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Carbon Leakage from Fuel Taxes: Evidence from a Natural Experiment

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Abstract
We exploit a fuel tax increase in Portugal to identify its effect on cross-border fuel sales and associated carbon leakage in the Spanish border regions. Using a difference-in-difference strategy, we find that while gasoline sales remained unaffected, diesel sales in Spanish border regions increased by 6–9%. Synthetic control methods confirm these estimates and attribute this differential effect by fuel type to routes frequented by heavy-duty vehicles, with large diesel tanks. We estimate a carbon leakage equivalent to 14–20% of Portugal's annual mitigation commitment for road transport emissions. Our findings imply that heavy goods vehicles' strategic behavior undermines the potential mitigation effects and revenue gains of transport climate policy, underscoring the need for coordinated policies in similar federal or quasi-federal contexts.

Keywords Carbon leakage · Fuel tax · Cross-border fuel sales · Carbon price · Road transportation · Climate policy

JEL Classification Q58 · R48 · H23 · H26

1 Introduction

As climate-related crises worsen, policymakers 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 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

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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 cross-border fuel purchases, 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.

Cross-border fuel purchase substitution has been well documented in many territories, including Europe (Banfi et al. 2005; Jansen and Jonker 2018; Leal et al. 2009; Morton et al. 2018) and the US (Manuszak and 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 and Gulati 2016; Li et al. 2014; Scott 2012; Tiezzi and 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 low-price country when the latter is considered close enough, this paper explores whether a tax-motivated price change further increases cross-border fuel purchases. In short, we seek to determine the elasticity of cross-border fuel purchases 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 (1214 km), characterized by numerous crossing points, while gasoline and diesel prices have traditionally been much lower in Spain, an ideal mix to ensure cross-border fuel purchases are an everyday reality. In February 2016, Portugal raised its fuel tax by six cents of a euro, making cross-border fuel substitution, 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 for the average effect and a synthetic control approach (Abadie 2021) for heterogeneous effects analysis. 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

[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.

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 cross-border fuel substitution follows a 'business-as-usual' pattern, diesel sales increase by around 6–9% in the border provinces. These results are consistent across different specifications and matching procedures, including propensity score and entropy balance matchings (Abadie and Imbens 2011; Hainmueller 2012). They are also consistent with alternative difference-in-differences estimators like the doubly-robust estimator proposed by Sant'Anna and Zhao (2020) or the synthetic difference-in-differences proposed by Arkhangelsky et al. (2021). 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 1.8 for diesel and 0.1 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 analyze heterogeneity across the border (treated) provinces, we construct synthetic provinces for each of the seven border 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. 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 55,000–80,000 tCO_2, equivalent to 14–20% 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, border differences in taxes on purchase decisions 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 and 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 and carbon leakage 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—also called 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 and Jonker 2018; Leal et al. 2009; Manuszak and 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 Sect. 3, we describe the data used and the identification strategies we employ. Section 4 presents our main results and Sect. 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. Similarly, the timing of the tax implementation could influence its salience, either amplifying or diminishing its effects. In this context, despite the tax hike occurring during a period of low fuel prices in both countries, the price disparity between them exhibits a relatively stable trend above its minimum level, fluctuating by approximately 20 cents for gasoline and around 10 cents for diesel. 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 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

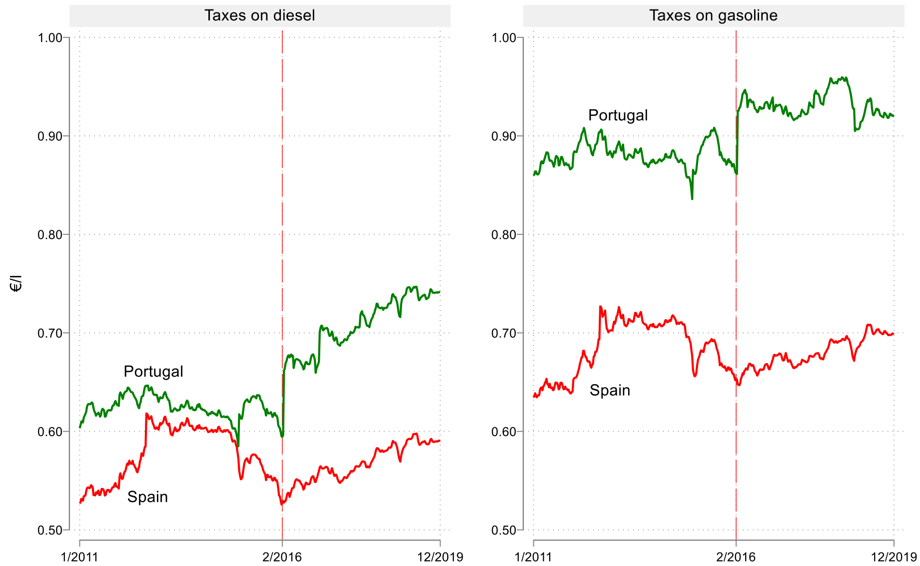

Fig. 1 All fuel taxes in Portugal and Spain (€/l). *Notes*: This figure plots the evolution in all diesel and gasoline taxes in Spain and Portugal. The vertical line signals the six-cent increase in ISP in Portugal. Overall, following the tax hike, the ISP on diesel and gasoline increased to €0.34 and €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)

Fig. 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)

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

cheaper. Importantly, Fig. 2 shows national averages under imperfect competition. Petrol stations on both sides of the border may behave strategically in price setting, potentially playing an important role in regional demand. Unfortunately, we do not observe these prices at the petrol station level.

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.

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 (Fig. 8). 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

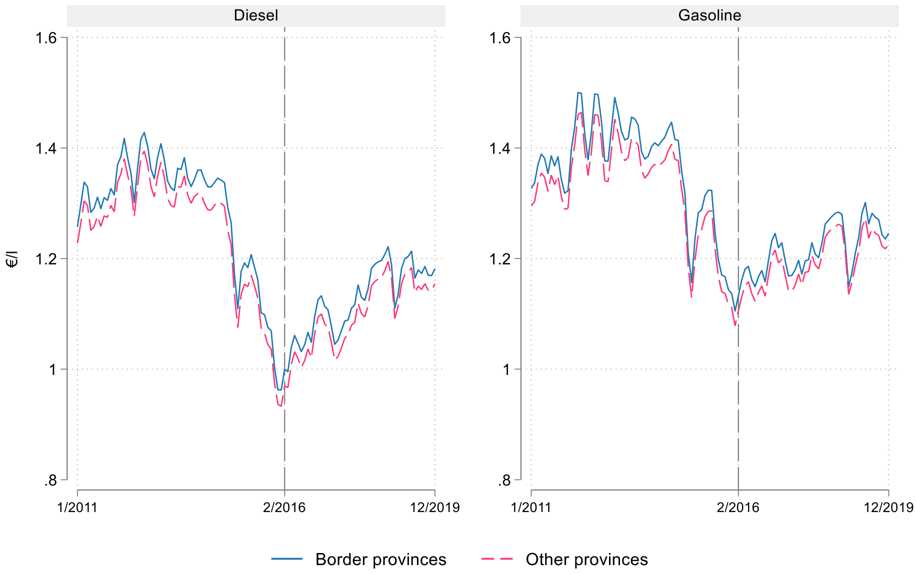

Fig. 4 Gasoline and diesel price evolution in treated and control Spanish provinces

consumption as a response to the tax change in Portugal, above and beyond the prevailing regional pattern, such as, any existing cross-border fuel substitution. In the following section we outline our research design in detail.

