, this paper can be related to several strands of this literature. First, several papers show that tax-driven changes in fuel prices have higher elasticities than market-driven changes –the case, for example, of changes in fuel tax in the US (Tiezzi & Verde, 2016; Li et al., 2014; Scott, 2012; Davis and Kilian, 2011) and carbon taxes in Sweden (Andersson, 2019) and British Columbia, Canada (Antweiler & Gulati, 2016). This outcome, however, has not previously been analyzed from a cross-border perspective, which is of obvious relevance in the current context of the ramping up of climate policies. Second, the literature analyzing the influence on domestic fuel demand from cross-border price differences – aka fuel tourism – has primarily delivered information about cross-border (final) price elasticities but with no clear focus on tax-motivated price changes (Banfi et al., 2005; Coglianese et al., 2017; Coyne, 2017; Ghoddusi et al., 2022; Jansen & Jonker, 2018; Leal et al., 2009; Manuszak & Moul, 2009; Morton et al., 2018). Here, we show that tax-driven fuel tourism can be fuel specific.

A number of papers have studied horizontal tax externalities in multi-jurisdictional taxation for different goods. In the most similar study to the current one, Marion and Muehlegger (2018) analyze the case of the diesel taxes owed by interstate truck drivers in the US and show how they evade taxes by underreporting the amount of fuel consumed and their mileage in high-tax states. A part of this literature has focused on cross-border cigarette taxes (Agaku et al., 2016; DeCicca et al., 2013; Harding et al., 2012; Lovenheim, 2008). The main lesson to be drawn from these papers is that the health benefits from a higher tax on cigarettes are not fully captured because of smuggling and other cross-border tax avoidance strategies. Here, we assert the same rationale for transport fuel, only that besides any potential health benefits (also present in the transportation sector), any climate policy gains are foregone due to carbon leakage, to which we must add a notable tax revenue loss.

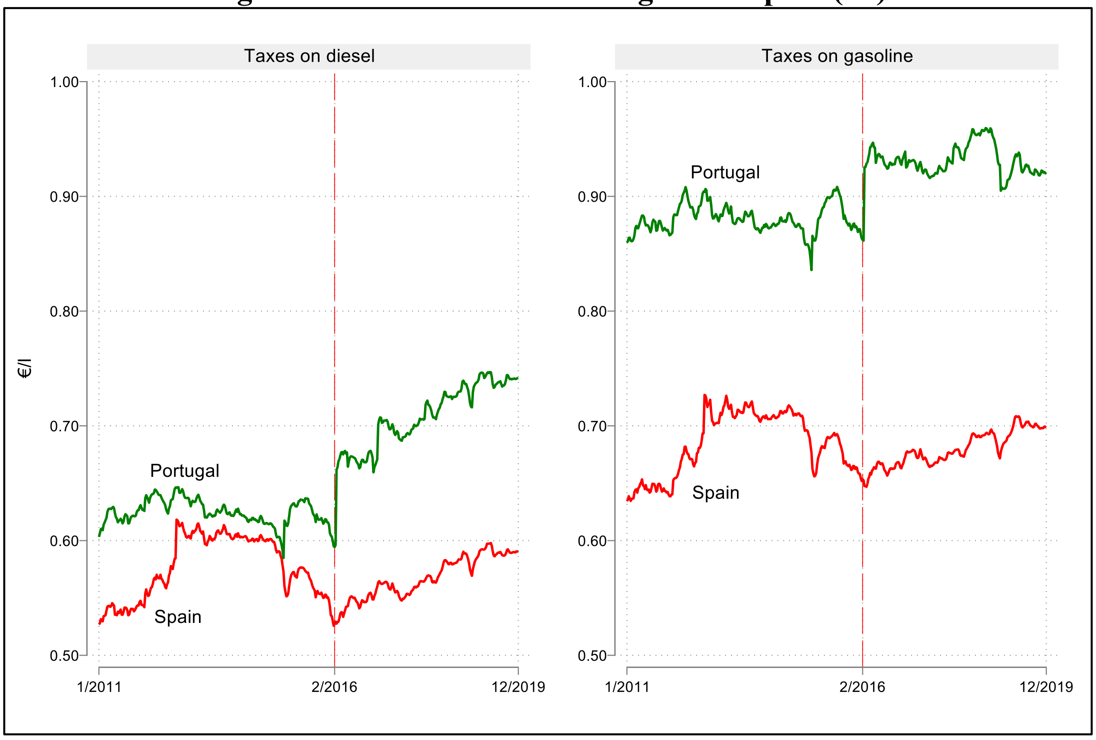
In the section that follows, we describe the setting of this natural experiment, i.e. the fuel tax increase in Portugal, and report transport fuel demand data for both Spain and Portugal. In Section 3, we describe the data used and the identification strategies we employ. Section 4 presents our main results and Section 5 discusses the main policy implications to be derived from them. Section 6 concludes.

2. Fuel prices in Portugal and Spain

In February 2016, the Portuguese government raised excise taxes on transportation fuels: the ISP saw an increase of 0,06 €/l. Figure 1 shows the evolution of all fuel taxes – including those on both diesel and gasoline– in Spain and Portugal between 2011 and 2019. While taxes on diesel are lower in both countries, the difference in the case of gasoline is more marked, although after February 2016, the gap between the two countries widened for both fuel types.

However, fuel prices tend to be somewhat volatile and these tax differences do not necessarily translate proportionally to final fuel prices; indeed, the tax increase can be offset by the fuel price variation. This being the case, the relative price differences between Spain and Portugal would not have been as dramatic as the tax increase itself might suggest. Figure 2 shows final fuel prices in the two countries. Spain has traditionally charged lower prices than Portugal, especially as regards gasoline. One month before the introduction of the Portuguese tax increase, the average pump price of gasoline in Portugal stood at an average of €1.31 per liter compared to €1.11 in Spain. This 20-cent difference climbed to 25 cents after the rise in tax. Diesel prices, in contrast, were more similar before the new tax: on average, diesel in Spain was about 9 cents cheaper before the rise in ISP and 15 cents cheaper after. Hence, the price differential of Spanish gasoline continued to be greater than that of diesel prices when compared to the respective price at the pumps in Portugal: Spanish gasoline being about 25 cents cheaper and Spanish diesel 15 cents cheaper.

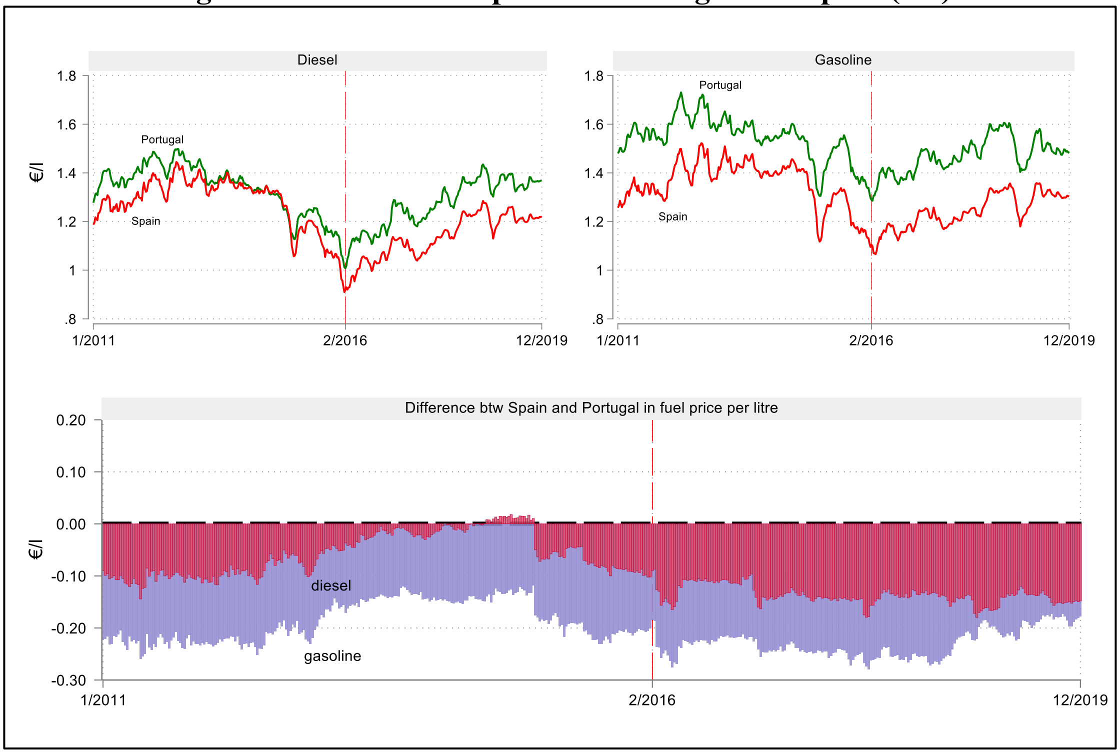
Figure 1. All fuel taxes in Portugal and Spain (€/l)



Notes: This figure plots the evolution in all diesel and gasoline taxes in Spain and Portugal. The vertical line signals the six-cent increase in ISP in Portugal. Overall, following the tax hike, the ISP on diesel and gasoline increased to €0.34 and €0.58 per liter, respectively. This represents 52 and 62%, respectively, of all fuel taxes. Source: Weekly Oil Bulletin prices History, provided by Directorate-General Energy (DG-ENER)

However, these differences in fuel price are only of any relevance to those regions located near the border between Spain and Portugal. Figure 3 identifies Spain's provinces, our observation unit, and differentiates between the seven border provinces that serve as our treated group (in orange) and the remaining control provinces (in green). As such, we assume that the strategic tax avoidance behavior we seek to identify manifests itself solely in these seven provinces while all the other provinces will be totally unaffected.

