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Pier Basaglia, Sophie M. Behr, Moritz A. Drupp

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De-Fueling Externalities: Causal Effects of Fuel Taxation and Mediating Mechanisms for Delivering Climate and Health Benefits

Abstract

This paper provides a comprehensive evaluation of the world's largest environmental tax reform. We compare carbon and air pollutant emissions of the German transport sector and synthetic counterfactuals following the 1999 eco-tax reform, and find average reductions in external damages of around 80 billion Euros. We further show that the eco-tax induced low-carbon innovation and document much stronger demand responses to eco-tax increases than to market price movements, primarily driven by increased tax salience in newspapers. Our results highlight the key roles of salience and fuel substitution in mediating the effectiveness of fuel taxes to deliver climate and health benefits.

JEL-Codes: Q580, H230, I180, R480.

Keywords: environmental policy, fuel tax, carbon tax, tax elasticity, salience, fuel substitution, innovation, climate, pollution, health.

Pier Basaglia
Department of Economics and Center for Earth System Research and Sustainability (CEN), University of Hamburg / Germany
piero.basaglia@uni-hamburg.de

Sophie M. Behr
Climate Policy Department
DIW Berlin / Germany
sbehr@diw.de

Moritz A. Drupp
Department of Economics and CEN
University of Hamburg / Germany
moritz.drupp@uni-hamburg.de

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1 Introduction

Fuel taxation is a key policy instrument to reduce negative externalities of fossil fuelled transportation (Parry et al., 2007; Sterner, 2007; Hintermann et al., 2021) and has seen renewed interest due to concerns about climate change, air pollution, and energy security (e.g., Grigolon et al., 2018; Parry et al., 2021). Understanding how fuel taxation affects fuel demand is essential to effectively leverage this tool for policy. Many assessments assume that demand responses to tax changes are equivalent to those of market-driven price variations and estimate limited impacts of carbon taxes (e.g., Green, 2021). In contrast, recent work highlights the considerable role of tax salience effects (e.g., Chetty et al., 2009; Li et al., 2014), which may suggest that more modest taxes may achieve politically targeted fuel reductions. Additionally, carbon abatement represents only part of the economic benefits that can justify fuel taxation. Importantly, transportation causes considerable health damages linked to air pollution (e.g., Schlenker and Walker, 2016; Knittel et al., 2016) and reducing fossil fuel use can thus yield substantial health benefits (e.g., Shaw et al., 2014; Parry et al., 2015). Accounting for such health co-benefits may be important for gathering public support for fuel pricing.

We investigate the effectiveness of fuel taxation to reduce carbon and air pollutant emissions with a quasi-experimental assessment of the world's largest implicit carbon tax reform: the German eco-tax. The reform increased fuel taxes in Europe's biggest transport sector in yearly steps from 1999 to 2003 up to 15.35 cents per liter. In 2003, implicit carbon costs due to the eco-tax amounted to €58 (\$65) per tCO_2 for diesel and €66 (\$74) for gasoline. This was then the second highest effective carbon price globally—higher alone than federal fuel taxes in the US, where regulation has mainly focused on standards (Jacobsen et al., 2023), and only slightly lower than the Swedish carbon tax on transport fuels that was levied on a much smaller tax base (Andersson, 2019).

Our analysis starts by estimating causal effects of the eco-tax on emissions of CO_2, $PM_{2.5}$, and NO_X in the German transport sector. Using the synthetic control method (SCM) (e.g., Abadie, 2021), we build counterfactual Germanies with weighted combinations of control countries and compare emission paths of the German transport sector and its synthetic counterfactuals.[1] Our results imply that, between 1999 and 2009, the eco-tax led to emission gaps in the transport sector of around 10% for CO_2, 27% for $PM_{2.5}$, and 13% for NO_X on average across specifications, and to an average reduction in external damages of around 80 billion euros when using official cost estimates.[2] While modeling studies consistently indicate considerable positive health impacts due to lower fossil fuel use (e.g., Shaw et al., 2014; Choma et al., 2021), this paper is the first observational study to quantify the climate *and* health benefits of fuel or carbon taxation in a quasi-experimental framework. Our assessment of the world's largest environmental tax reform complements studies on the role of emission standards to reduce climate and pollution externalities in the transport sector (e.g., Auffhammer and Kellogg, 2011; Jacobsen et al., 2023; Reynaert, 2021) and we substantially extend investigations on the effectiveness of carbon or fuel taxes that focused exclusively on CO_2 abatement.[3]

We further use the generalized SCM (Xu, 2017) to quantify the impacts of the eco-tax on the development of low-carbon patented technologies, building on Aghion et al. (2016), who use transport fuel prices to proxy carbon prices and link them to an increase in innovation in clean technologies in the automobile sector. In contrast, we investigate low-carbon innovation induced by environmentally-motivated taxation, which may yield a greater response due to the higher salience (Sterner, 2012b). By focusing on economy-wide patent data, our empirical strategy captures innovation in response to an implicit carbon price that accounts for unreg-

[1] We draw on a growing literature using SCMs to evaluate policies (e.g., Lindo and Packham, 2017; Cunningham and Shah, 2018), particularly for environmental regulations (e.g., Andersson, 2019; Isaksen, 2020; Bayer and Aklin, 2020; Leroutier, 2022).

[2] Our findings are robust to a host of placebo and sensitivity tests, including in-time placebos, the use of alternative donor pools, sets of predictors, different pre-treatment time frames, the exclusion of one donor country at a time, and permutation tests that sequentially apply the SCM to every potential donor country. We also use generalized SCMs to model unobserved heterogeneous time-varying shocks with interactive fixed effects models, and restrict the donor pool to EU countries only to rule out that effects are driven by EU-wide regulation, like emission standards (e.g., Reynaert, 2021).

[3] Andersson (2019), Mideksa (2021) and a contemporaneous paper (Runst and Höhle, 2022) examine the effectiveness of carbon or fuel taxes to reduce CO_2 emissions using the SCM. We go beyond in several dimensions by investigating effects on air pollution and low-carbon innovation, and by disentangling effects by fuel type to illuminate trade-offs between climate and health benefits. We investigate additional mechanisms mediating tax effectiveness and provide first direct evidence on the key role of tax salience.

ulated companies, upstream equipment manufacturers (Sanyal and Ghosh, 2013), downstream suppliers (Popp, 2019) and new entrants to the market (Noailly and Smeets, 2015), departing from existing firm-level observational studies exploiting policy inclusion criteria (e.g., Calel and Dechezleprêtre, 2016; Calel, 2020). We find that the eco-tax has led to a 6% average yearly increase in patented low-carbon technologies concerning the transport sector. Our results thus indicate considerable potential for fuel or carbon taxes for incentivizing technological innovation to increase the fuel efficiency and contribute to reducing abatement costs (e.g., Popp, 2019).

Next, we enrich our causal analyses with additional explorations of mediating mechanisms, focusing in particular on the roles of fuel substitution and tax salience.[4] We build on a large literature exploring effects of gasoline and energy prices on fuel demand and emissions (e.g., Dahl and Sterner, 1991; Levin et al., 2017; Linn, 2019; Parry et al., 2021), which often relies on fuel and energy prices as proxies for carbon prices and use price changes over time to estimate impacts on fuel demand. Yet, fuel prices are prone to endogeneity concerns, likely biasing price elasticity estimates downwards (e.g., Kilian, 2009; Davis and Kilian, 2011; Coglianese et al., 2017). We use annual variations in fuel-specific tax rate changes, coupled with an instrumental variable approach, and a set of distributed lag models to account for potential tax anticipation effects (c.f., Kilian and Zhou, 2023). Our focus on fuel-specific demand adjustments departs from previous studies that rely on changes in gasoline consumption as a proxy for aggregate emission reductions (e.g., Davis and Kilian, 2011; Rivers and Schaufele, 2015) and helps to illuminate the role of fuel substitution. Accounting for gasoline-to-diesel substitution is crucial in the European context given its high diesel share (Zimmer and Koch, 2017), and allows quantifying trade-offs between climate and health benefits.

We first estimate price and tax elasticities of demand for gasoline and diesel to disentangle behavioral responses. Our preferred specifications yield a tax-exclusive price elasticity of demand for gasoline (diesel) of -0.32 (-0.26) and an eco-tax elasticity of demand of -2.7 (-1.1). Fuel-specific eco-

[4] Analyzing other mechanisms suggests that the eco-tax has likely contributed to fostering fleet renewal of passenger cars and to fewer passenger-kilometers travelled without reduced overall economic activity.

tax elasticities are thus 4 to 8.5 times higher than the tax-exclusive price elasticity (a ratio referred to as *tax saliency ratio*), in line with prior findings that changes in taxes are more potent than equivalent market-driven price changes (e.g., Li et al., 2014; Rivers and Schaufele, 2015; Andersson, 2019).[5] This underscores potentially large biases in policy evaluations that rely on responses to market-driven fuel price changes as a proxy for the effect of environmental taxes.

We then use these fuel-specific tax elasticities to perform simulations and find that around three-thirds of the (simulated) reduction in CO_2 emissions is attributable to lower gasoline use, partly driven by gasoline-to-diesel substitution. Conversely, almost all decreases in $PM_{2.5}$, and more than half of decreases in NO_x emissions, are driven by lowered diesel use due to the eco-tax. This highlights important trade-offs that can arise between climate and air pollution targets, which is particularly relevant for price instruments set on the carbon content of fuels that can foster fuel substitution. Such fuel substitution is—with the exception of Linn (2019)—not accounted for in existing policy evaluations. We complement Linn (2019) by relaxing the assumption that consumers respond similarly to fuel taxes as to other changes in fuel prices. We find that accounting for tax salience effects illuminates a much more sizable trade-off between climate and health benefits. This trade-off, and the associated inefficiency in targeting both climate and pollution targets with one price instrument, is a more general feature of second-best taxation (e.g., Knittel and Sandler, 2018), especially when it is not feasible to tax externalities directly (Jacobsen et al., 2023). Nonetheless, both our causal estimates and simulation results using disentangled elasticities provide evidence that the German eco-tax has lead to sizable reductions in these "untaxable" air pollution externalities.

Finally, we advance the literature on the role of salience for environmental policy (e.g., Li et al., 2014; Rivers and Schaufele, 2015; Huse and Koptyug, 2022) by developing a framework to quantify the role of salience changes in the media in driving the effects of the eco-tax. Similarly to

[5] Kilian and Zhou (2023) reconsider the analysis by Li et al. (2014) using a distributed lag model—as in Coglianese et al. (2017)—and find that the tax elasticity is not significantly different from tax-exclusive price elasticity in the US after accounting for anticipation effects. In our setting, even after accounting for anticipatory behaviour, we still document sizable and significant *tax saliency ratios*.

Li et al. (2014), who show that a tax change is associated with a greater increase in media coverage than a comparable change in the tax-exclusive fuel price, we rely on media analysis to explicitly investigate tax salience. Specifically, we construct a newspaper-based index to capture the evolution of eco-tax salience based on textual analysis of German newspaper articles (c.f., Gentzkow et al., 2019). Leveraging annual variations in our salience index within our elasticity models, we find that greater tax salience is associated with lower consumption of both gasoline and diesel and that these effects increase with the real eco-tax rate. Our simulations suggest that the salience of the eco-tax is responsible for around 70% (55%) of the observed contraction in gasoline (diesel) consumption. These results provide first direct evidence for the hypothesis that consumers react more strongly to fuel taxes the more salient they are and imply that targeted measures to increase salience may have considerable potential to enhance the cost-effectiveness of price instruments to internalize externalities.

The paper proceeds as follows. Section 2 details the methodology for the SCMs and elasticity models. Section 3 discusses the data. Section 4 presents results derived from SCMs, while Section 5 reports results on fuel and tax elasticities, simulations and additional mediating mechanisms. Section 6 quantifies climate and health benefits, while Section 7 concludes. The Online Appendix (OA) contains institutional details on the eco-tax reform and supporting materials for our analyses.