3 Methodology

We exploit the exogeneity of the tax increase in Portugal to analyze to what extent domestic fuel consumption is explained by the cross-border tax. In this section, we describe 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. Methodologically, each method provides different levels of results: while the difference-in-differences strategy is intended to identify the average effect of the cross-border tax on the entire border provinces and thus determine the resulting carbon leakage, the synthetic control focuses at the case study level, examining the effect specific effect to particular provinces and providing a more nuanced analysis of the heterogeneity of the cross-border tax effect. Finally, we also describe the data used.

3.1 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

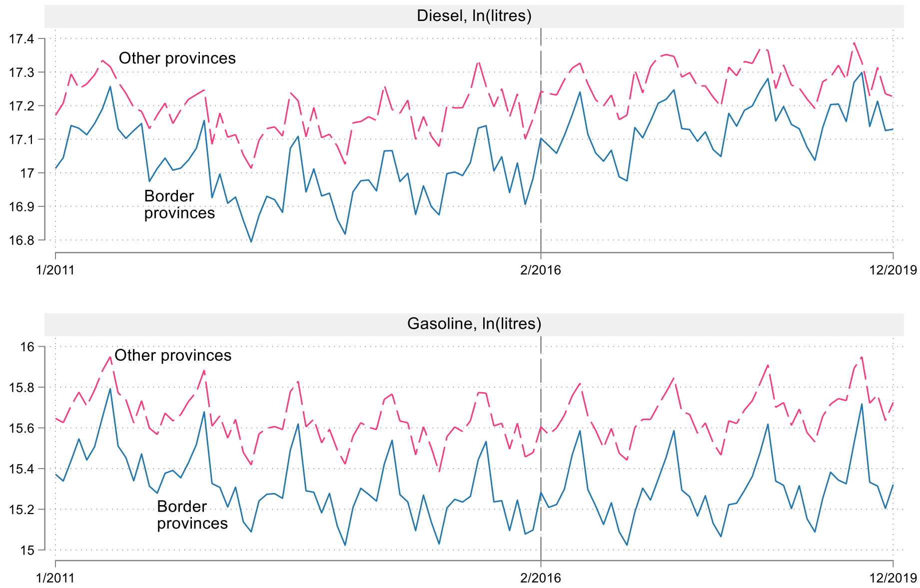

Fig. 5 Fuel consumption in treated (border) and control Spanish provinces. *Notes*: This figure shows the average consumption of gasoline and diesel (in liters) at the provincial level for seven provinces sharing a border with Portugal (Border provinces) and for the remaining forty-one Spanish provinces. Our identification strategy relies on the fact that, before the tax change in Portugal –our treatment (dashed vertical line)– both groups evolved in parallel

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.

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

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

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, the province's population (in logs) to account for the province scale effect and (monthly) average daily traffic as measured by permanent control stations in main highways. Fixed

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***
ln(avg. daily traffic)	9.602	9.030	0.572***
PSM matched sample			
ln (income)	6.663	6.669	−0.006
Share inhab. in Prov. Capital	0.266	0.278	−0.012
ln(population)	12.921	12.975	−0.054
ln(before-tax price of diesel, 2016)	0.105	0.122	−0.018*
ln(before-tax price of gasoline, 2016)	0.195	0.214	−0.019**
ln(avg. daily traffic)	9.117	9.057	0.060
Entropy balanced sample			
ln (income)	6.654	6.669	−0.015
Share inhab. in Prov. Capital	0.272	0.278	−0.006
ln(population)	12.997	12.975	0.022
ln(before-tax price of diesel, 2016)	0.113	0.122	−0.009
ln(before-tax price of gasoline, 2016)	0.200	0.214	−0.014
ln(avg. daily traffic)	9.083	9.057	0.026

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). ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$

effects include those of the province (NUTS 3), NUTS 2 region-year (*Comunidad Autónoma*), month and year and, finally, month-year effects.[2]

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 rows show the differences between the treated and control provinces. The treated provinces are significantly poorer, less populated, with higher average prices and lower average daily traffic 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 using matching procedures. This serves to make our estimators doubly robust (Bang and Robins 2005). In the second group of rows, we use a propensity score matching (nearest neighbor) procedure. 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 rows, we use the entropy balancing procedure (Hainmueller 2012), which involves a generalization of the propensity score matching: instead of using only

[2] It is important to note that the isolated variables composing the treatment variable (T_{it}), are part of the province ($Border_i$) and monthly ($TaxChange_t$) effects.

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.

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 Fig. 5), event estimates are also provided to further assess their plausibility (by assessing pretreatment differences in trends, i.e., pre-trends).

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 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 Figs. 4 and 8 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. We do, however, control for some of the other potential confounders by means of observables; 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.[3] These unobserved factors could affect differently border provinces even in the absence of the tax change in Portugal, casting doubts on the key assumption of parallel trends. Recent research has shown that although pre-trends testing may be intuitive to assess the plausibility of post-treatment parallel trends, conditioning the analysis on passing pre-trends tests can introduce several statistical issues (Roth 2022). 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 and Gardeazabal 2003; Abadie et al. 2010, 2015). Moreover, by focusing on the case-study level (heterogeneity in the treatment effects by province), the synthetic control methodology enables a more nuanced understanding of the geographic determinants driving the average effect.

3.2 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

[3] 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.

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 Eq. (2) is the impact of the cross-border tax increase on domestic fuel consumption:

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

Table 9 in the appendix shows the mean values of the predictor variables used for both the observed border provinces and their synthetic controls. Here, instead of population and the average daily traffic, we use the number of filling stations per capita. Note that we did not use this variable before because of potential issues of endogeneity (not an issue for synthetic methods) 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 10 and 11 show the synthetic control weights used.

The synthetic control method provides specific estimates for each border province. This allows us to focus more closely on the effects of each particular border province and its related geographical characteristics, altogether resulting in a more informative tool for policy making.

3.3 Data

Our main variable of interest is transportation fuel sales at Spanish filling stations, aggregated at the monthly provincial level (NUTS 3). 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 having been excluded). We obtain these from the Spanish National Markets and Competition Commission (CNMC Data 2021). 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 (2021) and *Geoportal Gasolineras* (Ministerio Transición Ecol. 2021). These covariates, together with other relevant socio-demographic characteristics obtained from the Spanish Institute of Statistics (INE 2021) and DGT (2021)—namely, population of the provinces, share of that population in the provincial capital, income and average traffic intensity in main highways—are used to balance treated and control provinces. Table 2 shows descriptive statistics and dataset sources.

Table 2 Descriptive statistics

Variable	Mean	Min	Max	Source
Income	872.30	630.71	1 249.04	INE (2021)
Share inhab. in Prov. Capital	0.32	0.09	0.77	INE (2021)
Population	896 919	78 863	6 686 513	INE (2021)
Diesel sales (liters)	41 700 000	613 089	242 000 000	CNMC Data (2024)
Gasoline sales (liters)	9 606 808	360 411	76 100 000	CNMC Data (2024)
Before-tax price of Diesel	1.19	0.66	1.47	Min. Tr. Ecol. (2024)
Before-tax price of Gasoline	1.27	0.80	1.56	Min. Tr. Ecol. (2024)
Avg. daily traffic	18 322.47	2 636.50	91 024.60	DGT (2021)
Border prov. (Treated = 1)	0.13	0	1	–

This table shows descriptive statistics and sources of the datasets used. These are monthly averages expanding from January 2011 to December 2019

4 Results

4.1 Average Treatment Effects on the Treated: Difference-in-Difference Results

Table 3 shows the main results from the difference-in-difference strategy for the various samples. We report our results for both diesel (top panel) and gasoline sales (bottom panel). We provide treatment effects for the full sample (column 1), for the corresponding matched sample (column 2) and for the entropy balanced sample (column 3). According to our model, diesel sales in border provinces increased by about 8.6% compared to sales in the control group (column 1). This is 8.3% in the matched sample, with fewer observations, and 8.9% in the entropy balanced sample.[4] 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 8–9% in response to the cross-border fuel tax increase.