Figure 2. After-tax fuel prices in Portugal and Spain (€ /l)



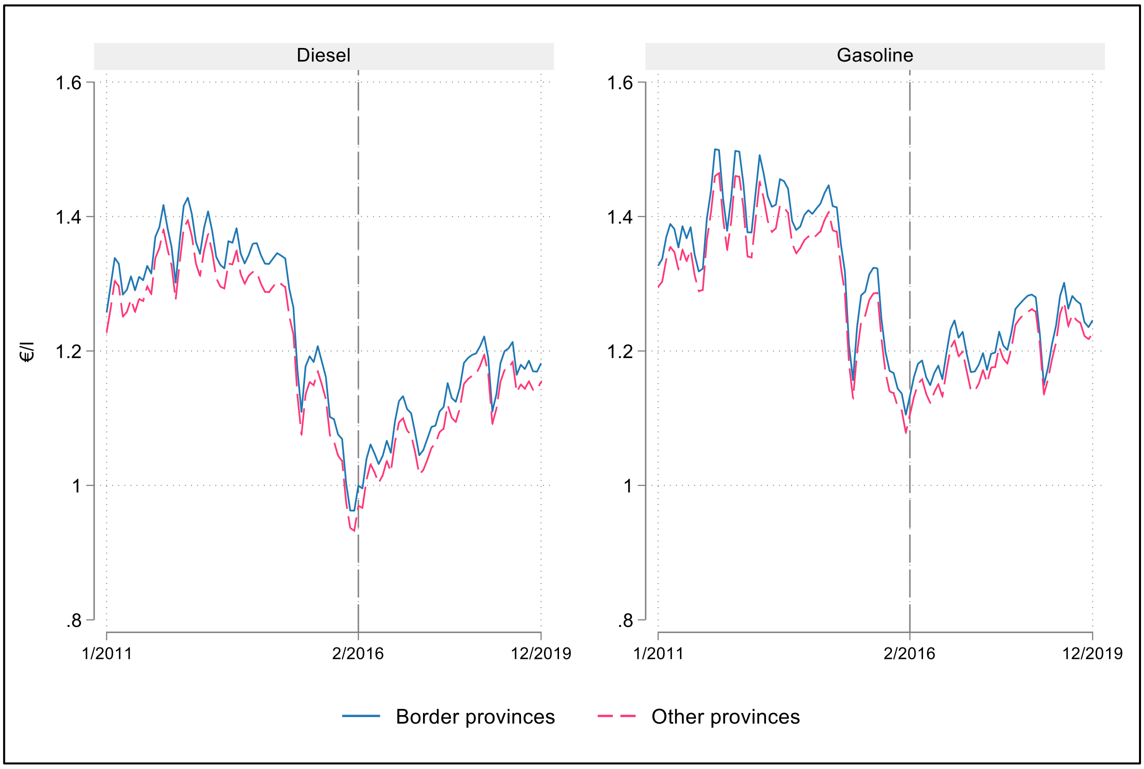
Notes: The upper panel plots the evolution in after-tax fuel prices – diesel and gasoline – in Spain and Portugal. The vertical line signals the six-cent increase in ISP in Portugal. The graph in the lower panel shows price differences between the two countries (where zero represents no difference and negative values represent cheaper prices in Spain). Source: Weekly Oil Bulletin prices History, provided by Directorate-General Energy (DG-ENER)

Figure 3. Spanish provinces (NUTS 3)

Note: Spanish provinces are NUTS 3 regions. In orange, provinces bordering Portugal (in light gray); in green, the remaining provinces serving as controls.

Our natural experiment relies on the similarity between our treated and control provinces in all aspects regarding their transport fuel demand. Importantly, because transportation fuel can be considered a homogenous product, price is expected to be a highly relevant demand factor, ceteris paribus. Figure 4 compares the evolution in the fuel prices of the treated and control provinces between 2011 and 2019. On average, fuel prices have remained largely parallel, with those in the border provinces 2 cents per liter higher than those in the other provinces. Thus, on average, the drivers in our control group have no incentive to fill their tanks in the provinces of the treated group, the incentive existing solely for drivers from/to Portugal. This small, yet parallel, difference is further confirmed when we examine the evolution in fuel prices in each border province compared to the price evolution in that of its immediate neighbor (Figure A1). Only Zamora and Salamanca are capable of attracting drivers from Ourense and Cáceres (also treated), respectively, but not to any greater degree after the rise in the Portuguese fuel tax. In other words, we detect a parallel trend in prices. In short, our strategy is designed to identify changes in fuel consumption as a response to the tax change in Portugal, above and beyond the prevailing regional pattern, such as, any existing fuel tourism. In the following section we outline our research design in detail.

Figure 4. Gasoline and diesel price evolution in treated and control Spanish provinces



3. Research design

Causal identification requires careful research design. Here, we exploit the exogeneity of the tax increase in Portugal to analyze the extent to which domestic fuel consumption is explained by the cross-border tax. In this section, we describe the data used and the two empirical strategies employed —difference-in-difference and a synthetic control procedure— addressing the key assumptions that each method requires for a net causal identification.

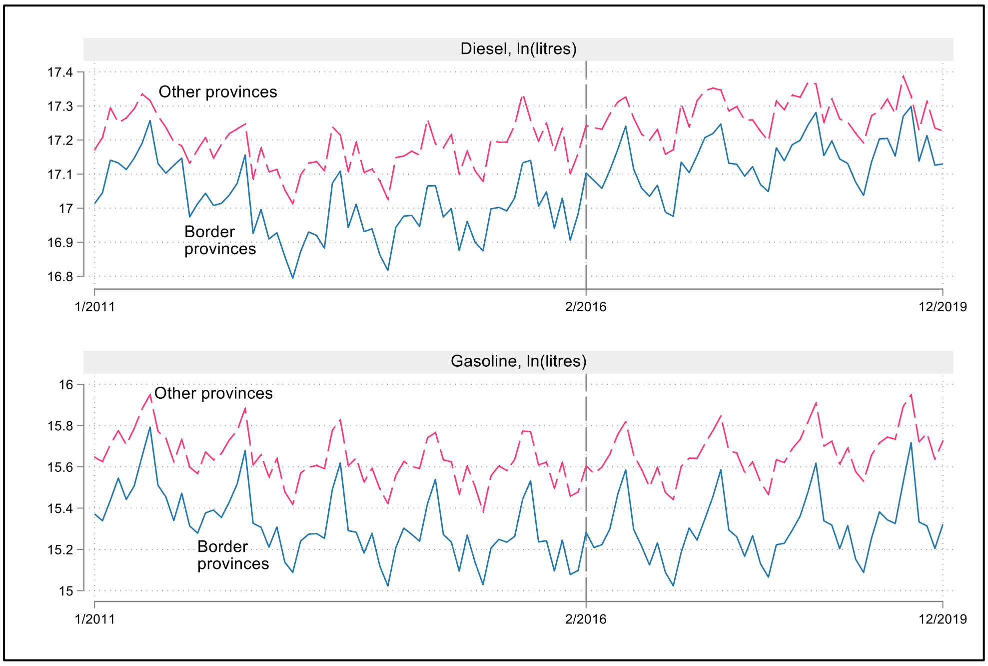
3.1. Data

Our main variable of interest is transportation fuel consumption at Spanish filling stations, aggregated at the monthly provincial level. Our data sample spans January 2011 to December 2019 and includes 48 peninsular provinces (the Canary Islands and the autonomous cities of Ceuta and Melilla, all in Africa, having been excluded). We obtain these from the Spanish National Markets and Competition Commission (CNMC). We also record average fuel prices, the number of filling stations, and how many of these are located near the Portuguese border (taken from CNMC and *Geoportal Gasolineras*). These covariates, together with other relevant demographic characteristics obtained from the Spanish Institute of Statistics (INE) –namely, population of the provinces, share of that population in the provincial capital and income– are used to balance treated and control provinces. As mentioned, the treated provinces consist of all those that share a border with Portugal and, hence, whose filling stations are exposed to fuel tourism and tax avoidance; the controls consist of all the remaining, comparable, provinces.

3.2. Difference-in-difference estimation

The validity of our difference-in-difference approach rests on the fact that Portuguese fiscal policy can be considered exogenous from Spanish fuel consumption and, related to this, that the parallel trends assumption holds, i.e., had the tax not been increased, fuel consumption in the treated and control groups would have followed the same parallel trends as before the intervention. The plausibility of this assumption can only be assessed by examining pre-trends: that is, if fuel consumption in the border provinces followed the same evolution as that in the other (comparable) Spanish provinces before the tax hike in Portugal. Then, we could reasonably assume that had there been no change in the tax rate, these trends would have continued to follow the same parallel course, indicating that any significant differences can be attributed to the change in tax policy. Figure 5 shows this assumption to be plausible in our context: before the intervention in February 2016, treated and control provinces followed a largely parallel trend in terms of both their diesel and gasoline consumption.

Figure 5. Fuel consumption in treated (border) and control Spanish provinces



Note: This figure shows the average consumption of gasoline and diesel (in liters) at the provincial level for seven provinces sharing a border with Portugal (Border provinces) and for the remaining forty-one Spanish provinces. Our identification strategy relies on the fact that, before the tax change in Portugal –our treatment (dashed vertical line)– both groups evolved in parallel.

We estimate the following two-way fixed effects difference-in-difference model:

$$\log(FC)_{it} = \alpha + \beta T_{it} + \lambda X_{it} + \gamma_i + \eta_t + \varepsilon_{iqt} \quad (1)$$

where FC represents the fuel consumption (either diesel or gasoline) in province i in month t. The main variable of interest is $T_{it} = Border_i \times TaxChange_t$, where $Border_i = 1$ if the province is a border province and $TaxChange_t = 1$ after February 2016. Therefore, β is our difference-in-difference coefficient, identifying the change in fuel consumption in Spanish border regions as a response to a tax change in Portugal. X_{it} is the set of relevant control covariates, including the logarithm of after-tax fuel prices, regional GPD per capita (in logs), share of population in the province's capital as a measure of the level of urbanization and the province's population (in logs) to account for the province scale effect. Fixed effects include those of the province (NUTS 3), NUTS 2 region-year (Comunidad Autónoma), month and year and, finally, month-year effects.

Because certain differences in the covariates might confound our effect of interest, Table 1 shows the different strategies adopted in making the control and treatment groups as comparable as possible in terms of these very covariates. The first group of columns show the differences between the treated and control provinces. The treated provinces are significantly poorer, less populated and with higher average prices than the controls. Although these differences can be controlled for by using them as control variables in the main regressions, we seek to improve comparability by means of matching procedures. This serves to make our estimators doubly robust (Bang & Robins, 2005). In the second group of columns, we use a propensity score matching (nearest neighbor) procedure in order to make the control group more comparable. This improves comparability between the treated and control groups in terms of the relevant covariates. However, one disadvantage of using propensity score matching is that the sample is reduced to the provinces that have common support in the covariates. In the third group of columns, we use the entropy balancing procedure (Hainmueller, 2012), which involves a generalization of the propensity score matching: instead of using only provinces with common support, the entropy balance reweights observations in the control group so that the mean and variance of the covariates resemble the mean and the variance of the treated group. Hence, in contrast to propensity score matching, where some units are discarded, entropy balancing uses all the observations in the control group, properly reweighted. This means that entropy balancing minimizes information loss from the pre-processed data. Again, differences between the treated and control groups are further reduced for most of the covariates.