2 Methodology

2.1 The Synthetic Control Method

This section introduces the SCM (e.g., Abadie and Gardeazabal, 2003; Abadie et al., 2010; Abadie, 2021), and its generalized version denoted GSCM (Xu, 2017), and explains how we leverage them to estimate causal effects of fuel taxes on emissions of carbon dioxide and air pollutants as well as on the development of low-carbon patented technologies.

The SCM estimator. Suppose there are $J + 1$ countries. Each country is indexed by j, where $j = 1$ denotes the *treated* country (i.e., Germany), while $j = 2, ..., J+1$ are *untreated* countries (the *donor pool*), which may be used to construct a control group. The T time periods are divided into pre-treatment and post-treatment (i.e., after the eco-tax reform in 1999) with T_0 as the period prior to the policy ($t = t_0, t_{-1}, ..., T_0$). Denoting the intervention as I, the SCM considers that the observed outcome, y_{jt}, is the effect from the treatment, $\alpha_{jt} I_{jt}$, and the counterfactual outcome, y_{jt}^J:

$$y_{jt} = \alpha_{jt} I_{jt} + y_{jt}^J \,. \tag{1}$$

The idea of the SCM is to construct a vector of weights over J donor countries such that their weighted combination mimics the pre-treatment outcome of the treated country. This weighted combination of donor units is the called a synthetic Germany. Defining X_1 as the $k \times 1$ vector of the k characteristics of Germany in the pre-intervention period, and X_0 as the $k \times J$ vector with the same pre-treatment characteristics for donors, the SCM algorithm identifies non-negative donor weights $\boldsymbol{W}$, such that $\sum_{w_2}^{w_{J+1}} = 1$, to minimize the divergence between pre-treatment characteristics $\boldsymbol{X_1}$ and $\boldsymbol{X_0}$ of the treated country and the untreated donors. More formally, the vector $\boldsymbol{W}^*$ is chosen to minimize the mean square prediction error (MSPE) over k pre-treatment characteristics:

$$MSPE = \sum_{m=1}^{k} v_m \left(X_{1m} - X_{0m} W\right)^2 , \tag{2}$$

where $\boldsymbol{V}$ is a matrix of non-negative components measuring the relative importance of each predictor, v_m. Given optimal weights w_j^* for each $j = 2, ..., J+1$ donor country, the synthetic control at any time t is the weighted combination of the outcome variable (e.g., CO_2 emissions in the transport sector) in the donor countries, $\sum_{j=2}^{J+1} w_j^* \, y_{jt}$. The treatment effect α_{1t} is then the difference between emissions in the treated country y_{1t} and emissions in the synthetic counterfactual in the post-treatment period, $t > T_0$:

$$\hat{\alpha_{1t}} = y_{1t} - \sum_{j=2}^{J+1} w_j^* \, y_{jt} \,.\text{[6]} \tag{3}$$

[6]The average treatment effect is thus given by: $\hat{\beta_{1T}} = \frac{1}{T} \sum_{t=t_1}^{T} (y_{1t} - \sum_{j=2}^{J+1} w_j^* \, y_{jt})$.

Table 1: Overview of the specification choices for the SCMs

Specification	Lagged outcome variable	Selected literature examples
Baseline	Lagged outcome in 1998 (t_0)	Andersson, 2019; Kaul et al., 2022; Leroutier, 2022
Lags (Mean)	Pre-treatment outcome mean	Abadie and Gardeazabal, 2003; DeAngelo and Hansen, 2014
Lags (All)	Lagged pre-treatment outcome ($t_0, t_{-1}, ..., T_0$)	Bohn et al., 2014; Dustmann et al., 2017; Isaksen, 2020
Lags (Selected)	Lagged outcome in 1971, 1980, 1991, 1998	Cavallo et al., 2013; Cunningham and Shah, 2018
Reunification	Lagged outcome in 1991 and 1998	*Specific to the German case* (c.f., Abadie et al., 2015)
Tax anticipation	Lagged outcome in 1999 (t_1)	Abbring and Van den Berg, 2003; Coglianese et al., 2017
No covariates	Lagged pre-treatment outcome ($t_0, t_{-1}, ..., T_0$)	Gobillon and Magnac, 2016; Lindo and Packham, 2017

Notes: The Table summarizes the different SCM specifications we consider. *Specification* denotes the name that we use for SCM specification henceforth. *Lagged outcome variable* specifies the number and the years of the pre-treatment outcome lags. All except *No Covariates* include as predictors (i) GDP per capita (PPP, in million 2011 USD), (ii) gasoline and (iii) diesel consumption per capita, (iv) the share of the urban population, and (v) the number of vehicles per 1000 people. Our SCM specifications for NO_X emissions also include (vi) $PM_{2.5}$ emissions in the transport sector as a general proxy for air pollution to further account for the impact of unilateral policies affecting emission levels. We refer to the specification used by Andersson (2019) as the *Baseline* model. We start the post-treatment period in 1999 even if the first fully treated year is 2000 to capture anticipation effects (c.f. Section A in the OA for more details). Our *Tax anticipation* specification provides results when we set t_1 in the year 2000 for comparison.

Choice of SCM predictors. There are various methods for choosing the relative importance of predictors (v_m) (Abadie and Gardeazabal, 2003; Abadie et al., 2010). The standard approach is to select the matrix $\boldsymbol{V}$ along with the weights $\boldsymbol{W}$ so that the difference between Germany's and synthetic Germany's emissions in the pre-treatment is minimized.[7] Despite being a primarily data-driven approach, there is some discretion in specifying the SCM, which may lead to "cherry picking" combinations of predictors to influence the result (e.g., Ferman et al., 2020).[8] Given a lack of consensus on how to choose the best specification, we report results for a range of specifications used in previous SCM evaluations (see Table 1).

Statistical inference for the SCM. A key advantage of the SCM is that it offers an approach to causal analysis that does not rely on parallel pre-intervention trends like difference in difference methods. Yet, it does not allow to employ standard (large-sample) inferential methods, primarily because the number of suitable donors and time periods are usually very limited. Abadie et al. (2010, 2015) and Abadie (2021) suggest using placebo experiments using permutation techniques to make inferences. We implement cross-sectional placebo tests by sequentially applying the SCM

[7] This is done using the *synth* package in STATA developed by Abadie et al. (2010).

[8] While Kaul et al. (2022) point out that including the entire pre-treatment periods of the outcome variable as a predictor causes all other covariates to be obsolete, Ferman et al. (2020) advise using all pre-treatment periods as it is less arbitrary.

algorithm to every potential donor country and compare estimated placebo effects with the baseline results for Germany, after accounting for the quality of the pre-treatment match, which we do by scaling effects by the relevant pre-treatment root MSPE (RMSPE). Examining whether potential comparison countries show larger treatment effects helps assess the robustness of our results. A p-value is then computed as the proportion of control units that have an estimated effect at least as large as Germany's. Suppose that the estimated standardized effect for some post-treatment period is $\hat{\alpha_{1t}}$ and that the distribution of in-place placebo is $\hat{\alpha}_{jt}^{PL} = \{\hat{\alpha_{jt}} : j \neq 1\}$, the one-sided and two-sided p-values are then given by:

$$p = Pr(\, \hat{\alpha}_{jt}^{PL} \geq \hat{\alpha_{1t}}\,) \quad \text{and} \quad p = Pr(\, \hat{\alpha}_{jt}^{PL} \leq \hat{\alpha_{1t}}\,)\,, \tag{4}$$

$$p = Pr(\, |\hat{\alpha}_{jt}^{PL}| \geq |\hat{\alpha_{1t}}|\,) = \frac{\sum_{j \neq 1} 1\,(\,|\hat{\alpha}_{jt}^{PL}| \geq |\hat{\alpha_{1t}}|\,)}{J}\,. \tag{5}$$

Following Firpo and Possebom (2018) and Abadie and L'hour (2021), we implement a one-sided test, which allows constructing p-values based on placebo effects, $\hat{\alpha}_{jt}^{PL}$, that yield reductions in post-treatment emissions, as only reductions in emissions due to fuel taxes are of interest for the rank statistics of country-level treatment effects (we additionally report two-sided p-values). To evaluate how the significance of the effects of fuel taxation unfolds over time—since the eco-tax rate was increased in yearly steps from 1999 to 2003 (see Figure 3)— we apply the permutation-based inference procedure described above for each post-treatment year.

Generalized SCM with interactive fixed effects models. Drawing on Gobillon and Magnac (2016) and Xu (2017), we additionally rely on GSCMs based on a linear interactive fixed effects (IFE) model (Bai, 2009). The GSCM expands the SCM in several dimensions (see Xu, 2017). First, the GSCM allows explicitly absorbing unobserved heterogeneous time-varying shocks specific to each country with IFE. In our setting, this is particularly relevant as the 2007/2008 financial crisis had a different impact on Germany relative to other economies in the donor pool. Second, the GSCM enhances the interpretability of SCM results by providing uncertainty estimates such as standard errors and confidence intervals to conduct statistical inference. Third, by including relevant control variables, our

IFE model can explicitly capture heterogeneous influences of other policies across countries, such as the different effects of EU-wide emission standards on European economies and their emissions (c.f., Bai, 2009). Finally, an further advantage of the GSCM estimator is its built-in cross-validation scheme which automatically selects the model specification, limiting arbitrariness and reducing the risks of over-fitting.[9]

2.2 Semi-elasticity models

We subsequently estimate price and tax elasticities of gasoline and diesel demand and use these to perform simulations to investigate how tax effectiveness is mediated by salience and fuel substitution using log-linear semi-elasticity models. We estimate fuel-specific elasticities, using two different specifications (c.f., Andersson, 2019). First, we calculate real price elasticities and compare them to typical fuel demand elasticities (c.f. Equation 6: *Real price elasticities*). Second, in line with Li et al. (2014), we split the real price into its three main elements: the eco-tax, other existing fuel taxes (henceforth the energy tax), and the remaining tax-exclusive component, here called the raw price (c.f. Equation 7: *Eco-tax elasticities*). The estimated elasticities from Equation 7 are then used to simulate predicted pathways of CO_2 and air pollution emissions under different taxation regimes. The resulting static log-linear models are given as:

$$log(y_t) = \beta_0 + \varphi_1 p_t^{real} + \beta_2 D_t^{eco} + \lambda' \mathbf{X}_t + \epsilon_t \tag{6}$$

$$log(y_t) = \beta_0 + \varphi_2 p_t^{excl} + \varphi_3 p_t^{eco} + \varphi_4 p_t^{energy} + \beta_2 D_t^{eco} + \lambda' \mathbf{X}_t + \epsilon_t \tag{7}$$

Elasticity estimates obtained leveraging annual data within a static model typically lie somewhere between short- and long-term elasticities, and are regarded as "intermediate" (Dahl and Sterner, 1991). Outcome y_t refers to log fuel consumption per capita for gasoline or diesel in liters.[10] p_t^{real} is the real retail price, including VAT. p_t^{excl} is the retail price excluding the energy and eco-tax but with VAT, in real terms. p_t^{eco} and p_t^{energy} refer to the eco and energy tax, respectively, including VAT and are included in the models

[9] A key difference is that the GSCM employs dimension reduction before re-weighting implying that, unlike the standard SCM, weights cannot be directly interpreted.

[10] Prior to taking logs, we convert fuel consumption to liters.

as separate terms (c.f. Equation 7). D_t^{eco} is a dummy equal to one after the implementation of the eco-tax and zero otherwise. $\mathbf{X}_t$ is a vector of control variables that includes GDP per capita, the unemployment rate, and a time trend. The error terms are denoted by ϵ_t. We estimate the model using an OLS. As autocorrelation is detected, we use the Newey-West-estimator, which is robust against autocorrelation and heteroskedasticity.[11]

A standard concern with estimating fuel elasticities is an endogeneity problem, where fuel demand can also affect supply and thus prices (e.g., Kilian, 2009; Coglianese et al., 2017; Kilian and Zhou, 2023). Endogeneity due to reverse causality is arguably a lesser source of concern in a single EU country setting, as crude oil prices are set in a global market and changes in demand in a single country are thus expected to have a relatively marginal impact on overall demand. One possibility to still address this issue is to adopt an instrumental variable (IV) approach. In line with Li et al. (2014) and Andersson (2019), we complement our OLS regressions with an IV approach and use the (brent) crude oil price as an IV to validate the demand elasticities of the real price of gasoline and diesel (Equation 6).