In the case of gasoline, our results differ strikingly. Here, the cross-border tax does not appear to affect gasoline sales at all.[5] This is counterintuitive also because the price of gasoline is about 20 cents cheaper in Spain than in Portugal, while diesel is only 10 cents cheaper. Note that this does not mean that there is no cross-border fuel substitution for gasoline; rather, for gasoline drivers this 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. Hence, 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.

In-time placebo tests (Table 13 in the Appendix), i.e. moving the treatment date to February of the four previous years, while dropping the observations from the period

[4] Table 4 in the Annex show estimations without covariates. Results remain highly consistent with those in Table 3.

[5] In Table 4 in the annex, we show DiD estimates with no control covariates. For gasoline, this results in a small significant negative effect that vanishes when potential confounders are controlled for in Table 3.

Table 3 Difference-in-difference estimates

	(1)	(2)	(3)
ln(Diesel sales)			
Border × *ISP*	0.086***	0.083***	0.089***
	(0.030)	(0.024)	(0.026)
Constant	14.831	40.333**	36.603**
	(15.890)	(17.530)	(16.577)
R-squared	0.768	0.841	0.985
R2 adj	0.757	0.816	0.985
ln(Gasoline sales)			
Border × *ISP*	−0.011	0.011	0.007
	(0.013)	(0.016)	(0.015)
Constant	7.676	6.201	16.259
	(10.751)	(13.876)	(13.341)
R-squared	0.818	0.868	0.986
R2 adj	0.810	0.847	0.986
Observations	4644	1432	4644
Number of id_province	43	36	43
Sample	All	PS match	Entropy B
Control vars	YES	YES	YES
Province FE	YES	YES	YES
Year FE	YES	YES	YES
Month FE	YES	YES	YES
Year-month FE	YES	YES	YES
Year x Region FE	YES	YES	YES
Cluster s.e	Province	Province	Province

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. Robust standard errors, clustered at the province level, in parentheses. ***$p<0.01$, **$p<0.05$, *$p<0.1$

Table 4 Synthetic control estimates

Province	Effect	*p* value
Badajoz	0.07*	0.08
Cáceres	0.01	0.56
Huelva	0.17*	0.08
Ourense	−0.06	0.51
Pontevedra	−0.03	0.70
Salamanca	0.07	0.26
Zamora	0.20**	0.02

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. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$

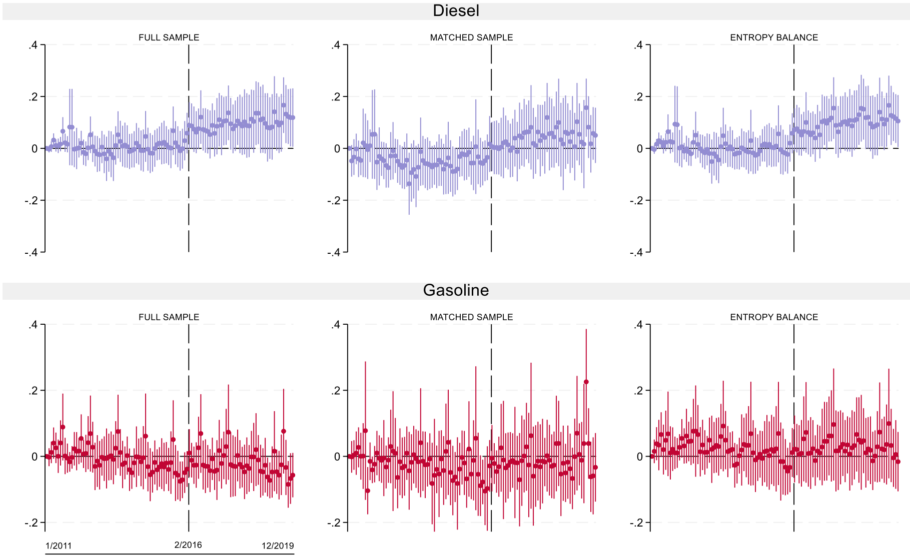

Fig. 6 Event study for diesel (top) and gasoline(bottom) sales. *Notes*:This figure plots results from an event study of the difference in fuel consumption –both diesel and gasoline– between border and non-border Spanish provinces by sample and matching strategy

actually treated, further confirm these results. Thus, in-time placebos for diesel or gasoline show no significant effect.

Figure 6 shows the event coefficients according to the different sampling specifications when considering all the borders. In all cases, the coefficients add further plausibility to our parallel trends assumption: i.e., before the Portuguese tax hike, any differences in fuel sales between the treated and control provinces were not significantly different from zero.[6] 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, versus 37 and 39.5% of gasoline-fueled cars, respectively (ACEA 2022). This, however, cannot account for the full story. A more plausible

[6] Although we cannot reject zero pre-trends from event estimates (hence providing plausibility of parallel trends), we also cannot reject pre-trends that, under smooth extrapolations to the post-treatment period, would bias treatment estimates. For example, one could extrapolate an upward-sloping linear trend within the 95% CI from the last placebo in January 2011 to the last treatment effect in December 2019. This would suggest that diesel sales in border provinces might have been on an upward trend different from that in the control provinces, violating our parallel trends assumption. Based on observed pre-trend patterns, Rambachan and Roth (2023) propose a sensitivity test to assess a bound (M) on how much the counterfactual difference in trends can change to not reject the null effect. Applying the proposed test to collapsed annual data, we find $M<0.04$ in 2017 and $M<0.06$ in 2018 and 2019 (breakdown values). This means our estimates remain significant, provided that the parallel trends violation comes from a linear difference in trends ($M=0$) or with deviations no greater than the breakdown values M for each annual estimate. Essentially, the slope of that trend cannot change by more than M across consecutive periods to rule out the zero effect. See Appendix Figure 2.

explanation is that heavy goods vehicles, run on diesel and fitted with large tanks with a capacity for up to 1500 L of fuel, drive the cross-border tax response.

Overall, these estimates translate into 30 million additional liters of diesel consumed per year in the border provinces because of the cross-border tax, representing an annual carbon leakage of 80,000 tCO_2. In the following section, we analyze each border province using the synthetic control method to further disentangle this effect.

4.2 Heterogeneity in the Treatment Effects: Synthetic Control Results

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 sales, 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 4). In contrast, in the case of gasoline sales, 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 sales, 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 10 in the appendixes 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. Table 4 shows the estimated effects for each province and their statistical significance according to this method.

Only the effects for Badajoz, Huelva and Zamora are statistically significant at the standard levels. Zamora increases its diesel sales by 20% (but not its gasoline sales), while Badajoz's and Huelva's diesel consumption is up by 7% and 17% respectively.[7] 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.

[7] 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.