Additionally, we refine the analysis by differentiating different treatment doses in terms of a province's share of filling stations located close to the frontier. Having a higher share might imply greater exposure to the treatment and, therefore, account for the bulk of response. To control for this, we replicate the above specification (1) by limiting the treatment group to border provinces with different ranges of filling station shares located close to the Portuguese border. Differences with regard to the baseline estimates should inform about the role that this factor potentially plays.

Table 1. Treated and control Spanish provinces by observable characteristics

Variables	T=0	T=1	Diff.
Full sample			
ln (income)	6.731	6.664	0.067***
Share inhab. in Prov. Capital	0.323	0.276	0.046***
ln(population)	13.282	12.972	0.310***
ln(before-tax price of diesel, 2016)	0.088	0.121	-0.033***
ln(before-tax price of gasoline, 2016)	0.182	0.212	-0.030***
Matched sample			
ln (income)	6.649	6.664	-0.015
Share inhab. in Prov. Capital	0.274	0.276	-0.002
ln(population)	12.941	12.972	-0.031
ln(before-tax price of diesel, 2016)	0.108	0.121	-0.013
ln(before-tax price of gasoline, 2016)	0.204	0.212	-0.008
Entropy balanced sample			
ln (income)	6.656	6.664	-0.008
Share inhab. in Prov. Capital	0.281	0.276	0.004
ln(population)	12.972	12.968	0.004
ln(before-tax price of diesel, 2016)	0.121	0.115	0.005
ln(before-tax price of gasoline, 2016)	0.212	0.208	0.003

Note: Mean values and differences (t-test) between treated (border with Portugal) and control provinces (no border) for the main control covariates for the year before the tax change in Portugal (i.e. 2015).

Table 2 shows the number of filling stations in each border province and their distribution according to the share of filling stations at different distances from the border. Compared to the other Spanish provinces, border provinces do not have a higher number of filling stations while in per capita terms they present similar magnitudes: border provinces have 0.27 filling stations per capita on average; the controls, 0.29. In per capita terms, the Spanish provinces with the most filling stations are Cuenca (0.51), Huesca (0.52), Lleida (0.43) and Teruel (0.44). Zamora, one of our border provinces, also has 0.43 filling stations per capita, placing it in the 90th percentile of the distribution. The distribution of these stations does not reveal a marked concentration near the border with Portugal, which might indicate that the higher relative number is not driven by its being a border province. To factor the distribution of filling stations in our empirical strategy, we analyze three additional samples according to three different exposures to the treatment (i.e. the border).

Table 3 shows the observables of these treated and control provinces for the three additional samples after the propensity score matching and entropy balancing have been applied. Conditional on data availability, we define the new treatment as conditional on having more than 20, 10 and 5% of filling stations within the first 25, 10 and 5 km of the border, respectively. As a result, we distinguish four different treatment levels according to different intensities: the first treatment is the baseline and it considers all (7) border provinces; the second restricts the treatment to provinces with at least 20% of their filling stations within 25 km of the frontier (that is, Pontevedra, Badajoz, Ourense and Huelva); the third restricts the treatment to provinces with more than 10% of their filling stations within 10 km of the border (that is, Pontevedra, Badajoz and Ourense); and, the fourth, includes only those provinces with more than 5% of their filling stations within 5 km of the border (that is, Pontevedra, Badajoz and Huelva). In the last three treatments, we exclude all the other frontier provinces. In all cases, entropy achieves a better balance of the covariates between the treated and control groups.

Table 2. Number of filling stations (FS) in border Spanish provinces and percentage of stations close to the Portuguese border

Province	# Filling stations	#FS per capita	FS within 5 km of border		FS within 10 km of border		FS within 15 km of border		FS within 25 km of border	
Badajoz	249	0.36	12	(5%)	34	(14%)	41	(16%)	54	(22%)
Cáceres	123	0.30	1	(1%)	3	(2%)	4	(3%)	11	(9%)
Huelva	122	0.23	9	(7%)	12	(10%)	15	(12%)	26	(21%)
Ourense	90	0.28	2	(2%)	12	(13%)	17	(19%)	35	(39%)
Pontevedra	171	0.18	12	(7%)	19	(11%)	36	(21%)	71	(42%)
Salamanca	96	0.28	4	(4%)	4	(4%)	9	(9%)	12	(13%)
Zamora	78	0.43	1	(1%)	3	(4%)	7	(9%)	11	(14%)

Note: This table shows the number of filling stations (FS) in each province sharing a border with Portugal and the percentage of FS within a specific distance of the Portuguese border.

The estimates can be considered as being unbiased as long as the parallel trends, the no anticipation and stable unit treatment value assumptions (SUTVA) hold. While parallel trends and no anticipation seem plausible here (see Figure 5), event estimates (pre-trends) are also provided to further assess their plausibility.

A SUTVA violation might originate from control provinces being affected by the cross-border tax hike. For instance, this would be the case if border provinces reacted to the tax border by lowering or raising their prices. This could affect neighboring provinces and, hence, lead to a SUTVA violation. However, this does not seem to be the case, as the provinces follow parallel trends as regards their average pricing (see Figure 4 and Figure A1 for further details). Other spillovers could be attributable to drivers (with origin or destination in Portugal) filling their tanks before/after the border provinces, which would impact fuel sales in the control provinces. This would be rational if, for instance, filling stations near the border increased their prices in response to the tax hike. Unfortunately, we are unable to observe actual filling behavior and, for this reason, our estimates should be read as a lower bound effect. We do, however, control for some of the other potential confounders by means of observables (including, the number of filling stations located close to the border); yet, we recognize that this remains vulnerable to unobservable factors for which we cannot control. In this regard, unobserved time-varying factors are not dealt with in a difference-in-difference strategy, only time-invariant factors are controlled for.[2] In what follows, the synthetic control methodology serves as a generalization of the difference-in-difference framework, accounting for these time-varying unobserved factors (Abadie & Gardeazabal, 2003; Abadie et al., 2010, 2015) and allowing us to investigate at the case-study level.

Table 3. Treated and control Spanish provinces. Alternative matched sample

	FS matched sample			**Entropy balanced sample**		
	T=0	**T=1**	**Diff.**	**T=0**	**T=1**	**Diff**
20% closer than 25km						
ln (income)	6.550	6.634	-0.084***	6.654	6.647	0.008
Share inhab. in Prov. Capital	0.276	0.230	0.046**	0.235	0.230	0.004
ln(population)	13.240	13.258	-0.018	13.254	13.265	-0.011
ln(before-tax price of diesel, 2016)	0.117	0.130	-0.013	0.251	0.253	-0.002
ln(before-tax price of gasoline, 2016)	0.218	0.224	-0.006	0.309	0.312	-0.003
10% closer than 10km						
ln (income)	6.616	6.681	-0.065**	6.647	6.681	-0.034
Share inhab. in Prov. Capital	0.231	0.214	0.017	0.213	0.214	0.000
ln(population)	12.979	13.289	-0.310**	13.312	13.289	0.023
ln(before-tax price of diesel, 2016)	0.111	0.133	-0.021	0.114	0.133	-0.019
ln(before-tax price of gasoline, 2016)	0.208	0.225	-0.017	0.210	0.225	-0.015
5% closer than 5km						
ln (income)	6.543	6.598	-0.055***	6.575	6.598	-0.023
Share inhab. in Prov. Capital	0.253	0.195	0.057***	0.194	0.195	-0.001
ln(population)	13.3	13.455	-0.154	13.492	13.455	0.037
ln(before-tax price of diesel, 2016)	0.104	0.125	-0.022	0.116	0.126	-0.010
ln(before-tax price of gasoline, 2016)	0.212	0.22	-0.009	0.212	0.220	-0.008

Note: Mean values for year 2015, the year prior to the tax change in Portugal.

[2] Note, however, that our difference-in-difference specification does capture some time-varying unobserved factors by including fixed effect interactions for region-year and month-year.

3.3. Synthetic control method

The synthetic control method estimates a counterfactual case scenario for each of the treated provinces by using control units as a donor pool. Control provinces are properly weighted by optimally chosen weights that minimize pre-treatment characteristics with the treated unit so as to resemble a synthetic treated unit. Thus, for example, we can compare observed Ourense with synthetic Ourense, the difference between the two being that the latter did not experience the increase in the Portuguese fuel tax. As discussed earlier, this method controls for unobserved time-varying heterogeneity.

More formally, the synthetic province serving as the counterfactual is represented by a vector of optimal weights $w = (w_2, \ldots, w_{J+1})'$, where $0 \leq w_j \leq 1$ for $j \in \{2, \ldots, J+1\}$ and $\sum_{j=2}^{J+1} w_j = 1$. The value of w in the synthetic unit is selected to resemble the pre-treatment characteristics of the unit of interest (a specific border province). The optimal weights w are chosen by minimizing the difference between the pre-intervention predictors for the treated units and each control unit, so that $w = arg \min_{w} [\boldsymbol{X_1} - \boldsymbol{X_0} w]' \boldsymbol{V} [\boldsymbol{X_1} - \boldsymbol{X_0} w]$, where X_1 and X_0 are the pre-treatment characteristics of the treated and control units, respectively, and V is a diagonal matrix that weights pre-intervention predictors in accordance with their power to predict the outcome (i.e. amount of fuel consumption).

The impact of the tax on fuel consumption can then be evaluated simply in terms of the difference between the actual outcome of the treated province and that of the optimally weighted control provinces (which resemble the treated unit). Thus, β_{it} in equation (2) is the impact of the cross-border tax increase on domestic fuel consumption:

$$\beta_{it} = FC_{1t} - \sum_{j=2}^{J+1} w_j FC_{jt} \qquad (2)$$

Table 4 shows the mean values of the predictor variables used for both the observed border provinces and their synthetic controls. Here, instead of population, we use the number of filling stations per capita. Note that we did not use this variable before because of potential issues of endogeneity and because it is only available from 2014 onwards, which would reduce the time span of the sample in the panel estimator. Here, however, this does not constitute a problem and, moreover, it reduces the mean squared prediction error (MSPE), which captures the difference between the observed unit and the estimated counterfactual and, hence, the match between the treated and the synthetic unit. This, together with using pre-treatment fuel consumption as a covariate, helps "soak up" the heterogeneity (Abadie et al., 2010). Tables A1 and A2 show the synthetic control weights used.