3 Data

Our analysis is structured in two parts. In each step, we combine several data. First, we resort to the SCM and GSCM to evaluate effects of the eco-tax on CO_2, $PM_{2.5}$ and NO_X emissions, and on low-carbon innovation, building on a panel dataset of OECD countries. Second, we estimate price elasticities relying on a time-series dataset constructed specifically for Germany. We then examine the mechanism of tax salience in detail, relying on textual analysis of German newspapers. Table A.1 in the OA provides a detailed overview of all data sources used.

Emissions in the transport sector. To analyze the effect of the eco-tax reform on CO_2, $PM_{2.5}$, and NO_X emissions of the transport sector with the SCM, we construct an annual panel dataset from in 1971 to 2009 and consisting of OECD countries. We obtain CO_2 emissions in metric tons by multiplying total CO_2 emissions from fuel combustion from the

[11] Standard errors are calculated using lags chosen following Newey and West (1994).

International Energy Agency (IEA) with the percentage share of total fuel combustion for transportation. Annual emissions of $PM_{2.5}$ and NO_X are extracted from the Emission Database for Global Atmospheric Research (EDGAR) v6.1.[12] GDP data refers to expenditure-side real GDP at current purchasing power parities (in million 2011 USD) from the Penn World Table. Data for population, the share of urban population and diesel and gasoline consumption per capita in kg of oil equivalent are from the World Bank, and the number of vehicles from Dargay et al. (2007).

We limit our dataset to OECD countries, as these share more structural similarities with Germany in terms of their economic situation, emissions, and form of government, which is desirable for the SCM (Abadie, 2021). To build a suitable synthetic control for Germany, we exclude a number of countries. First, data for the Baltic countries, Slovakia, Czech Republic, and Slovenia is very sparse (especially prior to 1989), which is why we cannot consistently use them for the SCM starting from 1971. Second, we exclude countries that have implemented an explicit CO_2 price in the transport sector. This concerns Finland, Sweden, Norway, and the Netherlands (Kossoy et al., 2015).[13] As a number of countries implemented carbon taxes in the transport sector in 2009 or shortly thereafter, our analysis focuses on the time frame up to 2009. Third, we exclude countries that implemented fuel taxes in the transport sector that are not labeled as carbon taxes—similar to the eco-tax in Germany. This includes Italy, the UK (OECD, 2001), and Spain (Bosch, 2001). Fourth, we exclude Japan due to its very successful top runner program implemented in 1998 that set requirements for the fuel efficiency of vehicles (Osamu, 2012). Fifth, we exclude Ireland due to its exceptional economic growth in the 1990s. Finally, we exclude

[12] We use EDGAR as this computes emissions relying on a consistent technology-based emission factor approach and harmonized sector definitions. This has clear benefits over national emission inventories, which have two key caveats: (i) a much shorter pre-treatment period (only from 1990 onwards) and (ii) methodological inconsistencies in officially-reported pollution data across time and countries, which may hinder direct comparability and may increase measurement error. Weights computed with shorter pre-treatment periods (T_0), and outcome variables with substantial random noise, may increase biases in SCM (Ferman and Pinto, 2021) and GSCM estimators (Xu, 2017).

[13] Although Denmark also implemented a carbon tax around the same time, it did not include the traffic sector, which is why Denmark remains in the sample (Andersson, 2019). Similarly, Poland also implemented a carbon tax, but remains in the sample as the cost per ton of CO_2 was just a few cents and thus negligible (Kossoy et al., 2015).

Austria and Luxembourg due to non-negligible fuel tourism.[14] These restrictions, mostly due to carbon and fuel taxation, leave us with a main sample of 20 countries for the time frame from 1971 to 2009.

Low-carbon innovation: Patent data. To measure innovation, we use patent data from the OECD Patent Database. Patent documents are categorized into climate change mitigation patents in accordance with the Y02 tagging scheme of the Cooperative Patent Classification. We extract a panel dataset of climate change mitigation patents related to transportation (Y02T category) filed by inventors in OECD countries spanning from 1985 (earliest availability) to 2009. We focus on triadic patent families to improve the quality and the international comparability of patent counts.[15] Triadic patents are a sub-set of patents taken at the European Patent Office, the Japan Patent Office and the US Patent and Trademark Office that protect the same invention. Since only patents applied for in all three are included, we address concerns related to home advantage and the influence of geographical location. Moreover, triadic patents are generally of higher value: patentees only take on the additional costs and delays of extending protection to other countries if they deem it worthwhile (Aghion et al., 2016).[16] Patents in our data are counted according to the earliest priority date, which corresponds to the first patent application worldwide and is, thus, closest to the invention date.

Consumption and real price of transport fuels. To estimate price and tax elasticities and disentangle the different taxation changes, we construct an annual time-series dataset for Germany, spanning from 1971 to 2009.[17] The data for the gasoline and diesel prices reflect yearly consumer

[14] Luxembourg's fuel sales are 5 to 8 times higher per capita than those of the neighboring countries (Dings, 2004). Austria, too, has very low taxes with a tax minimum in 2005 and a downward trend from 1997 onwards. This is a contrast to tax increases in Germany and Italy in 1999. As a result, more fuel tourism has likely taken place and emission data is not reliable (Dings, 2004).

[15] We treat multiple application filings of an invention (i.e., a patent family) as one innovation. We focus on patent families to capture the number of low-carbon technologies that are developed in Germany rather than the count of underlying patent applications.

[16] Considering the number of jurisdictions in which a patent application is filed is a common approach to capture patent quality (e.g., Calel and Dechezleprêtre, 2016).

[17] A peculiarity of Germany is its division until the year 1990. As there was no market economy in East Germany, there were no market prices and no taxes in the same sense as

prices for both fuels including VAT. We convert all nominal prices to real prices, including the energy and eco-tax rates and the strategic reserve component (the OA details data sources).

As VAT is not only imposed on the tax-free price p but also on the eco and energy taxes, τ^{eco} and τ^{energy}, and the strategic reserve, τ^{sr}, in the same way as on the price, the retail price p^r can be defined as:

$$p^r = (p + \tau^{eco} + \tau^{energy} + \tau^{sr}) * (1 + VAT) \quad (8)$$

To account for this, the VAT is already included in each retail price element.[18] All prices given in Deutsche Mark (DM) are converted to Euro, and all nominal prices and absolute tax rates into real 1995 prices and taxes. We chose 1995 as a convenient base year close to the implementation of the eco-tax. Whenever a tax rate changed within a year, we weighted rates according to the date at which the change took place and used these average tax rates. The (brent) crude oil price used for the IV regressions comes from the IEA. It is converted from USD per barrel to €/l using the Eurostat (2020) €/USD exchange rate.

Salience: Newspaper data. We further examine the role of salience in driving consumers' responses to the eco-tax reform. To this end, we rely on newspaper data as a proxy of tax salience within the media. We extract information from the Factiva database, which stores all articles published by major newspapers, and use this to develop a newspaper-based index to capture the evolution of salience of the eco-tax based on textual analysis of newspaper articles (Gentzkow et al., 2019). We focus our analysis on *Der Spiegel*, *Die Welt*, *Die Zeit*, and *Focus*.[19]

Our salience index is constructed using the number of articles published in leading German national newspapers after 1991 that discuss the effects

in West Germany. All prices that will be discussed in the paper thus relate only to West Germany prior to 1991, while price data from 1991 onwards, and all fuel consumption data, reflects the entirety of Germany.

[18]If the eco-tax was raised by 10 cents, the fuel price would increase by 11.90 cents with a VAT rate of 19%. Thus, the eco and energy tax rates include the VAT. In our calculations, the price increase is attributed to a change in the eco-tax rate.

[19]We restrict our analysis to the largest newspapers retrievable from Factiva, as relying on a single source provides consistent, comparable and more robust counts.

of the eco-tax on fuel prices scaled by newspaper-specific publishing trends specific to the topic of environmental taxation.[20] We scale our frequency counts to ensure that spikes in our index are not driven by newspaper-specific trends in reporting of environmental issues, which has experienced steadily growing attention in the German public media (Schmidt et al., 2013). To obtain newspaper article counts, we rely on a set of text-based search strategies that identify around 5,700 unique articles. After scaling the raw counts, we standardize each newspaper's series, average across all papers, and normalize the resulting index to 100 over the period. We follow the same standardization and normalization procedure proposed by Baker et al. (2016) to leverage newspaper data in an empirical setting. A detailed description of our search strategies and the steps undertaken to construct the salience index can be found in Section D.2 of the OA.

4 Results from the Synthetic Control Method

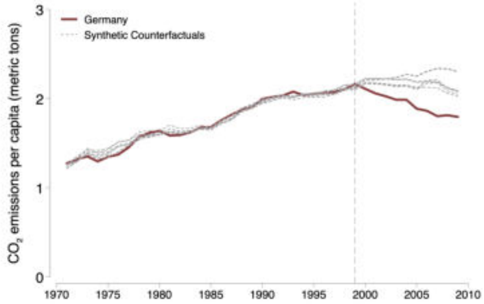
In this section, we present and discuss the implemented SCMs described in Section 2.2 to estimate the impact of the eco-tax on CO_2 and local air pollution emissions within the transport sector. Figure 1 and 2 graphically summarize our key findings, while additional supporting evidence can be found in Section B of the OA.

Emissions relative to synthetic counterfactual developments. Panels (a), (c) and (e) in Figure 1 plot the path of CO_2, $PM_{2.5}$ and NO_X emissions in the Germany transport sector (solid line) and in the synthetic Germanies (dashed lines) across our specifications (c.f. Table 1) from 1971 to 2009. The overlap between the solid and dashed line before 1999 captures the quality of the pre-treatment fit achieved by the SCM; the same graphical comparison after 1999 plots the dynamic treatment effects for the eleven years that followed. All panels reveal a sizable effect on emissions in the transport sector following the eco-tax reform.

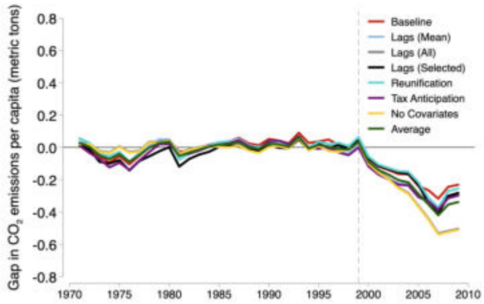
[20]There was no unified press prior to German reunification.