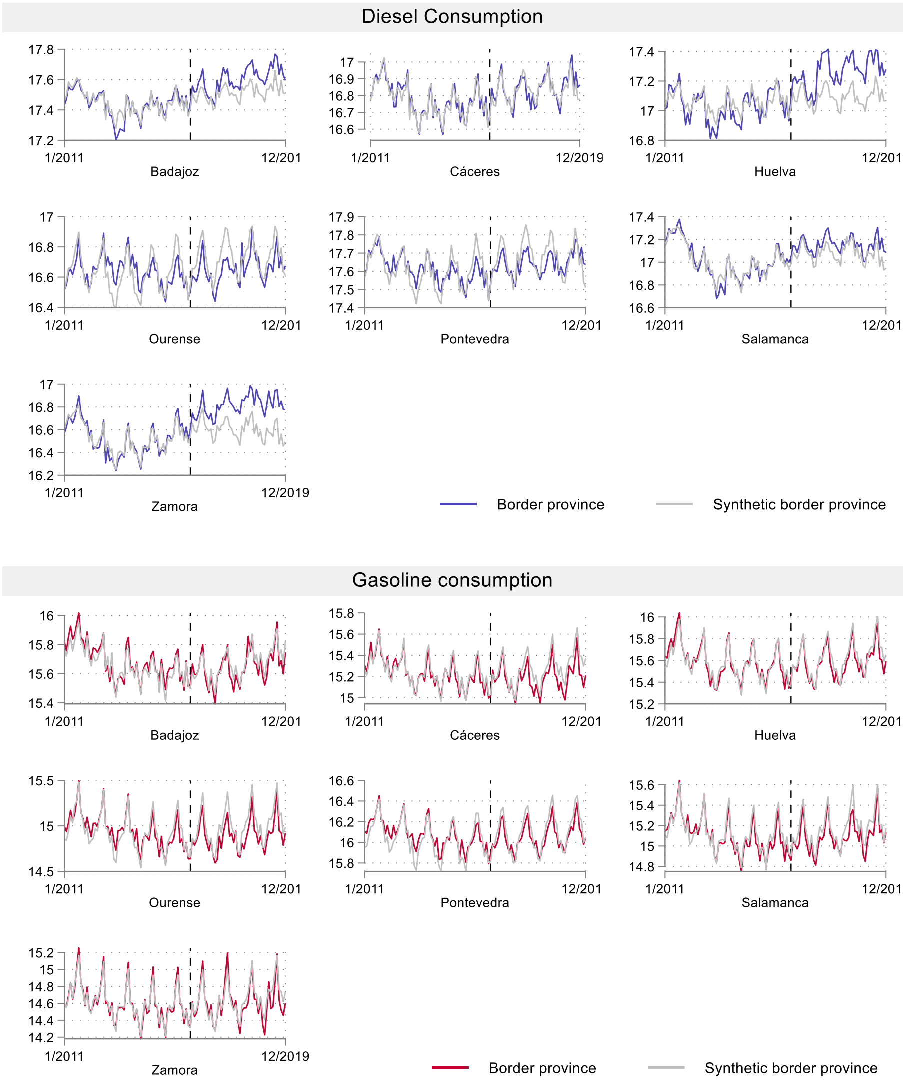

Fig. 7 Synthetic control estimates of fuel sales. *Notes*: This figure shows the (ln) consumption of diesel (top panel) and gasoline (bottom panel) in the seven border provinces (solid lines) compared to that of their counterfactual or synthetic control unit (dashed line), where that province is not 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

5 Robustness Checks

In this section, we examine our core estimates through several robustness checks. Firstly, we investigate whether the reported effects are influenced by the number of filling stations in the border provinces. Secondly, given the continuous and highly fluctuating nature of

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

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

fuel prices, and considering that our identification strategy relies on a binary variable indicating the change in tax regime in Portugal, we assess the robustness of the effect when focusing on a shorter period, allowing better control over time trends. Lastly, in light of recent developments in the differences-in-differences literature, we employ two additional estimators to further validate the robustness of our core results. The first is the doubly robust estimator, developed by Sant'Anna and Zhao (2020), specifically tailored for difference-in-differences models with time-varying covariates, as is the case here. Additionally, we utilize the Synthetic Difference-in-differences estimator, developed by Arkhangelsky et al. (2021), which combines the features of both difference-in-differences and synthetic control methods.

5.1 Filling Stations

Having a higher share of filling stations might imply greater exposure to the treatment and, therefore, account for the bulk of response. To control for this, we replicate the above difference-in-differences specification 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 5 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 two additional samples according to three different exposures to the treatment (i.e., the border). Table 14 in the appendixes 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 and 5% of filling stations within the first 25 and 5 km of the border, respectively. As a result, we distinguish three different treatment levels according to different intensities: the first treatment is the baseline and it considers all (7) border provinces (previous Table 3); 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) and the third restricts the treatment to provinces with more than 5% of their filling stations within 5 km of the border (that is, Pontevedra, Badajoz and Huelva). In these last two treatments, we exclude all the other border provinces. In all cases, entropy balancing achieves a better balance of the covariates between the treated and control groups.

Table 6 shows 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. 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.

5.2 Shorter Time Period

Our core results consider a sampled period that takes from January 2011 to December 2019, hence covering the long-run effects of the February 2016 tax change in Portugal. However, this is only accurate if we assume that our specification is able to capture underlying time trends during this period. To verify this assumption, we replicate the analysis with a shorter period, from January 2015 to December 2017, where the time trends better account for price variations.

Table 7 shows estimates for diesel are only slightly lower than those from longer periods but within the same range of one or two standard deviations, depending on the specification. For gasoline, results become statistically significant when focused on the shorter time period, indicating that potential short-run effects can also be relevant for gasoline. However, these are still half of those found for diesel.

5.3 Alternative Identification Methods

Recent developments in econometrics have revealed challenges associated with employing two-way fixed effects in difference-in-differences (DiD) models. These challenges include dealing with multiple time periods (Goodman-Bacon 2021; Callaway and Sant'Anna, 2021) and incorporating time-varying covariates (Sant'Anna and Zhao 2020). Although our two-way fixed effects model does not involve multiple periods (as there is only one treatment period after February 2016), it does incorporate time-varying covariates. In doing so, we are assuming homogenous treatment effects across covariates (i.e., no bad controls) and that time-varying covariates do not exhibit specific trends in both treated and control groups. Sant'Anna and Zhao (2020) propose a doubly robust estimator (DR-SZ) based on pre-treatment characteristics that combine the inverse probability weighting estimator by Abadie (2005) with the outcome regression approach proposed by Heckman et al. (1997), both of which address time-varying covariates in a DiD context.

Similarly, synthetic control methods have also evolved to accommodate multiple treated units, as seen in estimators proposed by Arkhangelsky et al. (2021), Ben-Michael et al. (2021), or Abadie and L'Hour (2021). Among these, the synthetic difference-in-differences

Table 6 Difference-in-difference estimates conditional on filling stations

	(1)	(2)	(3)	(4)	(5)	(6)
ln(Diesel sales)						
Border × *ISP*(25 km from border)	0.063*		0.079***		0.071***	
	(0.032)		(0.021)		(0.022)	
Border × *ISP*(5 km from border)		0.080**		0.085***		0.096***
		(0.033)		(0.013)		(0.014)
Constant	9.164	9.910	25.793*	31.804**	37.620***	34.413***
	(14.824)	(14.795)	(13.597)	(14.740)	(12.794)	(11.739)
R-squared	0.756	0.759	0.829	0.855	0.985	0.985
R2 adj	0.743	0.746	0.785	0.810	0.984	0.984
ln(Gasoline sales)						
Border × *ISP*(25 km from border)	−0.016*		0.013		−0.012	
	(0.008)		(0.016)		(0.007)	
Border × *ISP*(5 km from border)		−0.010		−0.036**		−0.013
		(0.009)		(0.013)		(0.012)
Constant	7.763	9.568	−9.930	17.064	15.311	13.417**
	(11.386)	(11.412)	(13.179)	(12.706)	(11.222)	(6.372)
R-squared	0.810	0.807	0.856	0.827	0.983	0.986
R2 adj	0.800	0.797	0.820	0.772	0.981	0.985
Observations	4,320	4,212	864	648	4,320	4,212
Number of id_province	40	39	26	17	40	39
Sample	All	All	PS match	PS match	Entropy B	Entropy B
Control vars	YES	YES	YES	YES	YES	YES
Province FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
Month FE	YES	YES	YES	YES	YES	YES
Year-month FE	YES	YES	YES	YES	YES	YES
Year x Region FE	YES	YES	YES	YES	YES	YES
Cluster s.e	Province	Province	Province	Province	Province	Province

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 sales of the border provinces as a result of the tax change in Portugal (ISP). This is shown for provinces with a higher share of filling stations within the first km after the border (and removing the other border provinces). These 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. ***$p<0.01$, **$p<0.05$, *$p<0.1$

method (SDID) developed by Arkhangelsky et al. (2021) aims to reconcile both the DiD and synthetic control methods. Unlike the traditional synthetic control method, the SDID uses time weights in addition to unit-specific weights. As a result, SDID does not rely on an exact pre-treatment match between the observed treated unit and the estimated counterfactual but on parallel trends between these two, as in the traditional DiD estimators. However, unlike traditional difference-in-differences, SDID controls for time-varying unobserved heterogeneity.