Table 4. Actual and synthetic predictor means for the period prior to the tax change

	BADA	Synt.	CAC	Synt.	HUE	Synt.	OUR	Synt.	PONT	Synt.	SAL	Synt.	ZAM	Synt.	ACG
ln (income)	6.53	6.69	6.54	6.62	6.55	6.71	6.75	6.81	6.75	6.73	6.79	6.83	6.80	6.83	6.74
% inhab. in capital city	0.22	0.28	0.23	0.27	0.28	0.34	0.33	0.31	0.09	0.26	0.43	0.43	0.34	0.40	0.32
ln(PS per capita)	-1.08	-1.33	-1.26	-1.05	-1.53	-0.99	-1.25	-1.14	-1.71	-1.57	-1.30	-1.26	-0.89	-0.99	-1.37
ln(price diesel, 2016)	0.24	0.22	0.26	0.25	0.26	0.22	0.26	0.25	0.26	0.26	0.24	0.26	0.25	0.24	0.24
ln(diesel liters, Oct2011)	17.51	17.51	16.89	16.87	17.03	17.06	16.66	16.69	17.68	17.70	17.25	17.24	16.69	16.68	17.35
ln(diesel liters, Aug2012)	17.53	17.52	16.95	16.93	17.17	17.17	16.89	16.89	17.74	17.76	17.13	17.12	16.68	16.66	17.36
ln(diesel liters, Jun2013)	17.26	17.33	16.66	16.67	16.94	16.99	16.66	16.69	17.59	17.60	16.71	16.84	16.36	16.37	17.21
ln(diesel liters, Apr2014)	17.43	17.42	16.76	16.74	17.11	17.07	16.62	16.63	17.55	17.57	16.90	16.90	16.46	16.44	17.25
ln(diesel liters, Jan2016)	17.37	17.36	16.63	16.62	16.93	16.95	16.46	16.48	17.44	17.47	17.00	16.94	16.52	16.49	17.19

Notes: This table shows the mean values of the predictors used to estimate the counterfactual scenario (i.e. the synthetic unit). Here we show values for diesel consumption. The last column (ACG: Average control group) shows the sample averages of the donor group to facilitate comparison with the optimally weighted averages in the synthetic units. (BADA. Badajoz; CAC: Cáceres, HUE: Huelva; OUR: Ourense; PONT: Pontevedra; SAL: Salamanca; ZAM: Zamora)

The synthetic control method provides specific estimates for each border province. As such, it not only serves as an assessment of the robustness of the difference-in-difference estimates that we report, it also allows us to focus more closely on the effects for each particular border province.

4. Results

4.1. Difference-in-difference results

Table 5 shows the main results from the difference-in-difference strategy for the various samples. We report our results for both diesel (columns 1 to 6) and gasoline consumption (columns 7 to 12). We provide treatment effects for the full sample, for the corresponding matched sample and for the entropy balanced sample. According to our model, diesel consumption in border provinces increased by about 8.2% compared to consumption in the control group (column 1). Consumption rose slightly to 10.6% in the matched sample, with fewer observations, and fell to 9.6% in the entropy balanced sample. The latter shows the best balance and is, hence, our preferred specification. The implication is, therefore, that diesel sales at filling stations in border provinces increased by about 10% in response to the cross-border fuel tax increase. This effect does not seem to change greatly when we limit the treatment group in terms of the percentage of filling stations near the border – remaining similar in magnitude and significance – suggesting that the effect is not driven by the latter.[3]

In the case of gasoline consumption, our results differ strikingly. Here, if we focus our attention on the matched and entropy balanced samples, the cross-border tax does not appear to affect gasoline consumption at all. Indeed, even the full sample estimates only show a (very small) significant negative sign, which vanishes when matching procedures are applied. Note that this does not mean that there is no fuel tourism for gasoline; rather, fuel tourism for gasoline drivers does not increase in response to the rise in fuel tax in Portugal. Our empirical strategy is designed to identify the response to a cross-border tax increase and not the response to price differentials (fuel tourism). The same is true for the different treatment specifications estimating responses in terms of the share of filling stations located at various distances from the border.[4]

Figure 6 shows the event coefficients according to the different sampling specifications, when taking all the borders into consideration. In all cases, the coefficients add further plausibility to our parallel trends assumption: i.e. before the Portuguese tax hike, any differences in fuel consumption between the treated and control provinces were not significantly different from zero, especially in the case of the consumption of diesel. In the case of gasoline, pre-treatment trends are better dealt with in the entropy balanced sample, our preferred specification, which confirms this differential effect by fuel type.

One potential explanation for this differential effect might be the higher share of diesel vehicles in both Spain and Portugal –in 2020, diesel cars represented 59.9 and 57.9% of the total in Portugal and Spain, respectively, vs. 37 and 39.5% gasoline-fueled cars, respectively (ACEA, 2022). This, however, cannot account for the full story. A more plausible explanation is that heavy goods vehicles, run on diesel and fitted with enormous tanks with a capacity for up to 1,500 liters of fuel, drive the cross-border tax response.

[3] In-time placebo tests (Table A3 in the Annex), i.e. moving the treatment date to February of the four previous years, while dropping the observations from the period actually treated, further confirm these results. Thus, in-time placebos for diesel show no significant effect, while for gasoline they even show a negative effect resulting from the reduction in the difference between Spanish and Portuguese prices, i.e., there is less cross-border consumption in the border provinces compared to the previous placebo periods.

[4] In fact, the price of gasoline is about 20 cents cheaper in Spain than in Portugal, while diesel is only 10 cents cheaper. Although this is not the object of our study here, tax-exclusive fuel tourism appears to be potentially higher for gasoline than for diesel. What our results show is that, unlike diesel sales, the sales of gasoline do not increase in the border provinces in response to the cross-border tax increase.

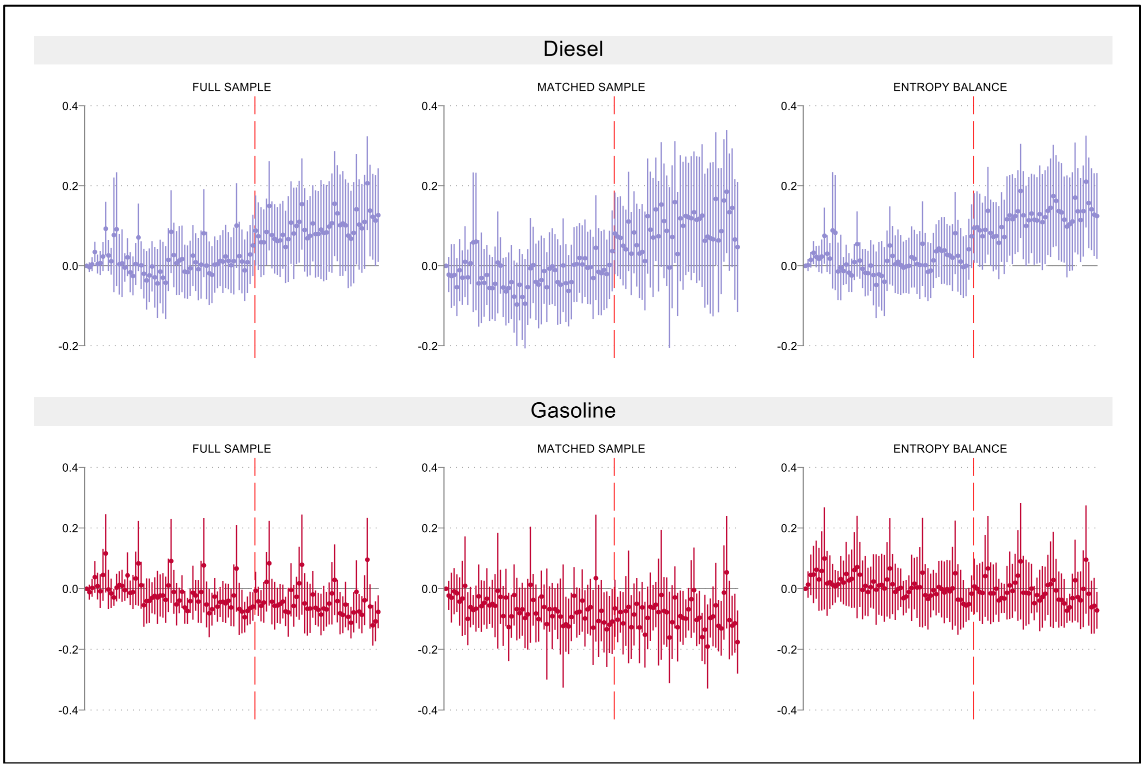
Table 5. Difference-in-difference estimates

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
ln(Diesel Consumption)												
ISP	0.082***				0.106***				0.096***			
	(0.028)				(0.026)				(0.027)			
ISP (25 km from border)		0.062*				0.092***				0.082***		
		(0.032)				(0.024)				(0.024)		
ISP (10 km from border)			0.007				0.023**				0.014*	
			(0.005)				(0.009)				(0.008)	
ISP (5 km from border)				0.076**				0.134***				0.102***
				(0.035)				(0.016)				(0.015)
Constant	25.515*	21.702	21.053	22.364*	21.343	30.834**	23.659	7.408	30.237*	35.447***	24.353**	31.228***
	(13.869)	(13.167)	(13.273)	(13.187)	(19.233)	(11.890)	(14.015)	(12.386)	(15.205)	(10.416)	(11.204)	(11.349)
R-squared	0.679	0.661	0.661	0.663	0.825	0.801	0.857	0.84	0.983	0.983	0.993	0.984
R2 adj.	0.665	0.644	0.644	0.646	0.8	0.751	0.806	0.791	0.982	0.982	0.992	0.983
ln(Gasoline consumption)												
ISP	-0.019**				-0.002				0.002			
	(0.009)				(0.013)				(0.009)			
ISP (25 km)		-0.021**				-0.005				-0.01		
		(0.010)				(0.025)				(0.011)		
ISP (10 km)			-0.019				-0.029				-0.005	
			(0.016)				(0.032)				(0.022)	
ISP (5 km)				-0.020**				0.016				-0.017*
				(0.009)				(0.024)				(0.009)
Constant	15.055*	16.159	16.319	17.561*	5.263	10.25	1.825	-3.812	8.35	11.993	11.171	15.816**
	(8.892)	(9.711)	(9.834)	(9.805)	(7.441)	(17.974)	(19.419)	(16.557)	(9.273)	(9.242)	(11.360)	(7.168)
R-squared	0.751	0.745	0.741	0.741	0.855	0.829	0.827	0.78	0.983	0.981	0.99	0.986
R2 adj.	0.74	0.732	0.728	0.728	0.835	0.786	0.765	0.712	0.982	0.98	0.99	0.986
Observations	5,400	5,076	4,968	4,968	1,512	864	648	648	5,400	5,076	4,968	4,968
Number of id_province	50	47	46	46	40	35	30	17	50	47	46	46
Sample	All	All	All	All	PS match.	PS match.	PS match.	PS match.	Entropy B.	Entropy B.	Entropy B.	Entropy B.
Control vars.	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Province FE	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Year-month FE	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Year x Region FE	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Cluster s.e.	Province	Province	Province	Province	Province	Province	Province	Province	Province	Province	Province	Province

Notes: This table shows the two-way fixed effects difference-in-difference estimator for the different specifications and samples. Coefficients can be interpreted as the change in the fuel consumption of the border provinces as a result of the tax change in Portugal (ISP). This is shown for all border provinces and for those with a higher share of filling stations within the first km after the border (and removing the other border provinces). These latter coefficients show how the treatment effect varies in response to an increase in the share of filling stations located close to the border. Robust standard errors, clustered at the province level, in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Overall, our estimates translate into 42 million additional liters of diesel consumed per year in the border provinces because of the cross-border tax, representing an annual carbon leakage of 115,000 tCO_2. In the following section, we analyze each border province by means of the synthetic control method to further disentangle this effect.