Figure 1: Synthetic Control Method results for emissions

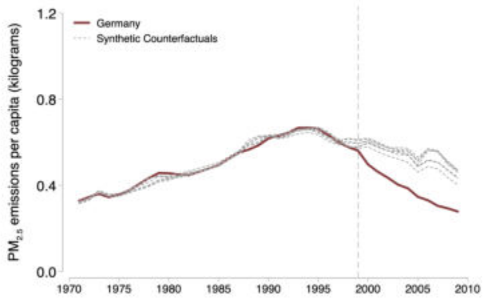
(a) Germany vs. Synth. Germany: CO_2



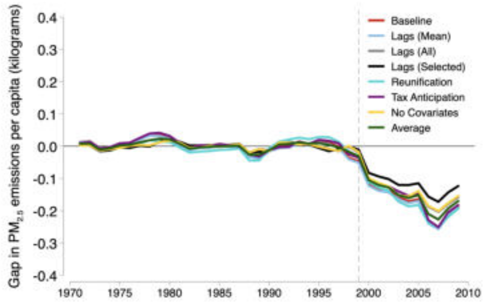
(b) Change in CO_2 emissions over time



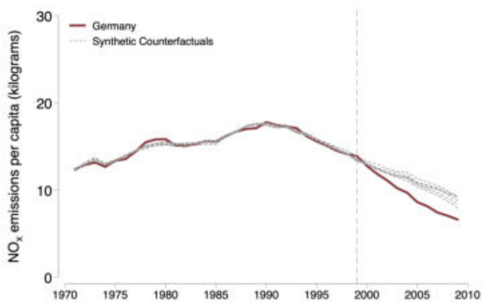
(c) Germany vs. Synth. Germany: $PM_{2.5}$



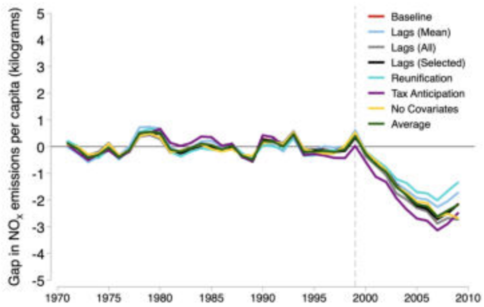
(d) Change in $PM_{2.5}$ emissions over time



(e) Germany vs. Synth. Germany: NO_X



(f) Change in NO_X emissions over time



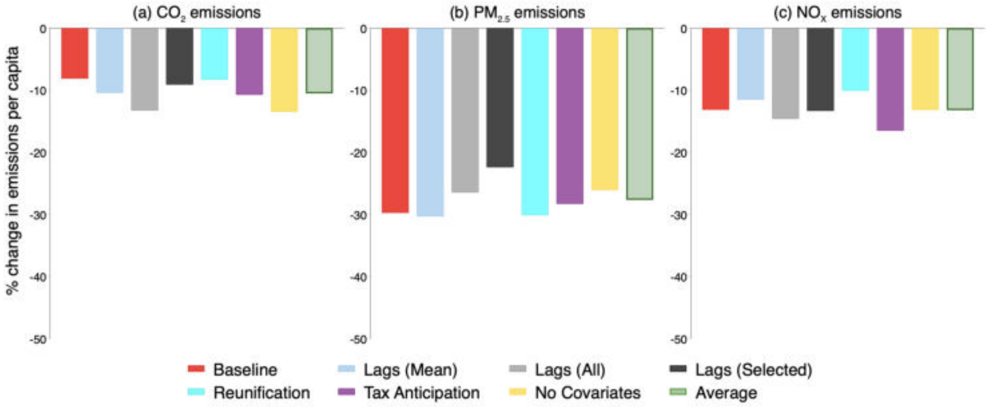
Notes: The figure plots the estimated reductions in CO_2, $PM_{2.5}$ and NO_X emissions relative to (synthetic) counterfactuals. Panels (a) and (b) refer to reductions in CO_2 emissions per capita in metric tons or percentage terms (as indicated on the respective y-axis). Panels (c) - (f) refer to reductions in $PM_{2.5}$ and NO_X emissions per capita expressed either in kg. Panels (a), (c) and (e) plot the absolute paths of emissions in Germany and Synthetic Germanies for our specifications (see Table 1). Panels (b), (d) and (f) report gaps in emissions over time relative to synthetic Germanies, estimated by our seven different SCM specifications and their average.

The validity of SCM effects depends on synthetic Germany's ability to replicate emissions from the German transportation sector prior to the eco-tax introduction. Panels (a) and (b) show that prior to the treatment, emissions from transportation in Germany and its synthetic counterpart exhibit a high degree of similarity, with an average absolute difference of slightly more than 0.02 metric tons of CO_2, less than 0.01 kg of $PM_{2.5}$ and around 0.22 kg of NO_X. Figure B.1 in the OA plots the distribution of country-specific weights across all specifications and shows that the composition of our synthetic Germanies varies considerably across outcomes and specifications. Tables B.1 - B.3 in the OA compares the values of key predictors for Germany prior to 1999 with those for our baseline synthetic Germany (c.f. Section 3). Overall, synthetic Germany exhibits a much more refined fit compared with the donor pool average.

Panels (b), (d) and (e) report the estimated gap in metric tons of CO_2 and kg of $PM_{2.5}$ and NO_X emissions across the seven SCM specifications (colored lines), where *Average* refers to the average of the estimated emission gaps from each synthetic counterfactual (green line). All specifications point to sizable decreases in CO_2, $PM_{2.5}$ and NO_X emissions in the transport sector following the eco-tax reform. Panel (b) shows that the distance between Germany and the synthetic Germanies is steadily growing between 1999 and 2007.[21] In 2007, this distance was on average -0.42 metric tons of CO_2 per capita, equivalent to a 19 percent reduction. Between 1999 and 2009, annual emission reduction amounted to 0.23 metric tons of CO_2 per capita on average, which cumulatively sums up to 208,216,572 tons of CO_2. Panel (d) presents the emission gap over time for $PM_{2.5}$. On average, 0.15 kg of per capita $PM_{2.5}$ less were emitted each year in comparison to a scenario with no eco-tax, which amounts to total $PM_{2.5}$ savings of around 135,632 tons. Finally, Panel (f) displays emission gaps for NO_X. Following the eco-tax reform, per capita NO_X emissions were lower by 1.5 kg, on average, with a cumulative reduction in NO_X of 1,347,190 tons.

[21] There are different possible explanations for the convergence in emissions after 2007. An obvious one is the financial crisis, which evolved into an economic crisis across the EU in 2008, which likely affected German transport differently than that of donor countries, implying that synthetic Germany may not describe the counterfactual after 2007/2008 as accurately as before. Another explanation is decreasing fuel taxes in real terms. As the last increase of the eco-tax took place in 2003, the real fuel tax on gasoline and diesel has been decreasing ever since then due to inflation.

Figure 2: Mean annual percentage gap in CO_2, $PM_{2.5}$ and NO_X emissions



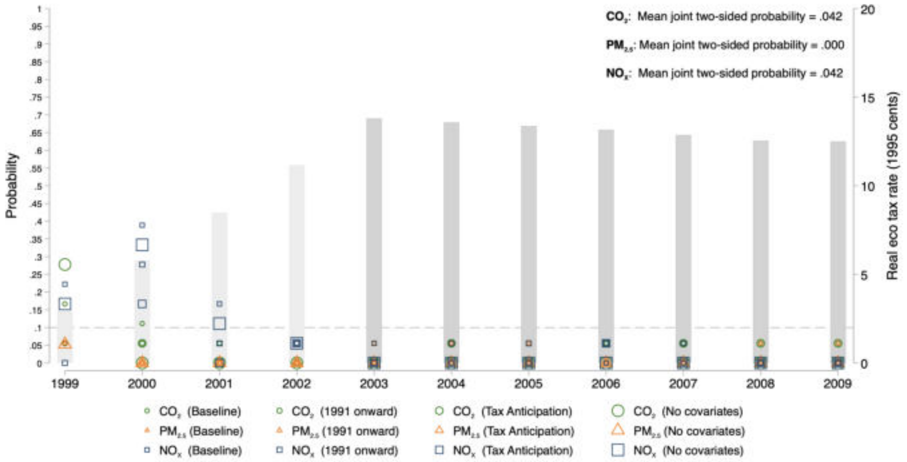
Notes: The figure plots the average annual percentage gap for each specification in CO_2, $PM_{2.5}$ and NO_X emissions between Germany and a synthetic counterfactual development reported in Figure 1.

Figure 2 plots mean annual changes in emissions in percentage terms to put into perspective the distribution of the effect magnitudes from different specifications. CO_2 per capita emissions of the transportation sector decrease, on average, from 8.1% to 13.4% between 1999 and 2009, conditional on the specification used, while $PM_{2.5}$ and NO_X per capita emission reductions range between 22.4% - 30.3% and 10% - 16.5%, respectively. Our finding that emission reductions due to the eco-tax are sizable is thus robust across a range of specifications from the SCM literature.

4.1 Inference from permutation tests

We rely on permutation tests to gauge the significance of our treatment effects. Figure 3 plots estimated one-sided p-values in each post-intervention year. We report yearly permutations for a number of SCM specifications: (i) *Baseline*, (ii) *Baseline* restricting the pre-intervention period after German reunification in 1991, (iii) *Tax Anticipation*, and (iv) *No covariates* following Ferman et al. (2020). Overall, the distribution of the estimated p-values is centered well below a 10% threshold level, and generally below a 5% threshold, throughout the post-intervention period, particularly after the last eco-tax rate increase in 2003. The mean joint two-sided p-values are below 5% for CO_2 and NO_X and below 1% for $PM_{2.5}$ (see Figure 3).

Figure 3: Inference results for the Synthetic Control Method



Notes: The figure plots estimated one-sided p-values (primary left-hand side y-axis) computed as the proportion of effects from control units as great as the treated unit in each post-intervention period, after scaling it by the relevant pre-treatment RMSPE (Abadie, 2021). Joint two-sided p-values represent the proportion of placebos that have a ratio of post-treatment RMSPE over pre-treatment RMSPE at least as large as the average ratio for Germany. The gray bars plot the annual real eco-tax rate in 1995 cents (secondary right-hand side y-axis). The darker gray bars indicate the post-treatment periods where the full nominal eco-tax rate increase fuel was in place.

4.2 Additional sensitivity and placebo tests

Our findings are robust to a host of standard sensitivity and placebo tests, including in-time placebos, the use of alternative donor pools and emission data sources, different pre-treatment time frames and the use of a generalized SCM (Xu, 2017).

In-time tests. For the in-time placebos, the year of treatment is shifted to a number of years prior to the actual ecological tax reform. Any sizable and enduring placebo effect would cast doubt on the validity of the results from Figure 1. Figure B.2 in the OA shows that the synthetic control closely resembles the actual emission trajectories in Germany after the placebo treatment and that no significant divergence is detected.

Alternative donor pools. To investigate the sensitivity to the composition of the donor pool, we perform the following tests: (i) implementing the SCM without any sample restriction, (ii) "leave-one-out" tests, following Abadie et al. (2015), where we sequentially exclude from the restricted donor pool all control countries that got a weight larger than 0.001 (0.1

percent). The results are summarized in Figures B.3 and B.4 in the OA and show that none of the possible alternative donor pool compositions consistently yield a non-negative gap in the post-intervention period.

Generalized SCMs. We construct GSCM counterfactuals by modeling emissions of countries with IFE models. First, we include controls to explicitly account for the impacts of EU membership, namely a binary EU member indicator and a dummy identifying EU member countries after 2005 (denoted *IFE only*).[22] Second, we additionally model each countries' emissions as a function of their economic activity (*Economic activity*), proxied by GDP per capita (Bayer and Aklin, 2020). Finally, we restrict the donor pool to EU countries (*EU only*) to further address concerns that effects may be partly driven by EU-wide regulation, such as emission standards (e.g., Reynaert, 2021). Wald tests for pre-treatment fitting checks show that all the different models capture the variability in the data well prior to the eco-tax reform, validating the main identification assumption. Table 2 summarizes our GSCM results. We report mean reductions of emissions due to the eco-tax with bootstrapped 95% confidence intervals. Our GSCM results are comparable in magnitude to the average SCM results reported in Figure 1, pointing towards slightly larger magnitudes in carbon reductions and almost identical average reductions in air pollution.[23]

4.3 Impacts on low-carbon innovation

Finally, we provide complementary evidence on the role of the eco-tax in spurring low-carbon innovation. Here, we turn to the GSCM since it con-

[22] We include this dummy to control for potential spillover effects due to the EU Emissions Trading Scheme (EU ETS), introduced in 2005, and the differential response of each jurisdiction to the EU-wide PM_{10} limits in cities, also introduced in 2005. These spillovers are not expected to be substantial, as transport emissions were not covered by the EU ETS and have not decreased due to the scheme (Bayer and Aklin, 2020). Further, Germany failed to attain the 2005 PM_{10} limits, triggering infringement proceedings in 2009, and EU-wide PM_{10} limits on were not very effective initially, with 70% of all EU cities with larger populations than 250,000 having exceeded the limits at some point as of 2007 (Wolff and Perry, 2010). A number of German municipalities responded by implementing low-emission zones from 2008 onward, restricting access for highly-polluting vehicles within city centers thereafter.

[23] For more details on the unfolding of the estimated gaps, Figure C.3 in the OA compares the dynamic treatment effects across all our different empirical strategies.