Table 8 shows the main parameter estimates using these two alternative methods for both diesel and gasoline sales. We also show results considering the shorter period as in the

Table 7 Difference-in-difference estimates (2015–2017)

	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	ln(Diesel)	ln(Diesel)	ln(Diesel)	ln(Gasoline)	ln(Gasoline)	ln(Gasoline)
$Border \times ISP$	0.068***	0.058***	0.069***	0.033***	0.035***	0.035***
	(0.013)	(0.015)	(0.012)	(0.012)	(0.012)	(0.009)
Constant	37.325**	36.232	47.207**	29.671*	49.599	39.076**
	(15.874)	(27.424)	(19.200)	(15.770)	(34.043)	(18.583)
R-squared	0.801	0.861	0.992	0.832	0.854	0.988
R2 adj	0.793	0.841	0.992	0.825	0.832	0.987
Observations	1,548	486	1,548	1,548	486	1,548
Number of provincies	43	34	43	43	34	43
Sample	All	PS match	Entropy B	All	PS match	Entropy B
Control vars	YES	YES	YES	YES	YES	YES
Province FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
Month FE	YES	YES	YES	YES	YES	YES
cluster s.e	Province	Province	Province	Province	Province	Province

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). Robust standard errors in parentheses. ***$p<0.01$, **$p<0.05$, *$p<0.1$

Table 8 Difference-in-differences according to alternative estimators

	DR-SZ	SDID
ln(diesel consumption)		
$Border \times ISP$(2011–2019)	0.061*	0.064***
	(0.035)	(0.025)
$Border \times ISP$(2015–2017)	0.049**	0.061***
	(0.019)	(0.015)
ln(gasoline consumption)		
$Border \times ISP$(2011–2019)	0.036	−0.01
	(0.067)	(0.01)
$Border \times ISP$(2015–2017)	−0.001	0.005
	(0.039)	(0.017)
Obs	4644	4644

This Table shows estimates for alternative relevant dif-in-dif estimators. First column shows doubly robust (DR-SZ) estimator proposed by Sant'Anna and Zhao (2020). The second column shows synthetic difference-in-difference estimator, proposed by Arkhangelsky et al. (2021). Robust standard errors in parentheses. ***$p<0.01$, **$p<0.05$, *$p<0.1$

previous robustness check. Results remain consistent in all cases: diesel sales increase as a result of the tax increase in Portugal, while gasoline sales do not. According to both DR-SZ and SDID, gasoline sales do not significantly increase at any standard level of significance, even when restricting the sample to the shorter period. This is particularly relevant for the SDID estimator, which, as mentioned, can also control for time-varying unobserved factors. Figure 11 in the appendixes illustrates the observed border provinces as compared to the estimated counterfactual.

6 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 estimates show a 6–9% rise in diesel sales in those Spanish provinces that share a border with Portugal in response to the tax hike in that country. This represents additional annual consumption of 21–30 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: 1.2–1.8 for diesel vs. 0.1–0.3 for gasoline.[8]

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 mentioned, this does not necessarily imply that the drivers of passenger cars do not take advantage of Spain's lower prices. 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 cross-border tax change.

The absence of a reaction from passenger car drivers can, potentially, be explained by the fact that cross-border fuel substitution may well have reached satiation, i.e., no increase in consumption results from the tax change because all drivers that engage in cross-border fuel substitution 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. This makes these drivers more elastic to cross-border tax changes. 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.

The Portuguese tax on petroleum and energy products (*ISP*) was 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 55,000 to 80,000 tCO_2 per year,[9] attributable exclusively to the consumption of diesel. While this is only 0.5% of

[8] In the case of diesel, the cross-price elasticity is derived from the 6–9% 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 1% over the 10% increase in the tax (that is, €0.06 of the average full tax levied on gasoline €0.60). The highest value of the estimate yields a short-term cross-price elasticity of 0.3.

[9] The total of million liters of diesel is derived from the difference between observed diesel consumption and the counterfactual liters consumed (without the cross-border tax according to our estimates). We calculate these figures taking our lower estimate (6%) and our higher estimate (9%). 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.

Portugal's total annual transport emissions, it represents 14–20% of the country's annual mitigation commitment by 2030 (NECP-Portugal 2019). According to the National Energy and Climate Plan 2021–2030, projected emissions for transport by 2030 are 11.7 M tCO_2, while in 2019 they were registered at 17 M tCO2. This means 4.3 M tCO2 mitigated in 11 years, hence 397,367 tCO_2 per annum: 80,000 tCO_2/397,367 tCO_2 (i.e. 20%). 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 context, 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 for 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, especially with the forthcoming implementation of the EU's new road transport emission trading system.

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 leakage documented herein implies an annual foregone revenue of €21 million, that is, 1.3% of the total revenue generated by diesel fuel taxation in Portugal in 2016 (European Commission, 2023). 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.

7 Conclusion

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, cross-border fuel substitution 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 in the road transportation sector can result in carbon leakage and foregone revenue, thereby significantly undermining both the environmental effectiveness and economic efficiency of such measures. We provide robust causal evidence that a rise in Portugal's fuel tax aimed at environmental goals increased diesel sales (and derived emissions) in neighboring border provinces in Spain, providing evidence of notable carbon leakage (i.e., emissions shifted from Portugal to Spain, while recorded as emission reduction in Portugal). Critically, our results are also robust in reporting a non-statistically significant effect in the case of gasoline sales, revealing a novel differential effect by fuel type. This differential effect is attributed to different elasticities to cross-border tax changes between heavy goods vehicles (which predominantly use diesel) and passenger vehicles (which use both diesel and gasoline). The higher elasticity of truck drivers, equipped with large-capacity diesel fuel tanks, drives the cross-border tax response.

Previous research has shown the key roles of salience and persistence of fuel taxes in shaping drivers' responses. Here we show fuel type might be as relevant. Additionally, we find that a lack of tax coordination across countries undermines mitigation policies in the transportation sector. These findings offer valuable insights for future climate policies, particularly by identifying road freight transport as the primary source of carbon leakage within the sector. As the implementation of an emission trading system for transport emissions approaches, enhanced tax coordination among Member States is essential to avoid the negative outcomes identified in this paper.

Appendix

See Tables 9, 10, 11, 12, 13, 14 and Figs. 8, 9, 10, 11.