Figure 6. Event study for diesel (top) and gasoline(bottom) consumption



Note: This figure plots results from an event study of the difference in fuel consumption –both diesel and gasoline– between border and non-border Spanish provinces by sample and matching strategy.

4.2. Synthetic control results: individual treatment effects

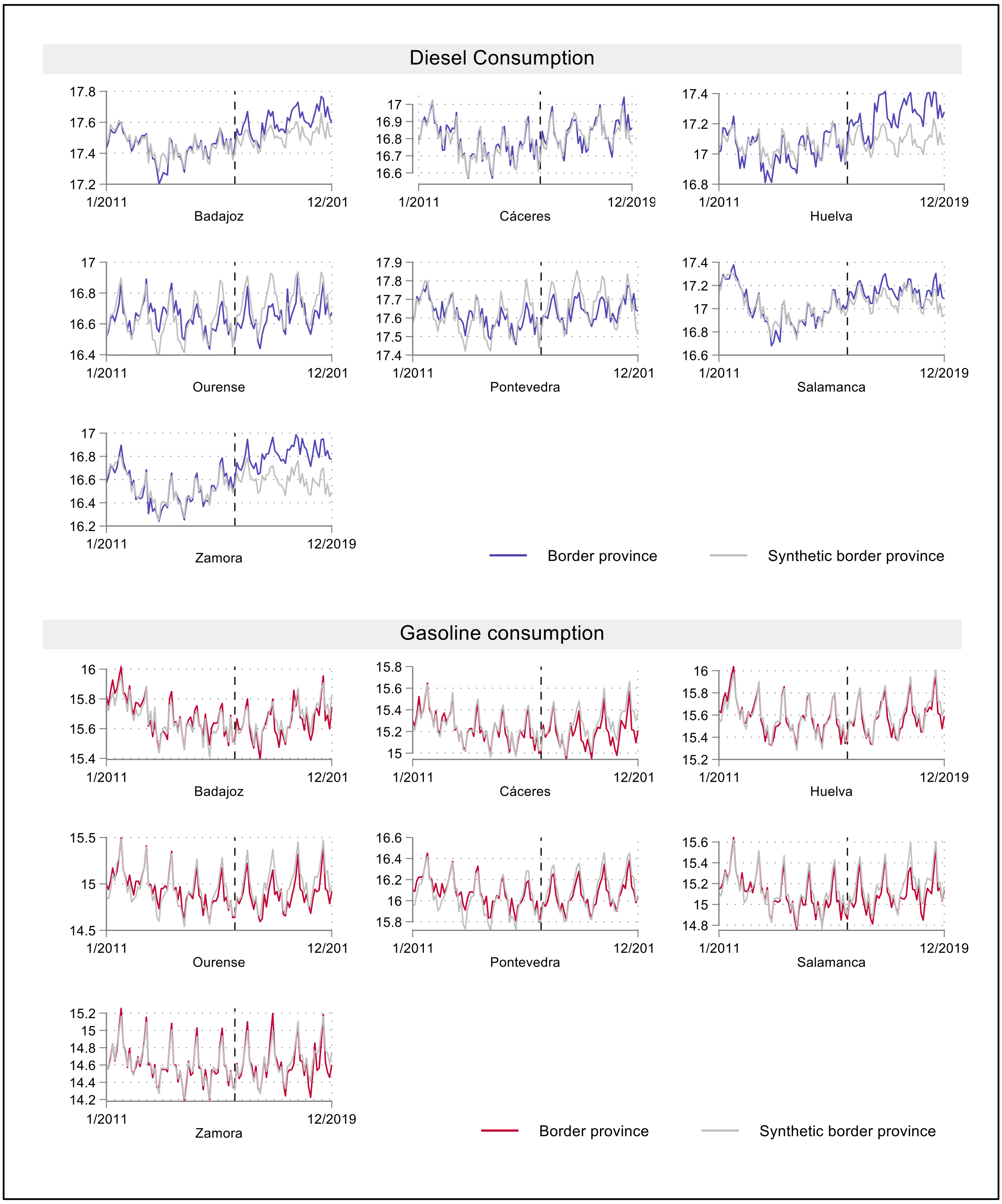
Figure 7 shows the fuel consumption trajectories for both diesel and gasoline in the synthetic border provinces (grey plots) and in the observed border provinces. Despite some small differences, the trajectories of the synthetic provinces provide a close match with those of the treated units (border provinces). In the case of diesel consumption, some provinces present a marked increase in their consumption over that of their counterfactual scenario: a visual inspection shows that Zamora, Badajoz, Huelva and Salamanca all present a greater divergence after treatment. This indicates that the cross-border tax change increased Zamora's diesel consumption by an average of 20%, Huelva's by 17% and Badajoz and Salamanca's by 7% each between February 2016 and December 2019 (Table 6). In contrast, in the case of gasoline consumption, no differences are detected between the observed and the synthetic consumption series, thus confirming our main findings from the difference-in-difference analysis and providing further robustness to our findings regarding diesel consumption.

To assess the statistical significance of the impact on diesel consumption, we construct p-values using the placebo-based inferential technique (Abadie et al., 2010). This involves applying the synthetic control method to each province in the sample as if it were a treated unit and then computing their respective synthetic controls to see if there is any post-policy treatment effect. If the estimated effect for the actual treated units – the border provinces – is relatively larger than that found for the control provinces, then we can assert the significance of the effect. Figure 8 shows the post- and pre-treatment MSPE ratios for the treated and placebo units: a relatively high ratio is indicative of a unit presenting a larger gap post-policy than pre-policy. We then calculate p-values as the ranking for this ratio over total units. Figure 8 shows the ranking of the post-/pre-treatment ratios and Table 6 shows the estimated effects for each province and their statistical significance.

Only the effects for Badajoz, Huelva and Zamora are statistically significant at the standard levels. Zamora increases its diesel consumption by 20% (but not its gasoline consumption), while Badajoz's and Huelva's diesel consumption is up by 7% and 17% respectively.[5] These provinces lie on the main freight transport routes, further suggesting that commercial trucks are the main channel by which both leakages, from carbon and from revenue, operate.

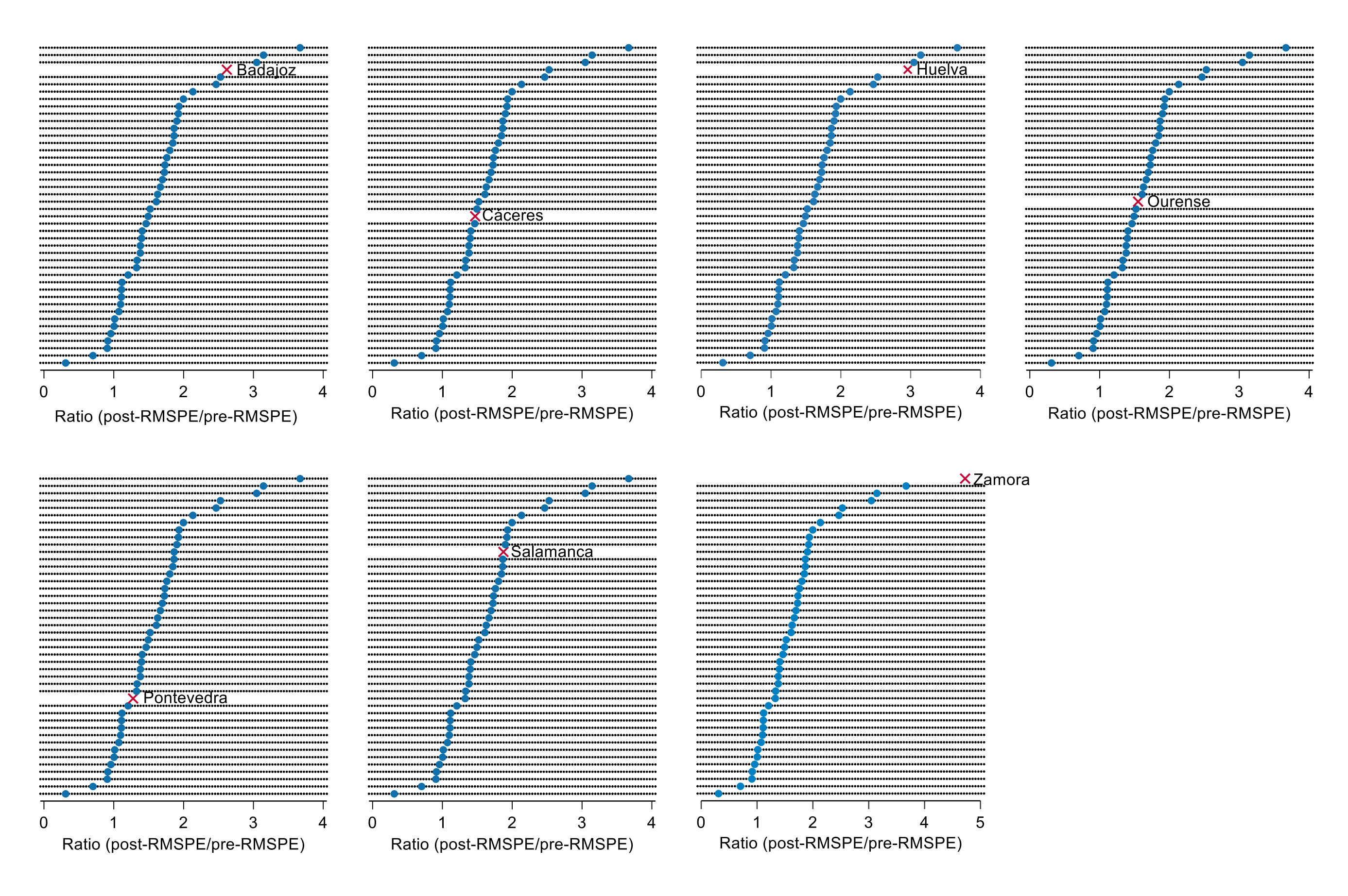
[5] Badajoz's and Huelva's lower statistical significance –compared to that of Zamora– is attributable to the fact that Girona, Gipuzkoa and La Rioja have a higher post- to pre-treatment MSPE ratio. Girona and Gipuzkoa both border France, where fuel prices are higher. La Rioja is not a border province but it shares a border with the Basque Country, which had higher fuel prices after the reform and enjoys high mobility with La Rioja. Likewise, Navarra, also a neighbor of La Rioja saw its regional fuel tax (known as "centimo sanitario") increased in January 2019, increasing its own fuel consumption at the expense of La Rioja. All these circumstances explain why Badajoz and Huelva does not have the highest ranking in its post to pre-treatment MSPE ratio.