Table 2: Effects of the eco-tax with a Generalized Synthetic Control

	IFE only	**Economic activity**	**EU only**
Panel A: CO_2 (t)			
Mean [95% CI]	-0.43 [-0.53; -0.34]	-0.39 [-0.50; -0.25]	-0.44 [-0.57; -0.29]
Panel B: $PM_{2.5}$ (kg)			
Mean [95% CI]	-0.15 [-0.26; -0.04]	-0.14 [-0.25; -0.07]	-0.21 [-0.27; -0.13]
Panel C: NO_X (kg)			
Mean [95% CI]	-1.98 [-3.32; -2.40]	-1.65 [-3.09; -0.14]	-3.34 [-5.33; -0.26]
Observations	1053	939	451
Countries	27	27	14
Wald test p-value	<0.001	<0.001	<0.001

Notes: Summary of average treatment effect and 95% confidence intervals for different model specifications. Wald test p-values refer to a Wald test for pre-treatment fitting checks (c.f. Xu, 2017). For each specification, we report the highest p-values across all panels. All models include interactive fixed effects and a binary indicator for German reunification. *IFE only* includes a binary EU membership indicator and a dummy variable identifying EU member countries after 2005 *Economic activity* additionally controls for GDP per capita at current purchasing power parities (in million 2011 USD), while *EU only* simply restricts the donor pool to countries that are part of the European Union until the end of our sample.

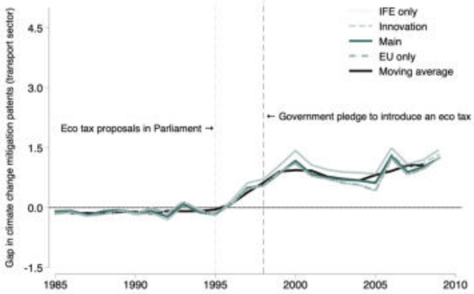
veniently enables absorbing level differences in unobserved determinants of innovative behavior across time with IFE. Figure 4 plots the estimated gaps in low-carbon patents per million of the population over time.[24] The extended pre-intervention period allows us to account for anticipatory behavior in the years leading up to the eco-tax reform (e.g., Lemoine, 2017). Overall, we observe that all our different specifications point to a sizable increase in low-carbon innovation following the eco-tax reform. We also detect some anticipatory innovation responses starting after the parliamentary debate on the eco-tax reform first gained momentum in 1995 (Beuermann and Santarius, 2006).

Figure 4 presents these magnitudes in percentage and cumulative terms, putting the estimated gaps into perspective. The gray area plots the cumulative number of additional patents throughout the post-intervention period (left-hand side secondary y-axis), while the green bar charts show the annual percentage increase in patents induced by the eco-tax with bootstrapped 95% confidence intervals (right-hand side secondary y-axis). On average, between 1999 and 2009, the eco-tax was responsible for an annual

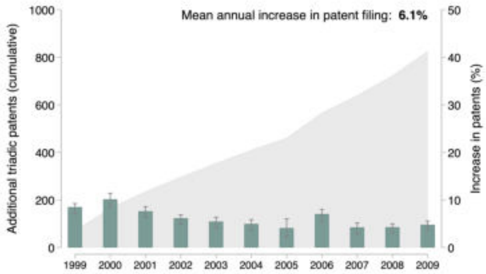
[24] We further report a smoothed specification using a three-year moving average to account for the fluctuating nature of patent data (Griliches, 1990).

Figure 4: Effects of the eco-tax on low-carbon patented technologies

(a) Germany vs. Synthetic Germany



(b) Change in patents over time



Notes: Our different GSCM specifications with IFE include different sets of controls. *IFE only*: (i) a binary variable identifying EU countries and (ii) a binary variable indicating whether a country was regulated by EU-wide regulations after 2005. *Innovation* further accounts for: (iii) total triadic patents per capita and (iv) share of climate change mitigation patents related to transportation. Our *Main* specification additionally controls for: (v) GDP per capita and (vi) squared GDP per capita. *EU only*: estimates our *Main* specification restricting the sample to countries in the EU and further adds (vii) a binary indicator which equals 1 after 1996 to capture the establishment of the general legal framework for regulating air pollution in the EU (Council Directive 1996/62/EC). *Moving average*: estimates our *Main* specification relying on a 3-year moving average instead of annual patent counts. Panel (b) refers to our *Main* specification. Percentage increases are computed as the estimated increase of triadic patents induced by the eco-tax scaled by the annual number of climate change mitigation patents related to transportation in Germany.

increase of 6.1% in climate change mitigation patents related to transportation, which cumulatively resulted in 826 additional patented technologies vis-a-vis a scenario without the eco-tax. This effect is around ten times as large as in a recent study that examined how the Swedish carbon taxes affected innovation in the transport sector (Brehm et al., 2022). Overall, this provides suggestive evidence that part of the emission reductions due to the eco-tax may have been facilitated by improved vehicle efficiency.

5 Results on Fuel and Tax Elasticities

This section leverages the semi-elasticity models described in Section 2.2 to disentangle effects of the eco-tax, the energy tax, and VAT in order to compare behavioral responses from changes to the eco-tax rate and equivalent fuel real price changes.

5.1 Real price elasticities for gasoline and diesel

Tables 3a and 3b report estimates from the *Real price elasticities* specification (c.f. Section 2.2) for gasoline and diesel consumption, respectively.[25] Using our estimate from column (3) in Table 3a, we derive a real price elasticity of gasoline of -0.54.[26] The IV regression yields a very similar price elasticity of demand of -0.50 (column (4) of Table 3a), indicating that endogeneity of gasoline prices is likely not a major concern in our setting. To test the instrument's relevance condition, we use an F-test for that single instrument. For the price of gasoline, the F-statistic is 69.47 suggesting that the relevance condition is fulfilled and that brent crude oil price can be considered a suitable instrument for gasoline prices. Table 3b displays results for diesel consumption from the real price elasticity specification (c.f. Section 2.2). The real price elasticity of demand for diesel shown in column (3) of Table 3b is somewhat lower than the one for gasoline at -0.34. The IV regression in column (4) yields an estimate of -0.28, which deviates slightly more than the IV and OLS regressions for gasoline, but is still sufficiently close to corroborate the magnitude of the real price elasticity for diesel. Overall, our estimates fall into the range of price elasticities of demand in the literature (e.g., Frondel and Vance, 2014).

5.2 Tax elasticities for gasoline and diesel

Table 4a displays results for gasoline consumption from the *Eco-tax elasticities* specification (c.f. Section 2.2).[27] The OLS results in column (3) in Table 4a indicate that the price elasticity of demand for the price excluding the energy and the eco-tax (but including the VAT) is -0.32. The energy tax elasticity of demand, instead, amounts to -0.22. Both elasticities are computed relying on coefficients that exhibit a considerably lower significance. This contrasts the eco-tax elasticity of demand, which is estimated

[25] Additional robustness results based on a shorter time frame (1991–2009) are presented in Tables C.2a and C.2b in the OA.

[26] To calculate elasticities from our log-level model estimates ($log(Y) = a + bX$), the coefficient for each tax is multiplied with the average sample mean of the real fuel price (89.8 cents for gasoline and 76.4 cents for diesel), as the elasticity of demand is given by $\epsilon = \frac{dY}{dX} * \frac{X}{Y}$. This implies that $\frac{dY}{dX} = be^a e^{bX}$. Plugging in, we obtain $\epsilon = \frac{be^a e^{bX}}{e^a e^{bX}} * X = bX$.

[27] We cannot reject the hypothesis of full pass-through, see Section C in the OA.

Table 3: Real price elasticities for transport fuels

(a) Gasoline consumption

	(1) OLS	(2) OLS	(3) OLS	(4) IV: Brent Crude
Real price of Gasoline	-0.00698	-0.00675*	-0.00603**	-0.00553*
	(0.00418)	(0.00395)	(0.00278)	(0.00305)
Dummy Eco Tax	-0.221	-0.186	-0.154	-0.161
	(0.146)	(0.123)	(0.131)	(0.129)
Trend	0.0117***	0.0240**	0.00158	0.00127
	(0.00401)	(0.00911)	(0.0138)	(0.0125)
GDP per capita		-0.0211	0.000174	0.000318
		(0.0127)	(0.0116)	(0.0102)
Unemployment rate			0.0292	0.0298*
			(0.0176)	(0.0165)
Instrument F-statistic				69.47
Observations	38	38	38	38

(b) Diesel consumption

	(1) OLS	(2) OLS	(3) OLS	(4) IV: Brent Crude
Real price of Diesel	-0.00482***	-0.00473***	-0.00440***	-0.00361***
	(0.00119)	(0.00140)	(0.00103)	(0.000856)
Dummy Eco Tax	-0.00672	-0.0272	-0.0205	-0.0415
	(0.0423)	(0.0571)	(0.0564)	(0.0561)
Trend	0.0326***	0.0273***	0.0189***	0.0176***
	(0.00135)	(0.00311)	(0.00587)	(0.00546)
GDP per capita		0.00938**	0.0177***	0.0199***
		(0.00415)	(0.00528)	(0.00420)
Unemployment rate			0.0107*	0.0126**
			(0.00558)	(0.00615)
Instrument F-statistic				168.86
Observations	39	39	39	39

Notes: The dependent variable is the log of fuel consumption in liters per capita, which refers to total fuel consumption or either gasoline or diesel consumption (as indicated by the column heading). Columns (4) use the brent crude oil price as an instrumental variable for the real fuel price. Prices are in 1995€. Results for gasoline consumption refer to 1972-2009 due to missing price data prior to 1972. Unemployment is measured as percentage of total labor force. Newey-West standard errors in parentheses are heteroskedasticity and autocorrelation robust. Standard errors are calculated relying on the automatic bandwidth selection procedure following Newey and West (1994). * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

at -2.7 and is thus around 8.5 times larger than the tax-exclusive price elasticity. The eco-tax elasticity of diesel demand is also significantly higher than that for the real price. Table 4b displays the results for the different tax rates for diesel. Using column (3) in Table 4b, the elasticity for the real price, excluding the energy and eco-tax, is -0.26. The energy tax elasticity of demand is -0.56, slightly higher than the price elasticity. The eco-tax elasticity is again the highest level at -1.1, about 4 times larger than the tax-exclusive price elasticity. It follows that an increase in the eco-tax predicts a stronger response in demand than that of a market-driven price change for both gasoline and diesel.[28]

Li et al. (2014) discuss two underlying reasons that would reconcile our findings and explain the estimated stronger response to the eco-tax. The first one is *persistence*, meaning that consumers rely on tax changes to build expectations for the future price of gasoline. A tax increase may thus be perceived as more enduring than market-driven price fluctuations,

[28]We additionally amend our semi-elasticity models with a lead to test whether consumers increased their purchases of transport fuel in anticipation of tax increases, which could potentially bias estimated price and eco-tax coefficients (Coglianese et al., 2017). We do not find evidence of a potential anticipatory effect, and the estimated real price and eco-tax elasticities are very similar to the main result reported in Tables 3a - 4b (see Figure C.1 in the OA). One explanation is that anticipatory behavior is a lesser source of concern when dealing with yearly data as compared to relying on monthly variation.