Table 9 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	Avg. control Group
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(Filling S. 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

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 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)

Table 10 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)	0	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

Table 10 (continued)

	Zamora	Huelva	Badajoz	Salamanca	Ourense	Pontevedra	Cáceres
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 11 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

Table 11 (continued)

	Zamora	Huelva	Badajoz	Salamanca	Ourense	Pontevedra	Cáceres
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

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

Table 12 Difference-in-difference estimates with no control covariates

VARIABLES	(1) *ln(Diesel)*	(2) *ln(g95)*
Border × *ISP*	0.079**	−0.029***
	(0.032)	(0.010)
Constant	17.229***	15.646***
	(0.017)	(0.030)
Observations	5184	5184
R-squared	0.683	0.767
R2 adj	0.668	0.756
Number of id_province	48	48
Sample	All	All
Control vars	NO	NO
Province FE	YES	YES
Year FE	YES	YES
Month FE	YES	YES
Year-month FE	YES	YES
Year × Region FE	YES	YES
cluster s.e	Province	Province

Robust standard errors in parentheses

$^{***}p<0.01$, $^{**}p<0.05$, $^{*}p<0.1$

Table 13 In-time placebo for difference-in-difference estimates

VARIABLES	(1) *ln(Diesel)*	(2) *ln(Diesel)*	(3) *ln(Diesel)*	(4) *ln(Diesel)*	(5) *ln(g95)*	(6) *ln(g95)*	(7) *ln(g95)*	(8) *ln(g95)*
Placebo DiD (Feb 2015)	0.008				−0.026			
	(0.020)				(0.019)			
Placebo DiD (Feb 2014)		−0.000				−0.025		
		(0.019)				(0.018)		
Placebo DiD (Feb 2013)			−0.015				−0.023	
			(0.020)				(0.018)	
Placebo DiD (Feb 2012)				−0.023				−0.013
				(0.019)				(0.019)
Constant	33.216*	33.697*	35.795**	35.668**	14.297***	14.281***	14.271***	14.263***
	(16.932)	(17.183)	(16.587)	(16.591)	(0.553)	(0.556)	(0.561)	(0.564)
Observations	2,666	2,666	2,666	2,666	2,666	2,666	2,666	2,666
R-squared	0.987	0.987	0.987	0.987	0.988	0.988	0.988	0.988
R2 adj	0.986	0.986	0.986	0.986	0.987	0.987	0.987	0.987
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

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

Table 14 Treated and control Spanish provinces. Alternative matched sample

	Propensity Score Matching (PSM) sample			Entropy balanced sample		
	T = 0	T = 1	Diff	T = 0	T = 1	Diff
20% filling stations closer than 25 km (Pontevedra, Badajoz, Ourense and Huelva)						
ln (income)	6.606	6.634	−0.028	6.641	6.634	0.007
Share inhab. in Prov. Capital	0.222	0.230	−0.008	0.235	0.23	0.005
ln(population)	13.427	13.258	−0.169*	13.225	13.258	−0.033
ln(before-tax price of diesel, 2016)	0.126	0.130	−0.004	0.127	0.13	−0.003
ln(before-tax price of gasoline, 2016)	0.217	0.224	−0.006	0.221	0.224	−0.003
ln(avg. daily traffic)	9.385	9.215	−0.169**	9.187	9.215	−0.028
5% filling stations closer than 5 km (Pontevedra, Badajoz and Huelva)						
ln (income)	6.535	6.598	−0.062***	6.571	6.598	−0.027
Share inhab. in Prov. Capital	0.248	0.195	0.052***	0.191	0.195	−0.004
ln(population)	13.4	13.455	−0.054	13.508	13.455	0.053
ln(before-tax price of diesel, 2016)	0.101	0.125	−0.025*	0.117	0.126	−0.009
ln(before-tax price of gasoline, 2016)	0.194	0.22	−0.026**	0.209	0.220	−0.011
ln(avg. daily traffic)	9.511	9.395	0.116	9.436	9.395	0.041

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

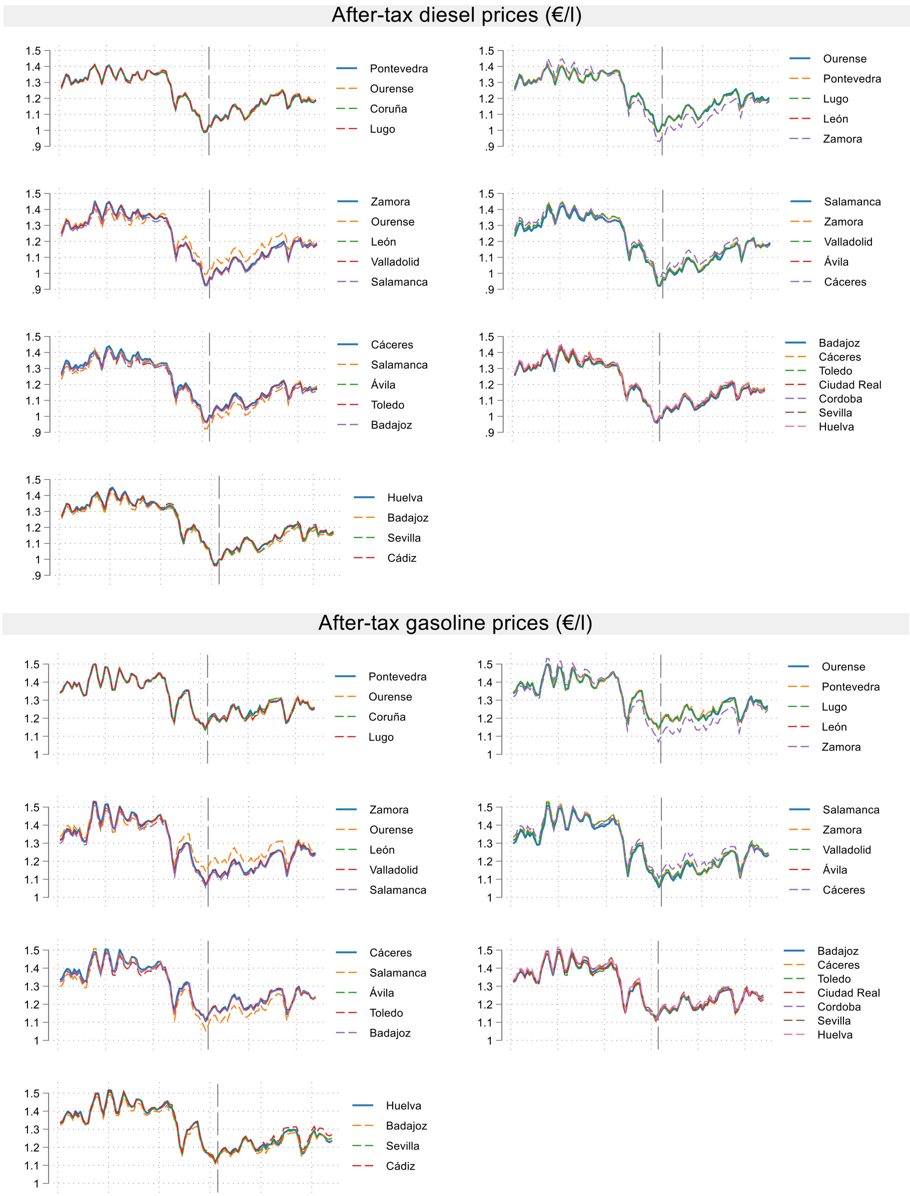

Fig. 8 Fuel price evolution in treated provinces vs. immediate neighboring provinces.*Notes*: Each graph plots the evolution in diesel (top panel) and gasoline prices (bottom panel) for a specific treated province (solid line) vs. the other Spanish provinces with which it shares a border (dashed lines). 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)