Figure 7. Synthetic control estimates of fuel consumption



Note: This figure shows the (ln) consumption of diesel (top panel) and gasoline (bottom panel) in the seven border provinces (solid lines) compared to that of their counterfactual or synthetic control unit (dashed line), where that province is not impacted by the Portuguese tax increase of February 2016 (vertical dashed line). The synthetic province is an optimally weighted average of the other Spanish non-border provinces. The credibility of the causal impact lies in how closely the synthetic unit resembles the (observed) border province, the effect being the difference between the latter and the synthetic unit after the tax has been raised.

Figure 8. In-space placebo tests



Note: These graphs show the ratio of post- to pre-treatment MSPE allowing inferences to be made by comparing each unit with its synthetic control. In this case, only Zamora, and to a lower extent Badajoz and Huelva, show high RMSPE ratios. Following Abadie et al. (2015), this empirical distribution of ratios can be used to calculate p-values as the probability of obtaining as large a ratio if these ratios were randomly assigned. For Zamora the value is 1/50=0.02, for Badajoz and Huelva it is 4/46=0.02

Table 6. Synthetic control estimates

Province	Effect	p value
Badajoz	0.07*	0.09
Cáceres	0.01	0.56
Huelva	0.17*	0.02
Ourense	-0.06	0.51
Pontevedra	-0.03	0.70
Salamanca	0.07	0.26
Zamora	0.20**	0.02

Note: This table shows the average difference between observed diesel consumption and the estimated counterfactual scenario after February 2016, when the fuel tax was increased in Portugal. We use the placebo-based inference by which we rank just how extreme the result of the actual treated unit is by means of the ratio between the pre- and post-treatment MSPE.

5. Discussion and policy implications

Our results highlight a novel differential effect by fuel type. Only diesel consumption appears, to react (and then very robustly) to the cross-border tax change, in marked contrast that is with gasoline consumption. Specifically, our main estimates show an approximate 10% rise in diesel consumption in those Spanish provinces that share a border with Portugal in response to the tax hike in that country. This represents an additional annual consumption of 42 million liters of diesel and implies a cross elasticity of demand (for Spanish fuel consumption) with respect to the Portuguese tax change that is roughly nine times greater for diesel than for gasoline: 1.9 for diesel vs. 0.2 for gasoline.[6]

We attribute this differential effect to drivers of heavy goods vehicles reacting to tax changes -given their large capacity diesel fuel tanks– while the drivers of passenger cars use gasoline- and diesel-fueled cars in similar proportions in the two countries (40 and 60%, respectively). As discussed, this does not necessarily imply that the drivers of passenger cars do not take advantage of Spain's lower prices and engage in fuel tourism. Simply, our empirical models are unable to identify this. However, it does imply that such behavior does not result in increased fuel consumption because of the tax change.

The absence of a reaction from passenger car drivers can, potentially, be explained by the fact that fuel tourism may well have reached satiation, i.e. no increase in consumption results from the tax change because all drivers that engage in fuel tourism are already engaging in it. Additionally or alternatively, car drivers are only sensitive to changes in the price at the pump, which are certainly less dramatic in our experimental setting than changes in the tax rate. Whatever the case, these drivers appear to be inelastic to cross-border tax changes, unlike truck drivers. A potential explanation for this is that the latter probably equip themselves better to track price changes using different navigation tools and applications, given that the potential savings are huge when filling their massive tanks. Yet, this does not fully align with a greater response to tax changes because of the higher salience or persistence of the tax. If this were the case, gasoline sales should have reacted just as strongly.

[6] In the case of diesel, the cross elasticity is derived from the 10% increase in demand for diesel in the Spanish border provinces divided by the 5% overall increase in diesel taxes in Portugal (that is, €0.06 of the tax increase over €0.95, the average full tax levied on diesel). In the case of gasoline, this is a non-statistically significant demand increase of 2% over the 10% increase in the tax (that is, €0.06 of the average full tax levied on gasoline €0.60).

The Portuguese tax on petroleum and energy products (ISP) was clearly environmentally motivated, insofar as it sought to "promote low-carbon economy and fight climate change". Yet, despite these intentions, our results indicate a carbon leakage of 115,000 tCO_2 per year,[7] attributable exclusively to the consumption of diesel. While this is only 1% of Portugal's total annual transport emissions, it represents 29% of the country's annual mitigation commitment by 2030 (NECP-Portugal, 2019).[8] However, far from being mitigated, these GHG emissions are simply being transferred to Spain, with obvious consequences for this country's mitigation objectives and strategies. The transport sector is Spain's main CO_2 emitter and freight transport is responsible for 25% of these emissions. Moreover, Spain faces an above-average fuel consumption compared to the EU due, among other reasons, to the fact that it opted to develop its road freight transport to the detriment of rail alternatives (NECP-Spain, 2020). In this regard, fuel tax harmonization would mitigate emission leakage from Portugal and also help Spain to reduce its overabundant fuel consumption.

In the context of carbon pricing, policies aimed at mitigating leakage theoretically encompass a range of measures, from carbon border adjustments to various forms of subsidy and exemption, such as free allowances and export rebates (see, for example, Böhringer et al., 2017; Kortum and Weisbach, 2017). Fowlie and Reguant (2021) advocate output-based subsidies in favor of sectors deemed highly vulnerable to carbon leakage, even though such subsidies might attenuate incentives to abate domestic emissions. Nevertheless, the reduction in emission leakage significantly outweighs the reduction in domestic abatement incentives. In the particular context of the EU, harmonizing fuel taxes alone could reduce within-EU leakage attributable to freight transportation; at the same time, for freight transportation to and from non-EU countries, additional leakage mitigation policies would be indispensable.

Finally, on the revenue side, if we consider the total tax rate levied on diesel fuel in Portugal (€0.71 per liter being the average during the post-treatment period), the carbon

[7] The total of 42 million liters of diesel is derived from the difference-in-difference specification using the dependent variable without logarithms. Because our estimates are at the monthly level, we obtain this annual figure by multiplying by twelve. In the case of CO_2 emissions, we apply a conversion factor of 2.68 kg of CO_2 for each liter of diesel consumed.

[8] According to the National Energy and Climate Plan 2021–2030, projected emissions for transport by 2030 are 11.7 M tCO2, while in 2019 they were registered at 17 M tCO2. This means 4.3 M tCO2 in 11 years, hence 397,367 tCO2 per annum.

leakage documented herein implies a significant annual foregone revenue.[9] The future EU carbon market for transport must take steps to mitigate carbon leakage, albeit if only within the EU, and provided that it is accompanied by the simultaneous harmonization of fuel taxation, especially for diesel fuel and for freight transport.

In order to meet the climate targets set for the next few decades, the reduction in CO_2 emissions is becoming more and more pressing and mitigation policies need not only be as effective but also as efficient as possible. As of today, freight transport – demand for which is subject to constant increases (IEA, 2023) – accounts for 27% of road transport emissions in the EU (EEA, 2022); however, it accounts for less than 1.7% of the vehicle fleet (ACEA, 2022). Hence, while the internal combustion engine continues to make up the lion's share of freight transport, targeting this sector appears appropriate from an efficiency perspective and may justify the adoption of stringent ad hoc approaches, especially given its high carbon leakage risk.

6. Conclusions

Reducing the GHG emissions of the transportation sector is critical to achieving the climate targets that have been set by most developed countries, especially the climate neutrality objectives fixed for the 2050 horizon. Yet, the socio-economic importance of this sector has precluded progress to date. Indeed, in marked contrast with the significant advances made in other activities, in the transport sector policies have failed to reduce GHG emissions below 1990 levels. In many developed countries, transport, today, is the main GHG emitter and, thus, there is a significant gap between this reality and the urgency of climate mitigation and the implementation of effective measures. In this sense, carbon pricing –the favored policy approach– has been environmentally relevant in no more than a handful of countries and significant progress is still awaited in this area. However, given the mobility of the transport sector, pricing instruments of this kind are exposed to the risk of carbon leakage. As is well documented in the empirical literature, fuel tourism in countries that share borders but not fuel price levels has become common practice.

This paper has shown empirically that climate policies based on pricing instruments implemented on the road transportation sector can result in carbon leakage and foregone

[9] 30 million euro, that is, 1.8% of the total revenue generated by diesel fuel taxation in Portugal in 2016 (European Commission, 2023).

revenue and, thus, casts serious doubts on the environmental effectiveness and economic efficiency of such measures. We report robust causal evidence that an environmentally motivated rise in Portugal's fuel tax increased diesel consumption by 10% in neighboring border provinces in Spain, providing evidence of notable carbon leakage. Importantly, our results are equally robust in reporting a non-statistically significant effect in the case of gasoline consumption. This differential effect by fuel type is clearly informative for future climate policies as it points to road freight transport as the main and only source of carbon leakage.