Table 4: Eco-tax elasticities for transport fuels

(a) Gasoline consumption

	(1)	(2)	(3)
Raw price of Gasoline (only VAT)	-0.00360	-0.00358*	-0.00357*
	(0.00279)	(0.00176)	(0.00179)
Energy Tax on Gasoline	-0.00625**	-0.00160	-0.00242
	(0.00254)	(0.00466)	(0.00476)
Eco Tax on Gasoline	-0.0342***	-0.0325***	-0.0306***
	(0.00821)	(0.00699)	(0.00700)
Dummy Eco Tax	0.0718	0.119**	0.104**
	(0.0447)	(0.0491)	(0.0438)
Trend	0.0145***	0.0327**	0.0240
	(0.00412)	(0.0130)	(0.0220)
GDP per capita		-0.0345	-0.0245
		(0.0259)	(0.0304)
Unemployment rate			0.00902
			(0.0230)
p-value Raw price = Eco-tax	0.005	0.001	0.003
Observations	38	38	38

(b) Diesel consumption

	(1)	(2)	(3)
Raw price of Diesel (only VAT)	-0.00324***	-0.00339***	-0.00346***
	(0.000825)	(0.00104)	(0.00104)
Energy Tax on Diesel	-0.00132	-0.00538	-0.00729**
	(0.00300)	(0.00348)	(0.00292)
Eco Tax on Diesel	-0.0170***	-0.0163***	-0.0143***
	(0.00201)	(0.00218)	(0.00359)
Dummy Eco Tax	0.101***	0.0890***	0.0794***
	(0.0196)	(0.0219)	(0.0174)
Trend	0.0353***	0.0266***	0.0187**
	(0.00180)	(0.00593)	(0.00774)
GDP per capita		0.0120	0.0201**
		(0.00964)	(0.00753)
Unemployment rate			0.00651
			(0.00816)
p-value Raw price = Eco-tax	0.000	0.000	0.023
Observations	39	39	39

Notes: The dependent variable is the log of fuel consumption in liters per capita, which refers to total fuel consumption or either gasoline or diesel consumption (as indicated by the column heading). Prices are in 1995€. Results for gasoline consumption refer to 1972-2009 due to missing price data prior to 1972. Unemployment is measured as percentage of total labor force. Newey-West standard errors in parentheses are heteroskedasticity and autocorrelation robust. Standard errors are calculated relying on the automatic bandwidth selection procedure following Newey and West (1994). * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

which, in turn, would stimulate a stronger consumer response. The second is *salience*, meaning that consumers are more aware of the price increase due to media coverage. We investigate the role of greater media salience in driving behavioral responses to changes in the eco-tax in Section 5.4, .

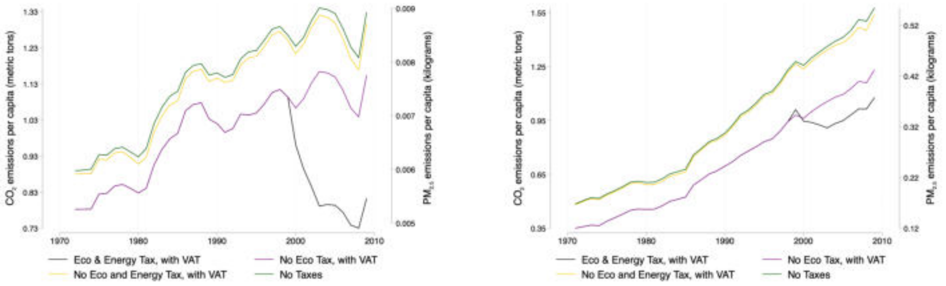
5.3 Emission scenarios and underlying mechanisms

We next rely on fuel-specific price and tax elasticities estimates from columns (3) in Tables 4a and 4b to compute CO_2 and $PM_{2.5}$ (and NO_X) emissions for different taxation scenarios, namely a scenario where no VAT and no taxes are introduced, a scenario where either VAT or VAT and the energy tax is added to the price of fuels, and, finally, a scenario where all are implemented.[29] We refer to this as the *Simulation Approach*.

[29] The combustion of one liter gasoline (diesel) emits 2.235kg (2.66kg) of CO_2 (US EPA, 2005). Using this factor, the predicted log gasoline (diesel) consumption values can first be turned into liters and then CO_2 emissions. To estimate $PM_{2.5}$ exhaust emissions from fuel consumption, we rely on average emission factors by the European Environment Agency (EEA) for gasoline (diesel) vehicles in Germany (Ntziachristos and

Figure 5: Predicted emissions by fuel under different taxation scenarios

(a) Gasoline consumption **(b)** Diesel consumption



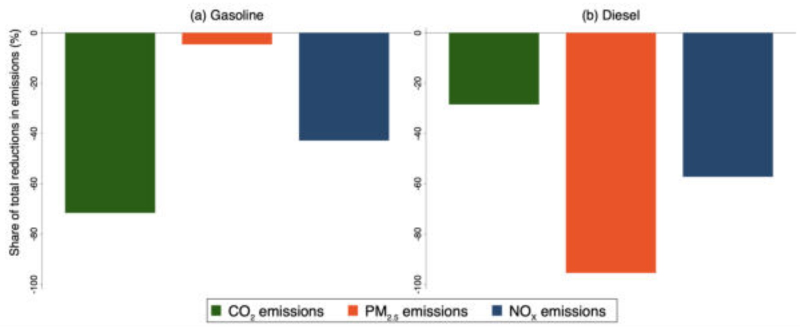
Notes: The figures plot predicted emissions from the eco-tax specification of our log-level semi-elasticity models (c.f. Section 2.2) under different taxation scenarios. We rely the estimated fuel-specific price and tax elasticities computed from our estimates from column (3) in Tables 4a and 4b. Panel (a) refers to predicted emissions from gasoline consumption, while Panel (b) covers diesel . In each panel the left-hand side primary y-axis refers to per capita CO_2 in metric tons, while the right-hand side secondary y-axis refers to per capita $PM_{2.5}$ in kg. The top green line displays predicted emissions when the eco and energy tax elasticities are set to zero, and VAT is deducted from the fuel price. For the yellow line, the eco and energy tax elasticities are set to zero but VAT is included. The purple line shows how predicted emissions change when the eco-tax is set to zero, but we include the energy tax and VAT. The black line provides predicted emissions using the full model with differentiated tax and price elasticities. The corresponding simulations for NO_X emissions can be found in Figure C.2 in the OA.

Predicted emissions in the Simulation Approach. Panels (a) and (b) in Figure 5 summarize the estimated evolution of CO_2 (left-hand side primary y-axis) and $PM_{2.5}$ (right-hand side secondary y-axis) emissions by fuel in the German transport sector under different tax regimes. The black line represents projected emissions accounting for all existing tax measures, including the eco-tax, energy tax, and VAT. The purple line plots the estimated evolution of emissions in the absence of the eco-tax, while the yellow line depicts the expected path of emissions with neither the eco-tax nor the energy tax, solely incorporating VAT. The green line shows predicted emissions without any tax policies. The gap between the black and purple line highlights the estimated emission gap attributable to the eco-tax, while the other lines represent alternative counterfactuals.

Panel (a) in Figure 5 shows that, between the years 1999 and 2009, the decrease in emissions of CO_2 ($PM_{2.5}$) from gasoline induced by the eco-tax was around 0.27 tons (0.002 kg) per capita on average per year. Similarly, Panel (b) provides the estimated emission reductions for diesel.

Samaras, 2019) of 0.02 grams (1.12 grams) of $PM_{2.5}$ per kg of gasoline (diesel). Although EEA only reports emission factors for PM without specifying the size range, it clarifies that PM mass emissions in vehicle exhaust mainly fall in the $PM_{2.5}$ category.

Figure 6: Share of total emission reductions by fuel due to the eco-tax



Notes: The figures above plot the share of total predicted emissions reductions by fuel type from our log-level semi-elasticity models (c.f. Section 2.2). The share of total emission reductions for each fuel type is computed from the estimated post-treatment gap in emissions from gasoline (diesel) consumption due to the eco-tax, which refers to the distance between the bottom black line and the purple line in Figure 5.

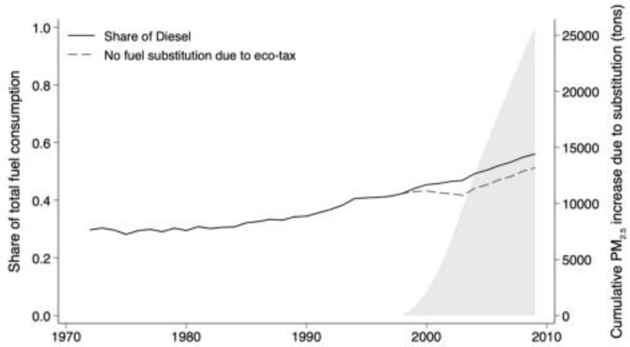
The corresponding mean decline in annual emissions of CO_2 ($PM_{2.5}$) from diesel induced by the eco-tax was around 0.11 tons (0.04 kg) per capita, i.e. less marked than for gasoline due to the lower eco-tax elasticity for diesel.

Panels (a) and (b) in Figure 6 contrast the estimated share of aggregate reductions in emissions attributable to contractions in either gasoline or diesel use for CO_2 and $PM_{2.5}$, additionally including reductions in NO_X emissions. On average across our time frame, contractions in gasoline (diesel) use were responsible for around 72% (28%) of overall reductions in CO_2 emissions. Conversely, reduced diesel use is responsible for almost the entirety (95%) of the reduction of $PM_{2.5}$ emissions. In other words, on average, reductions in diesel consumption have contributed around 21 (0.4) times more to the decline in $PM_{2.5}$ (CO_2) emissions relative to gasoline.

Fuel substitution and abatement trade-offs. Diesel fuel vehicles contribute considerably more to emissions of fine particulates, such as $PM_{2.5}$, than gasoline vehicles.[30] However, diesel vehicles have lower CO_2 emissions rates per traveled kilometer compared to gasoline vehicles, by around 20% for otherwise virtually identical vehicles (Linn, 2019), as diesel engines are typically much more fuel-efficient. It follows that policy measures that foster a switch from gasoline vehicles to diesel vehicles (e.g., taxes based on the carbon content of fuels), could, in turn, lead to a decrease in CO_2 emis-

[30] Relying on emission factors provided by the EEA for Germany, the average $PM_{2.5}$ emission factor for diesel vehicles is around 56 times larger than that for gasoline (Ntziachristos and Samaras, 2019).

Figure 7: Substitution towards diesel due to the eco-tax



Notes: The figures plots the annual predicted substitution towards diesel from our semi-elasticity models (c.f. Table C.3b in the OA).

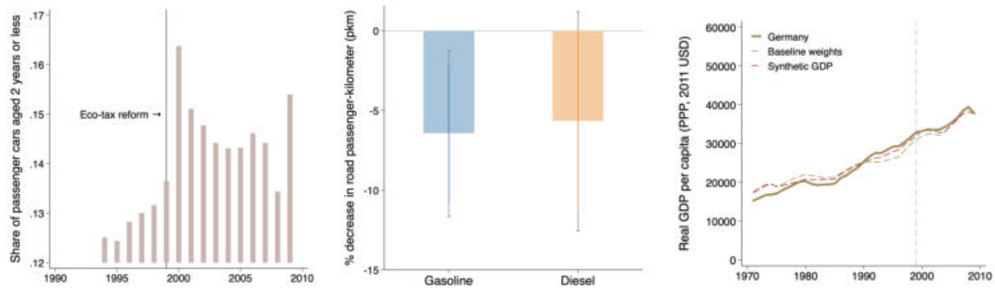
sions but also an increase in $PM_{2.5}$ emissions. Previous research on fuel and carbon taxation has not explicitly considered this trade-off in policy evaluations, with the exception of Linn (2019).

Figure 7 plots the estimated gasoline-to-diesel substitution induced by the eco-tax (c.f. Table C.3b in the OA), implying that part of the contraction in CO_2 linked to reduced gasoline consumption came at the expense of greater $PM_{2.5}$ emissions due to fuel substitution. We estimate that the share of diesel consumption is predicted to have increased by around 4% more than it would have had in the absence of the eco-tax throughout the post-treatment period. Our calculations suggest that gasoline-to-diesel substitution due to the eco-tax led to a cumulative increase in $PM_{2.5}$ exhaust emissions of around 25,000 tons from 1999 to 2009.