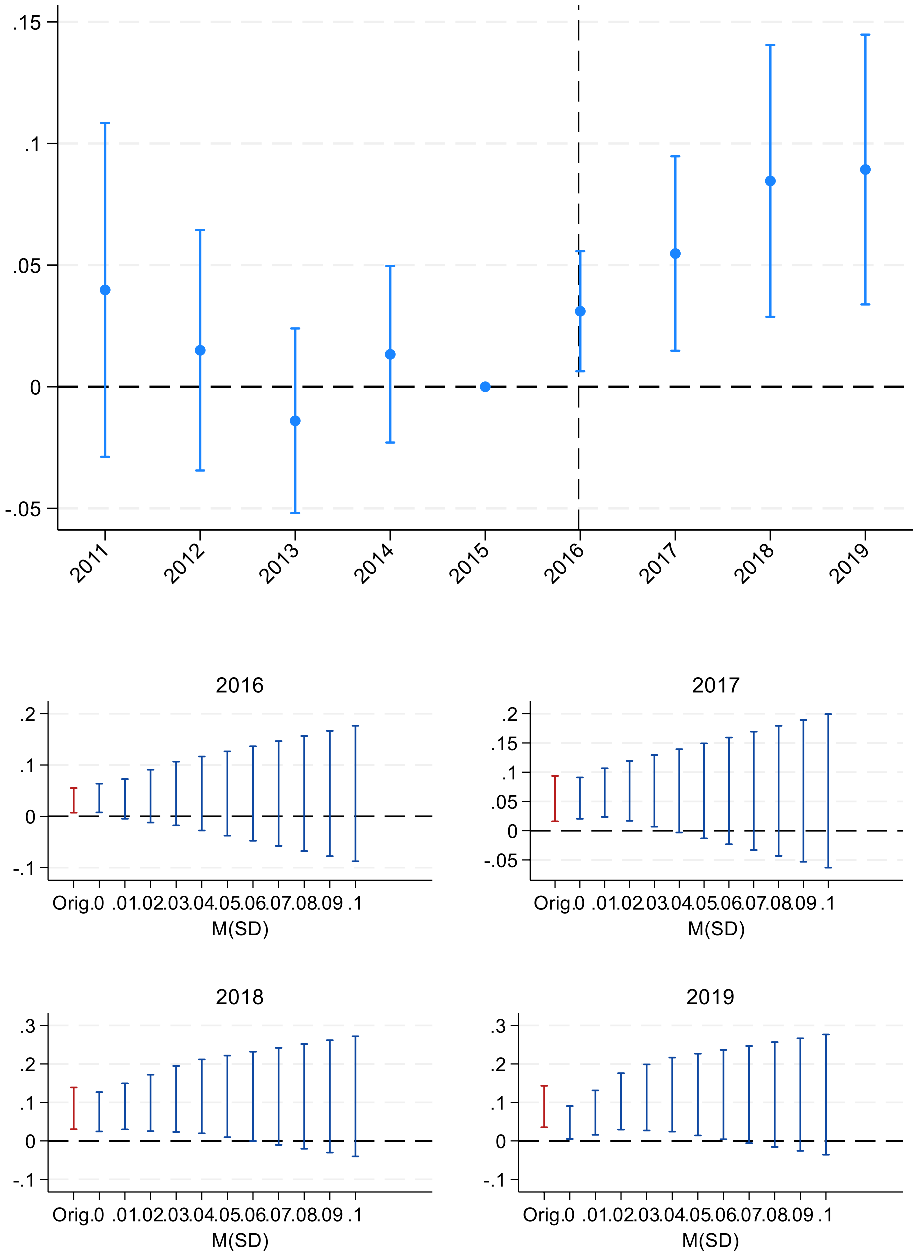

Fig. 9 Rambachan and Roth (2023) sensitivity tests on parallel trends. *Notes*: The top panel replicates event estimates for difference-in-differences on an annual basis for diesel sales. The bottom panel plots sensitivity tests using smoothness restrictions (Rambachan and Roth 2023). The original estimate for each year is shown in red (plotted in the top panel). Estimates for different M values are shown in blue

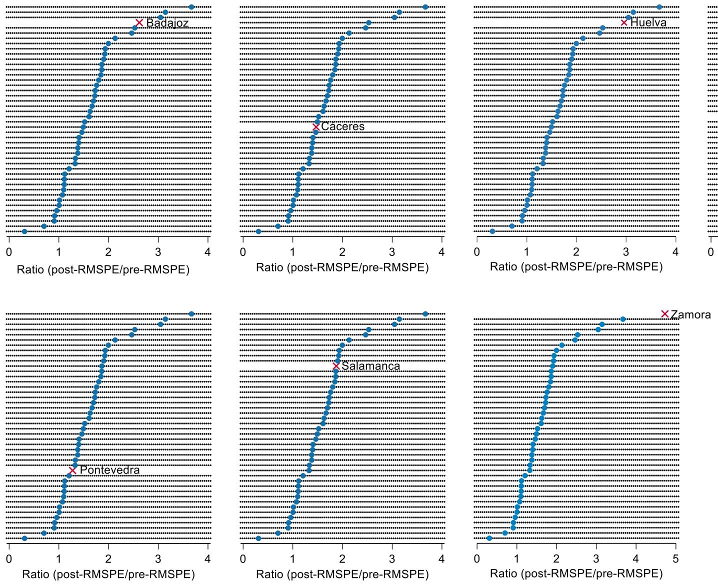

Fig. 10 In-space placebo tests. *Notes*: These graphs show the ratio of post- to pre-treatment MSPE allowing inferences to be made by comparing each unit with its synthetic control. In this case, only Zamora, and to a lower extent Badajoz and Huelva, show high RMSPE ratios. Following Abadie et al. (2015), 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 = 0.08

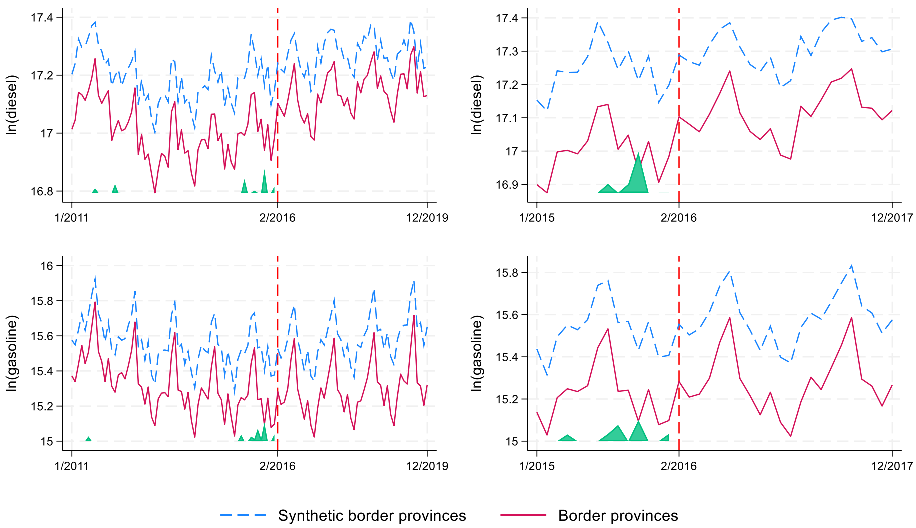

Fig. 11 Synthetic Difference-in-differences. *Notes*: This figure shows the average (ln)consumption of diesel (top panels) and gasoline (bottom panels) in the seven border provinces (solid lines) compared to that of their counterfactual (dashed line) with no tax cross border-tax increase, as estimated by the synthetic Difference-in-differences (Arkhangelsky et al 2021). This is shown for two different sampled periods. The credibility of the causal impact lies on parallel trends between observed border provinces and the synthetic border province. The synthetic border provinces are an optimally weighted average of the other Spanish non-border provinces. Green areas signal the time weights

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Declarations

Conflict of interest No interests to disclose.