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References

Abadie, A. (2021). Using Synthetic Controls: Feasibility, Data Requirements, and Methodological Aspects. *Journal of Economic Literature*, 59(2), 391–425. https://doi.org/10.1257/jel.20191450

Abadie, A., Diamond, A. & Hainmueller, J. (2010) Synthetic Control Methods for Comparative Case Studies: Estimating the Effect of California's Tobacco Control Program, *Journal of the American Statistical Association*, 105:490, 493-505, DOI: 10.1198/jasa.2009.ap08746

Abadie, A., Diamond, A. and Hainmueller, J. (2015), Comparative Politics and the Synthetic Control Method. *American Journal of Political Science,* 59: 495-510. https://doi.org/10.1111/ajps.12116

Abadie, A., & Gardeazabal, J. (2003). The Economic Costs of Conflict: A Case Study of the Basque Country. *American Economic Review*, 93(1), 113–132. https://doi.org/10.1257/000282803321455188

Abadie, A., & Imbens, G. W. (2011). Bias-Corrected Matching Estimators for Average Treatment Effects. *Journal of Business & Economic* Statistics, 29(1), 1–11. https://doi.org/10.1198/jbes.2009.07333

ACEA. (2022). *Vehicles in use Europe 2022*. https://www.acea.auto/publication/report-vehicles-in-use-europe-2022/

Agaku, I. T., Blecher, E., Filippidis, F. T., Omaduvie, U. T., Vozikis, A., & Vardavas, C. I. (2016). Impact of Cigarette Price Differences across the entire European Union on Cross-border Purchase of Tobacco Products among Adult Cigarette Smokers. *Tobacco Control*, 25(3), 333–340. https://doi.org/10.1136/tobaccocontrol-2014-052015

Andersson, J. J. (2019). Carbon Taxes and CO_2 Emissions: Sweden as a Case Study. *American Economic Journal: Economic Policy*, 11(4), 1–30. https://doi.org/10.1257/pol.20170144

Antweiler, W., & Gulati, S. (2016). Frugal Cars or Frugal Drivers? How Carbon and Fuel Taxes Influence the Choice and Use of Cars. https://dx.doi.org/10.2139/ssrn.2778868

Banfi, S., Filippini, M., & Hunt, L. C. (2005). Fuel Tourism in Border Regions: The Case of Switzerland. *Energy Economics*, 27(5), 689–707. https://doi.org/10.1016/j.eneco.2005.04.006

Bang, H., & Robins, J. M. (2005). Doubly Robust Estimation in Missing Data and Causal Inference Models. *Biometrics*, 61(4), 962–972. http://www.jstor.org/stable/3695907

Böhringer, C., K. E. Rosendahl, and H. B. Storrøsten (2017). Robust policies to mitigate carbon leakage. *Journal of Public Economics* 149, 35{46.

Coglianese, J., Davis, L. W., Kilian, L., & Stock, J. H. (2017). Anticipation, Tax Avoidance, and the Price Elasticity of Gasoline Demand. *Journal of Applied Econometrics*, 32(1), 1–15. https://doi.org/https://doi.org/10.1002/jae.2500

Coyne, D. (2017). How Political Boundaries Affect Gas Price Competition and State Motor Fuels Tax. *Proceedings of the Annual Conference on Taxation and Minutes of the Annual Meeting of the National Tax Associatio*n, 110, 1–51. https://www.jstor.org/stable/26794453

Davis, L. W., & Kilian, L. (2011). Estimating the effect of a gasoline tax on carbon emissions. *Journal of Applied Econometrics*, *26*(7), 1187–1214. https://doi.org/https://doi.org/10.1002/jae.1156

DeCicca, P., Kenkel, D., & Liu, F. (2013). Who Pays Cigarette Taxes? The Impact of Consumer Price Search. *The Review of Economics and Statistics*, 95(2), 516–529. http://www.jstor.org/stable/43554402

EEA-European Environment Agency. (2022). *Decarbonising Road Transport: The Role of Vehicles, Fuels and Transport Demand*. Publications Office of the European Union. https://books.google.es/books?id=Hf9OzwEACAAJ

EPA. (2023). *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021.* https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions

European Commission, & Directorate-General Taxaxion and Customs Union. (2023). *Excise Duty Tables (Tax receipts – Energy products and Electricity). Revenues from Taxes on Consumption*. https://taxation-customs.ec.europa.eu/system/files/2023-02/excise_duties_energy_products_en.pdf

Fowlie, M. L., & Reguant, M. (2021). Mitigating Emissions Leakage in Incomplete Carbon Markets. *Journal of the Association of Environmental and Resource Economists*, *9*(2), 307–343. https://doi.org/10.1086/716765

Gago, A., Labandeira, X., & López-Otero, X. (2014). A Panorama on Energy Taxes and Green Tax Reforms. *Hacienda Pública Española/Review of Public Economics*, 208, 145–190. DOI: 10.7866/HPE-RPE.14.1.5

Ghoddusi, H., Morovati, M., & Rafizadeh, N. (2022). Dynamics of Fuel Demand Elasticity: Evidence from Iranian Subsidy Reforms. *Energy Economics*, 110. https://doi.org/10.1016/j.eneco.2022.106009

Hainmueller, J. (2012). Entropy Balancing for Causal Effects: A Multivariate Reweighting Method to Produce Balanced Samples in Observational Studies. *Political Analysis*, 20(1), 25–46. https://doi.org/DOI: 10.1093/pan/mpr025

Harding, M., Leibtag, E., & Lovenheim, M. F. (2012). The Heterogeneous Geographic and Socioeconomic Incidence of Cigarette Taxes: Evidence from Nielsen Homescan Data. *American Economic Journal: Economic Policy*, 4(4), 169–198. https://doi.org/10.1257/pol.4.4.169

IEA. (2023). *Energy Technology Perspectives 2023*. https://www.iea.org/reports/energy-technology-perspectives-2023

Jansen, D.-J., & Jonker, N. (2018). Fuel Tourism in Dutch Border Regions: Are only Salient Price Differentials Relevant? *Energy Economics*, 74, 143–153. https://doi.org/https://doi.org/10.1016/j.eneco.2018.05.036

Kortum, S. and D. Weisbach (2017, June). The Design of Border Adjustments for Carbon Prices. *National Tax Journal* 70 (2), 421-446.

Leal, A., López-Laborda, J., & Rodrigo, F. (2009). Prices, Taxes and Automotive Fuel Cross-border Shopping. *Energy Economics*, 31(2), 225–234. https://doi.org/https://doi.org/10.1016/j.eneco.2008.09.007

Li, S., Linn, J., & Muehlegger, E. (2014). Gasoline Taxes and Consumer Behavior. *American Economic Journal: Economic Policy*, 6(4), 302–342. https://doi.org/10.1257/pol.6.4.302

Lovenheim, M. F. (2008). How Far to the Border?: The Extent and Impact of Cross-Border Casual Cigarette Smuggling. *National Tax Journal*, 61(1), 7–33. https://doi.org/10.17310/ntj.2008.1.01

Manuszak, M. D., & Moul, C. C. (2009). How far for a Buck? Tax Differences and the Location of Retail Gasoline Activity in Southeast Chicagoland. *The Review of Economics and Statistics*, 91(4), 744–765. http://www.jstor.org/stable/25651374

Marion, J. & Muehlegger, E. (2018). Tax Compliance and Fiscal Externalities: Evidence from U.S. Diesel Taxation, *Journal of Public Economics*, vol. 160(C), 1–13. https://doi.org/10.1016/j.jpubeco.2018.02.007

Morton, C., Lovelace, R., Philips, I., & Anable, J. (2018). Fuel Price Differentials and Car Ownership: A Spatial Analysis of Diesel Cars in Northern Ireland. *Transportation Research Part D: Transport and Environment*, 63, 755–768. https://doi.org/https://doi.org/10.1016/j.trd.2018.07.008

Naegele, H., & Zaklan, A. (2019). Does the EU ETS cause carbon leakage in European manufacturing? *Journal of Environmental Economics and Management*, *93*, 125–147. https://doi.org/https://doi.org/10.1016/j.jeem.2018.11.004

NECP-Portugal. (2019). *National Energy and Climate Plan 2021-2030*. Portugal. https://energy.ec.europa.eu/system/files/2020-06/pt_final_necp_main_en_0.pdf

NECP-Spain. (2020). *Integrated National Energy and Climate Plan 2021-2030*. https://energy.ec.europa.eu/system/files/2020-06/es_final_necp_main_en_0.pdf

OTEP (2020). *Observatorio Transfronterizo España/Portugal. Documento 9*. Secretaría General de Transportes y Movilidad Ministerio de Transportes, Movilidad y Agenda Urbana / Ministério da Economia (Portugal). https://www.mitma.gob.es/recursos_mfom/listado/recursos/observatorio_otep_no_9_esp5.pdf