Fleet renewal and passenger-kilometers. An important argument for regulating emissions in the transport sector is that it can prompt a more rapid adoption of more efficient vehicles (e.g., Jacobsen et al., 2023). Panel (b) in Figure 8 provides descriptive evidence of the change in fleet renewal rate by plotting the share of new passenger car registrations in the German fleet over time. We observe a discontinuity following 1999: after the eco-tax reform, the share of new passenger cars increased on average by 2%. Drawing a connection between this trend and our findings on low-carbon innovation (c.f. Section 4.3), it seems plausible that the eco-tax has played a role in accelerating the adoption of cleaner vehicles, which

Figure 8: Underlying mechanisms of reductions in emissions

(a) Fleet renewal **(b)** Passenger-kilometers **(c)** GDP per capita



Notes: Panel (a) plots the share of new passenger cars in the German fleet (aged 2 years or less) using data from the UNECE Statistical Database. Panel (b) plots the estimated percentage reductions in passenger-kilometers (pkm) by fuel for the average eco-tax rate of 13 cents. Data on pkm was retrieved from OECD Statistics. Panel (c) plots the evolution of GDP per capita in Germany and compares it with synthetic counterfactual developments.

could, at least partly, explain the contraction in emissions. We then resort to our semi-elasticity models to investigate how changes in the eco-tax rate affected the volume of road passenger transport, proxied by passenger-kilometers (pkm). Panel (c) in Figure 8 shows that, on average, the eco-tax is associated with a decrease in pkm by around 6.5% (5.7%).[31] These results offer suggestive evidence indicating that a share of the estimated emission reductions can be attributed to both an accelerated fleet renewal and a reduction in the volume of road passenger transport.

Decoupling. A common contention against the implementation of carbon taxation revolves around potential detrimental effects on economic growth. We thus investigate whether the observed reduction in emissions may have occurred alongside a reduction in economic activity. Figure 8 plots the evolution of GDP per capita in Germany relative to synthetic counterfactuals. Specifically, we rely on (i) the *Baseline* weights to construct a *no eco-tax* synthetic GDP development and (ii) an additional SCM specification where we further include lagged GDP in 1989 and 1991 as spe-

[31] We provide complementary, suggestive evidence that the eco-tax, and the consequent estimated reduction in pkm, led to fewer road casualties (fatalities and injuries), which represent a considerable externality of road transport (e.g., Anderson and Auffhammer, 2014). Again leveraging our semi-elasticity models, we find that the introduction of the eco-tax is, on average, associated with decreased road casualties by approximately 11% (c.f. Figure C.4 in the OA). This underscores that the externality reductions we capture here—focused solely on climate and health benefits linked to air pollution—likely represent a conservative estimate of the benefits generated by the eco-tax.

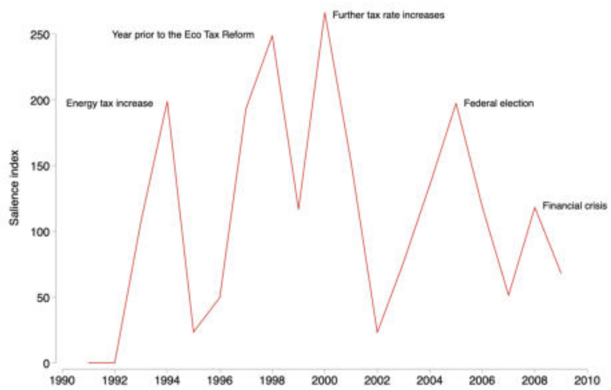
cial predictors to account for the effect of German reunification. In both cases, we do not document any observable long-term negative effects on GDP from the eco-tax reform.

5.4 Tax salience

Our analysis continues by quantifying the role of eco-tax salience in the media in driving the estimated effects of the eco-tax, drawing on a growing number of economic studies leveraging newspaper data as source of variation in the salience of events (e.g., Li et al., 2014; Baker et al., 2016; Basaglia et al., 2021; Beach and Hanlon, 2023).

Figure 9 plots the evolution of our newspaper-based eco-tax salience index. We leverage annual variations in the salience index to investigate how variations in media salience affect fuel-specific consumption responses.

Figure 9: Evolution of the salience index over time



Notes: Based on yearly series from 1991 to 2009. Authors' own calculations based on newspaper articles from Factiva (c.f. Section 3). A detailed description of the steps undertaken to construct the newspaper index can be found in Section D of the OA.

We amend our static log-linear semi-elasticity models (c.f. Section 2.2) by additionally interacting our salience index with the annual real rate of the eco-tax.[32] This allows us to empirically isolate how salience affects fuel use in accordance with the evolution of the eco-tax. Our identification strategy captures the additional effect on fuel consumption reduction (at a given tax rate) attributable to greater eco-tax media salience.[33]

[32]The interaction term will thus equal 0 prior to the eco-tax reform by design.

[33]Our regressions focus on salience in the previous year, as print media coverage tends to peak prior to actual or proposed changes to the eco-tax rate (c.f. Li et al., 2014).

Table 5: Effects of salience on fuel consumption

(a) Gasoline consumption

	(1)	(2)	(3)
Raw price of Gasoline (only VAT)	-0.00266	-0.00280	-0.000497
	(0.00242)	(0.00176)	(0.00130)
Energy Tax	-0.00610**	-0.00338	-0.00717
	(0.00234)	(0.00489)	(0.00427)
Eco Tax	-0.00656	-0.00773	0.00947
	(0.00492)	(0.00557)	(0.0105)
Eco Tax x Salience Index	-0.00531***	-0.00441**	-0.00199**
	(0.00132)	(0.00190)	(0.000739)
L.Eco Tax x Salience Index			-0.000459
			(0.00197)
L2.Eco Tax x Salience Index			-0.00622***
			(0.00208)
Controls	×	✓	✓
N	38	38	37

(b) Diesel consumption

	(1)	(2)	(3)
Raw price of Diesel (only VAT)	-0.00306***	-0.00326***	-0.00197***
	(0.000766)	(0.000900)	(0.000620)
Energy Tax	-0.00103	-0.00723**	-0.00773**
	(0.00293)	(0.00348)	(0.00342)
Eco Tax	-0.0119***	-0.00818***	0.000528
	(0.00129)	(0.00275)	(0.00367)
Eco Tax x Salience Index	-0.000999*	-0.00120*	0.000337
	(0.000497)	(0.000689)	(0.000440)
L.Eco Tax x Salience Index			-0.00166*
			(0.000891)
L2.Eco Tax x Salience Index			-0.00187*
			(0.000971)
Controls	×	✓	✓
N	39	39	37

Notes: The dependent variable is the log of fuel consumption in liters per capita, which refers to total fuel consumption of gasoline or diesel (indicated by column headings). Prices are in 1995€. Results for gasoline refer to 1972-2009 due to missing price data prior to 1972. Controls include: GDP per capita, the unemployment rate, a time trend and a binary variable that is equal to one after the implementation of the eco-tax in 1999 and zero otherwise. Newey-West standard errors in parentheses are heteroskedasticity and autocorrelation robust, calculated using the automatic bandwidth selection procedure following Newey and West (1994). Salience index is our newspaper-based index expressed in log terms (c.f., Section D.2). * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

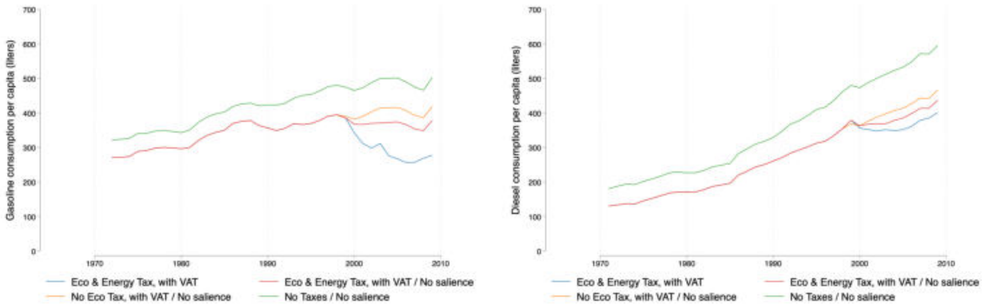
Column (2) in Table 5 reports our preferred coefficients of the amended elasticity model. The significant interaction term indicates that greater tax salience is associated with lower consumption of both gasoline and diesel and that these effects increase with the eco-tax rate. Furthermore, the eco-tax elasticities tend to converge to the real price elasticities after explicitly accounting for salience, suggesting that much of the divergence in the behavioral response for the increase in the eco-tax—relative to market-driven price changes—can be explained by tax salience in our model.[34] To put our coefficients to perspective, let's consider the average eco-tax rate for gasoline (diesel) in real terms of 13 cents per liter. Our estimates from column (2) suggest that when our salience index exhibits an increase of a standard deviation relative to the mean, the additional reduction of gasoline (diesel) consumption induced by salience amounts to 4.3% (1.2%).[35]

[34]Relying on column (2) in Table 5, the salience-exclusive gasoline (diesel) eco-tax elasticity of 0.62 (0.61) is 1.1 (1.8) times higher as real price elasticities (Table 3.

[35]Our salience index exhibits a mean of 100 with a standard deviation of 76. A standard deviation increase thus represents a 76% increase relative to the mean. Both fuel consumption and the salience index are expressed in log terms in our model. Denoting the coefficient of the interaction term as φ_6, we can interpret the estimated coefficients, $\hat{\varphi}_6$, as follows: For the average eco-tax rate of 13 cents, a standard deviation increase (or 76% increase relative to the mean) in our salience index will lead to an additional percentage reduction in fuel consumption amounting to $13 \times [(1.01^{\hat{\varphi}_6} - 1) \times 100] \times 0.76$.

Figure 10: Predicted fuel use under different tax and salience scenarios

(a) Gasoline consumption **(b)** Diesel consumption



Notes: The figures plot predicted fuel consumption from our amended log-level semi-elasticity models (c.f. Section 2.2 and 5.4) under different taxation scenarios. We rely on the estimated fuel-specific price and tax elasticities computed from our estimates from column (2) in Table 5a and 5b. Specifically, Panel (a) refers to predicted per capita gasoline consumption (in liters), while Panel (b) is based on predicted per capita diesel consumption (in liters). The top green line displays predicted emissions in the absence of taxes, which means both the eco and energy tax elasticities are set to zero, and the VAT is deducted from the fuel price. For the orange line, the eco-tax elasticity is set to zero but the VAT-inclusive energy tax is now included. The red line shows how predicted emissions change when we include both the eco and energy taxes with the VAT but we set salience (as proxied by our newspaper-based index) equal to zero. The bottom blue line provides predicted emissions using the full model described in Section 5.4 with the differentiated tax and price elasticities which additionally includes the salience interactive term.

Leveraging our results from column (2), Figure 10 plots predicted gasoline and diesel consumption in the German transport sector under different taxation regimes and compares their evolution with and without salience. We show that salience is responsible for around 70% (55%) of the contraction in gasoline (diesel) consumption in our simulation.

Finally, regressions in column (3) of Table 5 investigate lagged responses to salience using lags of the interaction term to test whether the detected larger demand response induced by tax salience endures beyond the exposure period. The coefficient of our lagged interactions reveal that the greater behavioral response induced due to salience lasts for multiple years after a spike in our index for both gasoline and diesel demand. These results provide suggestive evidence that a differential effect of fuel taxes vis-a-vis tax-exclusive prices could persist even in the long-run. Overall, these results corroborate the hypothesis that consumers react more strongly—relative to market prices—to environmental taxes that are salient.[36]

[36]Salience can interact with other mechanisms that may lead to larger *tax salience ratios* but are hard to isolate, including the expected persistence of the price increase (e.g., Li et al., 2014) or the moral desirability of demand reductions (e.g., Mideksa, 2021). Our tax salience effects may thus also capture increased persistence expectations or a stronger signal that demand reductions are socially desirable.

6 Quantifying climate and health benefits

While previous reports suggested that environmental improvements due to the German eco-tax have been limited (Steiner and Cludius, 2010), we document substantial reductions in emissions. To quantify climate and health benefits, we apply official cost estimates for emissions from the first comprehensive guidelines by the Umweltbundesamt (2012). We, first, apply these to a prior evaluation of carbon emission reductions and, subsequently, illustrate results for our simulations and SCM results.