References

Abadie A (2021) Using synthetic controls: feasibility, data requirements, and methodological aspects. J Econ Lit 59(2):391–425. https://doi.org/10.1257/jel.20191450

Abadie A, Gardeazabal J (2003) The economic costs of conflict: a case study of the Basque Country. Am Econ Rev 93(1):113–132. https://doi.org/10.1257/000282803321455188

Abadie A, Imbens GW (2011) Bias-corrected matching estimators for average treatment effects. J Bus Econ Stat 29(1):1–11. https://doi.org/10.1198/jbes.2009.07333

Abadie A, Diamond A, Hainmueller J (2010) Synthetic control methods for comparative case studies: estimating the effect of California's Tobacco Control Program. J Am Stat Assoc 105(490):493–505. https://doi.org/10.1198/jasa.2009.ap08746

Abadie A, Diamond A, 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

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

Agaku IT, Blecher E, Filippidis FT, Omaduvie UT, Vozikis A, Vardavas CI (2016) Impact of cigarette price differences across the entire European Union on cross-border purchase of tobacco products among adult cigarette smokers. Tob Control 25(3):333–340. https://doi.org/10.1136/tobaccocontrol-2014-052015

Andersson JJ (2019) Carbon taxes and CO_2 emissions: Sweden as a case study. Am Econ J Econ Pol 11(4):1–30. https://doi.org/10.1257/pol.20170144

Antweiler W, Gulati S (2016) Frugal cars or frugal drivers? How Carbon Fuel Taxes Influence Choice Use Cars. https://doi.org/10.2139/ssrn.2778868

Arkhangelsky D, Athey S, Hirshberg DA, Imbens GW, Wager S (2021) Synthetic difference-in-differences. Am Econ Rev 111(12):4088–4118

Banfi S, Filippini M, Hunt LC (2005) Fuel tourism in border regions: the case of Switzerland. Energy Econ 27(5):689–707. https://doi.org/10.1016/j.eneco.2005.04.006

Bang H, Robins JM (2005) Doubly robust estimation in missing data and causal inference models. Biometrics 61(4):962–972

Ben-Michael E, Feller A, Rothstein J (2021) The augmented synthetic control method. J Am Stat Assoc 116(536):1789–1803. https://doi.org/10.1080/01621459.2021.1929245

Böhringer C, Rosendahl KE, Storrøsten HB (2017) Robust policies to mitigate carbon leakage. J Public Econ 149:35–46

Callaway B, Sant'Anna PHC (2021) Difference-in-differences with multiple time periods. J Econom 225(2):200–230. https://doi.org/10.1016/j.jeconom.2020.12.001

Coglianese J, Davis LW, Kilian L, Stock JH (2017) Anticipation, tax avoidance, and the price elasticity of gasoline demand. J Appl Econom 32(1):1–15. https://doi.org/10.1002/jae.2500

European Commission, & Directorate-General Taxaxion and Customs Union. (2023) Excise Duty Tables (Tax receipts—Energy products and Electricity). Revenues from Taxes on Consumption.

Coyne D (2017) How Political boundaries affect gas price competition and State Motor Fuels Tax. In: Proceedings of the Annual Conference on Taxation and Minutes of the Annual Meeting of the National Tax Association, vol 110, pp 1–51. https://www.jstor.org/stable/26794453

CNMC Data (2021) Comisión Nacional de Mercados y Competencia. Estadística de Productos Petrolíferos. Retrieved Ferbuary 2021 from https://data.cnmc.es/

Davis LW, Kilian L (2011) Estimating the effect of a gasoline tax on carbon emissions. J Appl Economet 26(7):1187–1214. https://doi.org/10.1002/jae.1156

DeCicca P, Kenkel D, Liu F (2013) Who pays cigarette taxes? The impact of consumer price search. Rev Econ Stat 95(2):516–529

DGT. Direccion General de Tráfico (2023) Datos estaciones. Dirección General de Tráfico. Retrieved October 2023 from https://nap.dgt.es/dataset

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

Fowlie ML, Reguant M (2021) Mitigating emissions leakage in incomplete carbon markets. J Assoc Environ Resour Econ 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. Rev Public Econ 208:145–190. https://doi.org/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 Econ. https://doi.org/10.1016/j.eneco.2022.106009

Goodman-Bacon A (2021) Difference-in-differences with variation in treatment timing. J Econom 225(2):254–277. https://doi.org/10.1016/j.jeconom.2021.03.014

Hainmueller J (2012) Entropy balancing for causal effects: a multivariate reweighting method to produce balanced samples in observational studies. Polit Anal 20(1):25–46. https://doi.org/10.1093/pan/mpr025

Harding M, Leibtag E, Lovenheim MF (2012) The Heterogeneous geographic and socioeconomic incidence of cigarette taxes: evidence from Nielsen Homescan Data. Am Econ J Econ Pol 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

INE (2021). INEbase. Atlas Distribucion de renta. Retrieved Ferbuary 2021 from https://www.ine.es/dyngs/INEbase/listaoperaciones.htm

Jansen D-J, Jonker N (2018) Fuel Tourism in Dutch border regions: Are only salient price differentials relevant? Energy Econ 74:143–153. https://doi.org/10.1016/j.eneco.2018.05.036

Kortum S, Weisbach D (2017) The design of border adjustments for carbon prices. Natl Tax J 70(2):421–446

Leal A, López-Laborda J, Rodrigo F (2009) Prices, taxes and automotive fuel cross-border shopping. Energy Econ 31(2):225–234. https://doi.org/10.1016/j.eneco.2008.09.007

Li S, Linn J, Muehlegger E (2014) Gasoline taxes and consumer behavior. Am Econ J Econ Pol 6(4):302–342. https://doi.org/10.1257/pol.6.4.302

Lovenheim MF (2008) How far to the border? The extent and impact of cross-border casual cigarette smuggling. Natl Tax J 61(1):7–33. https://doi.org/10.17310/ntj.2008.1.01

Manuszak MD, Moul CC (2009) How far for a buck? Tax differences and the location of retail gasoline activity in Southeast Chicago land. Rev Econ Stat 91(4):744–765

Marion J, Muehlegger E (2018) Tax compliance and fiscal externalities: evidence from U. S. Diesel Taxation. J Public Econ 160(C):1–13. https://doi.org/10.1016/j.jpubeco.2018.02.007

Ministerio para la Transición Ecológica y el RD (2021) Geoportal Gasolineras. Retrieved February, 2021, from: https://geoportalgasolineras.es/geoportal-instalaciones/Inicio

Morton C, Lovelace R, Philips I, Anable J (2018) Fuel price differentials and car ownership: a spatial analysis of diesel cars in Northern Ireland. Transp Res D: Transp Environ 63:755–768. 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? J Environ Econ Manag 93:125–147. 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

Rambachan A, Roth J (2023) A more credible approach to parallel trends. Rev Econ Stud 90(5):2555–2591. https://doi.org/10.1093/restud/rdad018

Roth J (2022) Pretest with caution: event-study estimates after testing for parallel trends. Am Econ Rev: Insights 4:305–322

Sant'Anna PHC, Zhao J (2020) Doubly robust difference-in-differences estimators. J Econom 219(1):101–122. https://doi.org/10.1016/j.jeconom.2020.06.003

Scott KR (2012) Rational habits in gasoline demand. Energy Econ 34(5):1713–1723. 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/10.1016/j.enpol.2006.10.025

Tiezzi S, Verde SF (2016) Differential demand response to gasoline taxes and gasoline prices in the U.S. Resour Energy Econ 44:71–91. https://doi.org/10.1016/j.reseneeco.2016.02.003