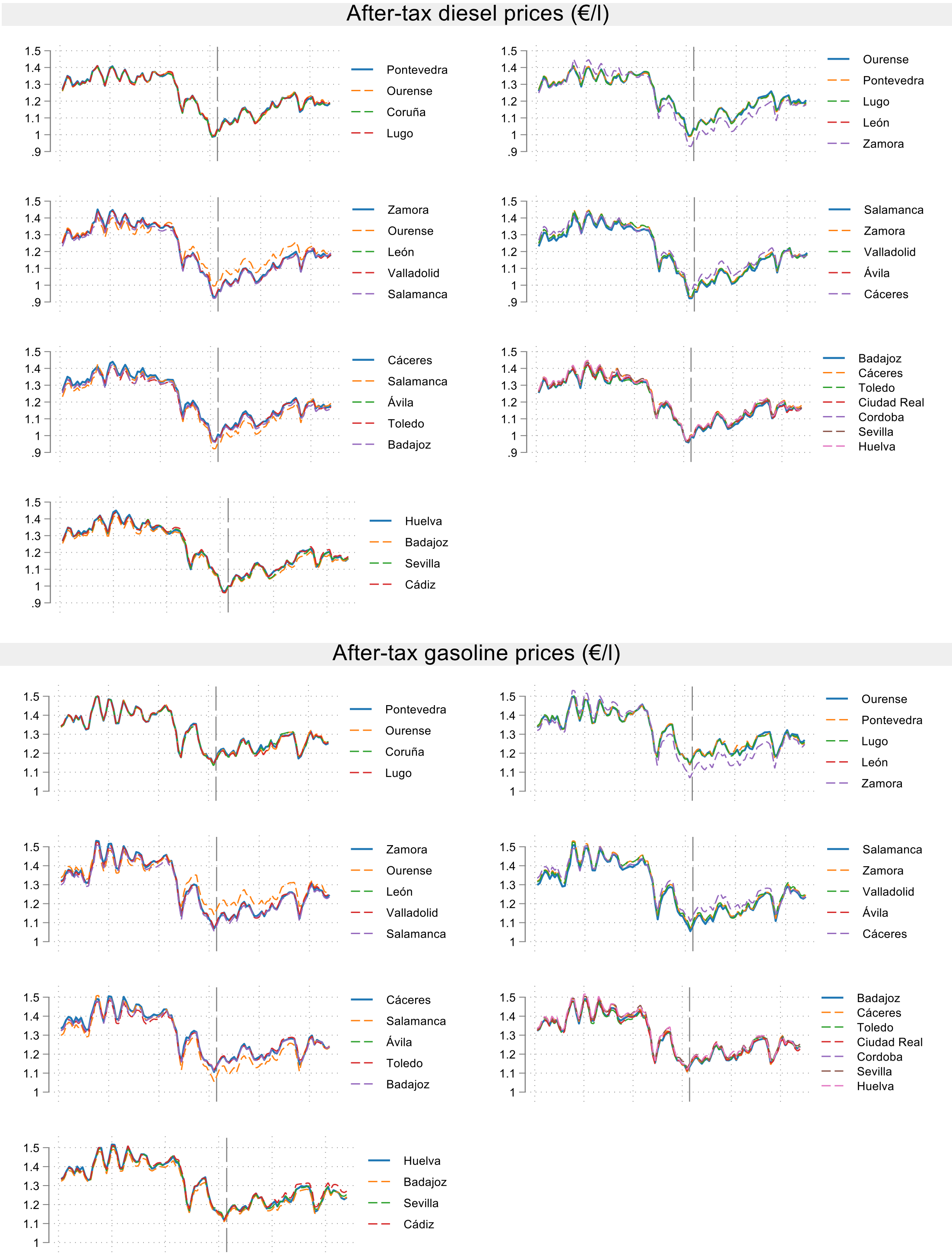
Scott, K. R. (2012). Rational Habits in Gasoline Demand. *Energy Economics*, 34(5), 1713–1723. https://doi.org/https://doi.org/10.1016/j.eneco.2012.02.007

Sterner, T. (2007). Fuel taxes: An Important Instrument for Climate Policy. *Energy Policy*, 35(6), 3194–3202. https://doi.org/https://doi.org/10.1016/j.enpol.2006.10.025

Tiezzi, S., & Verde, S. F. (2016). Differential Demand Response to Gasoline Taxes and Gasoline Prices in the U.S. *Resource and Energy Economics*, 44, 71–91. https://doi.org/https://doi.org/10.1016/j.reseneeco.2016.02.003

APPENDIX

Figure A1. Fuel price evolution in treated provinces vs. immediate neighboring provinces



Note: Each graph plots the evolution in diesel (top panel) and gasoline prices (bottom panel) for a specific treated province (solid line) vs. the other Spanish provinces with which it shares a border (dashed lines). When a dashed line rises above the main solid line, this means that the treated province shares a border with a province that charges higher fuel prices. This can confound our identification strategy only when that price difference coincides with the vertical line (February 2016: tax change in Portugal).

Table A1. Synthetic control weight per border province (diesel consumption)

	Zamora	Huelva	Badajoz	Salamanca	Ourense	Pontevedra	Cáceres
Álava	0	0	0	0	0	0	0
Albacete	0	0	0	0	0	0	0
Alicante	0	0	0	0	0	0	0
Almería	0	0.155	0	0	0	0	0
Ávila	0	0	0	0	0	0	0
Badajoz	-	-	-	-	-	-	-
Balears (illes)	0h	0	0	0	0.32	0.22	0
Barcelona	0.078	0	0.259	0.246	0	0	0
Burgos	0	0	0.011	0.126	0	0.099	0.092
Cáceres	-		-	-	-	-	-
Cádiz	0	0	0	0	0	0.128	0.235
Castelló	0	0	0	0	0	0	0
Ciudad Real	0	0	0	0	0	0	0
Córdoba	0	0	0	0	0	0	0
Coruña (A)	0	0	0	0	0	0	0
Cuenca	0	0.392	0.271	0	0.164	0	0.47
Girona	0	0	0	0	0	0	0
Granada	0	0	0	0	0	0	0
Guadalajara	0	0	0	0	0	0	0
Gipuzkoa	0	0	0	0	0	0	0
Huelva	-	-	-	-	-	-	-
Huesca	0.248	0.19	0	0	0.072	0	0
Jaén	0	0.058	0.207	0	0	0	0.044
León	0	0	0.065	0	0	0	0
Lleida	0	0	0	0	0	0	0
Rioja (La)	0	0	0	0	0	0	0
Lugo	0	0	0	0	0	0	0
Madrid	0	0	0	0	0	0.096	0
Málaga	0	0	0	0	0	0	0
Murcia	0	0	0	0	0	0	0
Navarra	0	0	0	0	0	0	0
Ourense	-	-	-	-	-	-	-
Asturias	0	0	0	0	0	0.093	0
Palencia	0.622	0	0	0.628	0	0	0
Palmas (Las)	0	0.046	0.121	0	0	0	0
Pontevedra	-	-	-	-	-	-	-
Salamanca	-	-	-	-	-	-	-
S.C. Tenerife	0	0	0	0	0	0	0
Cantabria	0	0	0	0	0	0	0
Segovia	0	0	0	0	0	0	0
Sevilla	0	0	0	0	0	0	0
Soria	0.051	0.001	0.066	0	0.146	0	0.158
Tarragona	0	0	0	0	0	0	0
Teruel	0	0	0	0	0.299	0	0
Toledo	0	0	0	0	0	0.339	0
València	0	0	0	0	0	0	0
Valladolid	0	0	0	0	0	0	0
Bizkaia	0	0	0	0	0	0.026	0
Zamora	-	-	-	-	-	-	-
Zaragoza	0	0.158	0	0	0	0	0

Note: This table shows the optimal weights for estimating each synthetic control unit for diesel consumption.

Table A2. Synthetic control weight per border province (gasoline consumption)

	Zamora	Huelva	Badajoz	Salamanca	Ourense	Pontevedra	Cáceres
Álava	0	0	0	0	0	0	0
Albacete	0	0	0	0	0	0	0
Alicante	0	0	0	0	0	0	0
Almería	0	0	0	0	0	0	0
Ávila	0	0.081	0	0	0	0	0
Badajoz	-	-	-	-	-	-	-
Balears (Illes)	0	0.059	0	0	0.268	0.463	0
Barcelona	0	0	0	0	0	0.016	0
Burgos	0	0	0	0.084	0	0	0
Cáceres	-	-	-	-	-	-	-
Cádiz	0	0.208	0.132	0	0	0	0.246
Castelló	0	0	0	0	0	0	0
Ciudad Real	0	0	0	0	0	0	0
Córdoba	0	0	0	0	0	0	0
Coruña (A)	0	0	0	0	0	0	0
Cuenca	0.47	0.226	0	0	0	0	0.164
Girona	0	0	0	0.029	0.056	0	0
Granada	0	0	0	0	0	0	0
Guadalajara	0	0.143	0	0	0	0	0.211
Gipuzkoa	0	0	0	0	0	0	0
Huelva	-	-	-	-	-	-	-
Huesca	0	0	0	0	0	0	0
Jaén	0	0	0.147	0	0	0	0
León	0	0	0	0	0	0	0
Lleida	0.159	0	0.154	0	0	0	0.01
Rioja (La)	0	0.047	0	0	0	0	0
Lugo	0	0	0	0	0	0	0
Madrid	0	0	0	0	0	0.093	0
Málaga	0	0.183	0	0	0	0	0
Murcia	0	0	0	0	0	0	0
Navarra	0	0	0	0	0	0	0
Ourense	-	-	-	-	-	-	-
Asturias	0	0	0	0	0	0	0
Palencia	0.213	0	0	0.251	0	0	0
Palmas (Las)	0	0	0.008	0	0	0	0
Pontevedra	-	-	-	-	-	-	-
Salamanca	-	-	-	-	-	-	-
S.C. Tenerife	0	0	0	0	0	0	0
Cantabria	0	0	0	0.451	0	0	0
Segovia	0.015	0	0.182	0.14	0.132	0.386	0
Sevilla	0	0	0.183	0	0	0	0
Soria	0.142	0	0	0.046	0.544	0	0
Tarragona	0	0	0	0	0	0	0
Teruel	0	0	0	0	0	0	0.17
Toledo	0	0.054	0.194	0	0	0.041	0.2
València	0	0	0	0	0	0	0
Valladolid	0	0	0	0	0	0	0
Bizkaia	0	0	0	0	0	0	0
Zamora	-	-	-	-	-	-	-
Zaragoza	0	0	0	0	0	0	0

Note: This table shows the optimal weights for estimating each synthetic control unit for gasoline consumption.

Table A3. In-time placebo for difference-in-difference (DiD) estimates

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
VARIABLES	***ln(Diesel)***	***ln(Diesel)***	***ln(Diesel)***	***ln(Diesel)***	***ln(g95)***	***ln(g95)***	***ln(g95)***	***ln(g95)***
Placebo DiD (Feb 2015)	-0.013				-0.045***			
	(0.023)				(0.013)			
Placebo DiD (Feb 2014)		-0.016				-0.046***		
		(0.018)				(0.014)		
Placebo DiD (Feb 2013)			-0.026				-0.049***	
			(0.021)				(0.012)	
Placebo DiD (Feb 2012)				-0.03				-0.041***
				(0.039)				(0.012)
Constant	17.000***	17.013***	17.048***	17.094***	15.315***	15.341***	15.380***	15.420***
	(0.002)	(0.004)	(0.006)	(0.015)	(0.001)	(0.003)	(0.004)	(0.005)
Observations	3,100	3,100	3,100	3,100	3,100	3,100	3,100	3,100
R-squared	0.924	0.925	0.933	0.940	0.902	0.908	0.916	0.914
R2 adj.	0.923	0.924	0.932	0.939	0.9	0.907	0.914	0.913
Sample	Entropy B.	Entropy B.	Entropy B.	Entropy B.	Entropy B.	Entropy B.	Entropy B.	Entropy B.
Control vars.	YES	YES	YES	YES	YES	YES	YES	YES
Province FE	YES	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES
Month FE	YES	YES	YES	YES	YES	YES	YES	YES
cluster s.e.	Province	Province	Province	Province	Province	Province	Province	Province

Note: Post-treatment data are removed to avoid confounding the placebo treatments. Robust standard errors in parentheses.
*** p<0.01, ** p<0.05, * p<0.1