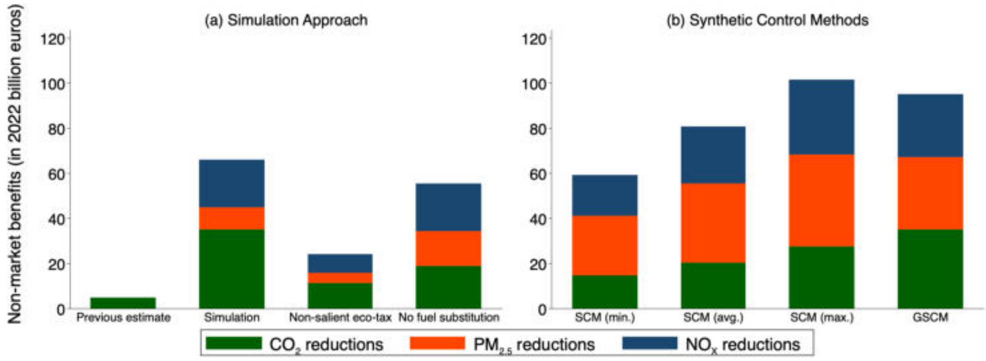
The Umweltbundesamt (2012) recommended a social costs of carbon (SCC) per ton of CO_2 emitted in 2010 by 80 Euros (in 2010 Euros), and provided dis-aggregated cost estimates for $PM_{2.5}$ in the transport sector, distinguishing costs of $PM_{2.5}$ released within (364,100 €/t) and outside of cities (122,800 €/t), recognizing that within city emissions contribute more to human health costs. Using their reported breakdown of the share of $PM_{2.5}$ within and outside of cities for different transport modes, we compute a weighted average of $PM_{2.5}$ damages. For external costs of NO_x, the Umweltbundesamt (2012) does not distinguish across locations, and uses a cost estimate of 15,400 €/t. We transform all cost estimates from a base year 2010 to 2022 values using official inflation statistics.

Steiner and Cludius (2010) estimate a price elasticity of fuel demand of -0.18 based on household survey data and attribute -0.1 to the tax elasticity component, with which they quantify reductions of CO_2 emissions due to the eco-tax, amounting to 120 kg CO_2 per household per year. Multiplying with the yearly number of households in Germany from 1999 to 2009, this sums up to 50.73 million tons of CO_2 emissions. Evaluating these emission reductions with the 2010 SCC in 2022 Euros yields a climate benefit of 4.9 billion Euros (first bar of Panel (a) in Figure 11).

We contrast this with results from our Simulation approach (Panel (a) in Figure 11). Simulating emission reductions of CO_2 relative to the counterfactual without the eco-tax yields 344 million fewer tons, and an aggregate climate benefit of around 35 billion Euros. We further simulate reductions of $PM_{2.5}$ and NO_x emissions of 36,368 tons and 1.08 million tons,[37]

[37] To estimate NO_x emissions from fuel consumption, we rely on estimates from the EEA on average emission factors for gasoline (diesel) vehicles in Germany (Ntziachristos and Samaras, 2019) of 5.61 (20.1) grams of NO_x per kg of gasoline (diesel).

Figure 11: Non-market benefits of the eco-tax



Notes: The figure above plots the estimated non-market benefits based on our estimates from (a) the Simulation Approach and (b) the Synthetic Control Methods on CO_2, $PM_{2.5}$, and NO_x reductions and compares their magnitudes with the implied benefit estimates from Steiner and Cludius (2010). Aggregate benefits are computed relying on pollutant-specific official cost estimates provided by the Umweltbundesamt (2012) and expressed in 2022 Euros.

translating into health benefits of 31 billion Euros. In sum, the Simulation Approach suggests that the eco-tax has reduced external damages by 66 billion Euros, 13 times as much as the previous estimate.

We further consider alternative scenarios. First, we consider a *non-salient eco-tax* scenario. We estimate that external damage reduction would have been around two-thirds smaller at 23 billion Euros in the absence of a salient eco-tax. Second, we consider a scenario with *no fuel substitution* from gasoline to diesel induced by the eco-tax.[38] External damage reductions would have amounted to 55.5 billion Euros with *no fuel substitution*, with a very different composition: While not switching to diesel would have led to much lower climate benefits (34.9 vs. 18.7 billion Euros), benefits to due reducing $PM_{2.5}$ would have been higher (30.9 vs. 36.7 billion Euros).

We now move to benefit estimates using our SCM approaches.[39] The first three bars in Panel (b) of Figure 11 show the results of our SCM for

[38]We compute the *no fuel substitution* scenario by holding annual traveled km per capita fixed. As gasoline vehicles are less fuel efficient than comparable diesel vehicles, this assumption implies that the foregone increase in diesel use due to fuel substitution translates into a 1.2 times increase in gasoline use to account for lower fuel efficiency (Linn, 2019). Foregone gasoline-to-diesel substitution is computed using column (3) in Table C.3b in the OA. We then add (subtract) the estimated foregone substitution towards diesel to predicted gasoline (diesel) use from column (3) in Tables 4a and 4b.

[39]The SCMs and simulation results for $PM_{2.5}$ emissions are not directly comparable, as the latter relies on conversion factors that do not account for non-exhaust emissions (Ntziachristos and Samaras, 2019).

specifications yielding minimal, average and maximal emission reductions whereas the last bar refers to our GSCM results. The average across all seven SCM specifications suggests climate and health benefits due to the eco-tax of 80.7 billion euros, more than 16 times as much as the estimate by Steiner and Cludius (2010).[40] The GSCM yields a slightly higher benefit estimate at around 95 billion Euros.

Overall, our results suggest that the eco-tax was orders of magnitude more effective in reducing external damages than previously suggested. Crucially, evaluations of fuel or carbon taxes that focus solely on climate benefits (e.g., Andersson, 2019; Mideksa, 2021; Runst and Höhle, 2022) miss a substantial share of benefits. For the case of the German eco-tax, we estimate that neglecting health benefits due to reduced air pollution would miss around 75% of the reductions in external damages.

7 Conclusion

This paper provides the most comprehensive assessment thus far of the effectiveness of how fuel taxation reduces climate and health externalities with a quasi-experimental evaluation of the world's largest environmental tax reform. Our various synthetic control method specifications demonstrate that the German eco-tax introduced in 1999 has led to sizable reductions in CO_2, $PM_{2.5}$ and NO_X emissions. Using official cost estimates, we show that the eco-tax has saved around 80 billion Euros of external damages between 1999 and 2009, with three-quarters of reductions in externalities relating to health benefits due to reduced air pollution.

We further document that the eco-tax has induced low-carbon innovation, leading to more than 800 additional patented technologies that may have contributed to lowering abatement costs. We also provide suggestive evidence that the eco-tax has likely contributed to fostering fleet renewal of passenger cars and to reduced passenger-kilometers traveled, without having reduced economic activity. We moreover show that fuel substitution

[40] Note that the EDGAR data and the emission factors used in the simulation approach are based on laboratory emission rates which tend to underestimate actual on-road nitrogen dioxides and particulate matter emissions (Crippa et al., 2018), also partly due to the recent *Dieselgate* scandal (Grange et al., 2020). Our estimated impacts on on-road emissions may thus represent lower-bound estimates.

plays a key role for navigating the trade-off between attaining climate and health targets linked to air quality. Finally, we show that the much higher demand response to the eco-tax is primarily due to increased tax salience, which we measure explicitly based on newspaper data. We thereby provide the first direct empirical evidence for the hypothesis that consumers react more strongly to fuel taxes the more salient they are.

Overall, our results highlight the key roles of co-pollution, innovation, fuel substitution and tax salience for the effectiveness of fuel taxes to reduce external damages and carry important policy implications. First, a sole focus on carbon abatement—as is common in the literature (e.g., Andersson, 2019; Leroutier, 2022; Runst and Höhle, 2022)—will substantially underestimate the potential of taxes on fossil fuels to reduce externalities.[41] Thus, accounting for health co-benefits is crucial when evaluating the benefits of carbon pricing. Accounting for such health co-benefits, which more immediately benefit those that bear the costs of higher fuel prices, may be crucial to gather support for fuel and climate policies (e.g., Löschel et al., 2021). Our finding is also crucial for the evaluation of distributional effects. While the consumer costs of fuel taxation tend to burden lower-income households disproportionately (e.g., Sterner, 2012a; Känzig, 2023), poorer households may also benefit disproportionately from better air quality (e.g., Banzhaf et al., 2019; Hernandez-Cortes and Meng, 2023). Consequently, the true incidence of fuel taxation is possibly less regressive as often suggested on the basis of the consumer cost distribution only (e.g., Drupp et al., 2021).

Second, and relatedly, it is important for evaluations of fuel and carbon pricing to consider the trade-offs that can arise between climate and air pollution targets (e.g., Linn, 2019; Parry et al., 2021). We show that this is particularly relevant in the context price instruments set on the carbon content of fuels that can foster gasoline-to-diesel substitution. While this general feature of second-best taxation (Knittel and Sandler, 2018) is less important in the US, due to a predominant share of gasoline-fuelled cars, it is key when evaluating fuel pricing schemes in Europe (Zimmer and Koch, 2017; Linn, 2019). We show that relaxing the assumption that consumers

[41] Our results likely still provide a lower-bound of eco-tax induced externality reductions, as the eco-tax may also have contributed to reducing congestion (e.g., Hintermann et al., 2021), fatality risk (e.g., Anderson and Auffhammer, 2014) or the reliance on fossil imports and related security concerns.

respond similarly to fuel taxes as to other sources of fuel price variation (Linn, 2019) suggests that policymakers have to navigate a much larger trade-off between climate and health benefits.

Third, we shed light on the potential of environmentally-motivated taxation to spur low-carbon innovation by capturing economy-wide responses to an implicit carbon tax. Our approach thus complements previous studies that focused on the innovation response of regulated companies (e.g., Calel and Dechezleprêtre, 2016), which generally find limited aggregate effects, and provides indirect evidence on the potential magnitude of the additional innovation occurring along the supply chain and across unregulated agents, for instance, due to pass-through of regulatory costs or knowledge spillovers. By permanently reducing abatement costs, induced innovation is a key dimension to capture when conducting a comprehensive cost-benefit assessment of the climate benefits of fuel and carbon taxation measures. Our results document that regulatory-induced innovation responses to a carbon price can be sizable when considering economy-wide effects.

Finally, our results underscore the crucial role of tax salience for fostering the effectiveness of fuel taxation and carbon pricing (c.f., Chetty et al., 2009; Li et al., 2014; Rivers and Schaufele, 2015). This implies that complementary informational measures may have considerable potential to foster climate, health and security benefits through a greater demand response at a given tax rate, and hence enhance the cost-effectiveness of price instruments to internalize externalities. This important role of salience, however, is a double-edged sword for policy design. On the one hand, this is good news for policies aimed at reducing external damages or attaining specific climate targets, as fuel or carbon taxes may yield larger demand responses than is routinely considered in policy analysis using price elasticities estimated solely on market-price movements (e.g., Edenhofer et al., 2019). On the other hand, tax salience may not only lead to stronger demand reductions but may also impede more stringent future policies due to stronger public resistance, such as in the case of the French "Yellow vests" (Douenne and Fabre, 2022). Indeed, while there were plans to further increase the eco-tax stringency over time, the yearly increases were discontinued in 2003 due to public resistance, and only picked up again in 2021, then under the explicit label of carbon pricing.

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Online Appendix

De-fueling externalities: Causal effects of fuel taxation and mediating mechanisms for delivering climate and health benefits

Authors: Pier Basaglia, Sophie Behr, and Moritz Drupp

Contents

Appendix A Background on the eco-tax and data sources

Taxing oils and fuels has a long history in Germany; the first mineral oil tax was established in 1939 for several fuels, including fuel oil, and other mineral oils such as gasoline and petroleum (Bundesministerium der Finanzen, 2014). In the 1980s, Binswanger (1992), suggested an ecological tax to internalize the externalities from the transport sector by implementing a tax at a low level and raising it until emissions have decreased to an environmentally sustainable level (Knigge and Görlach, 2005). The ecological fiscal reform (henceforth eco-tax reform) then came into effect in April 1999 taxing fuels, gas, electricity, and heating oil (Bundesgesetzblatt I, S.378, 1999; Steiner and Cludius, 2010). Note that this means that most of the first half of the year 1999 is not treated. In each year between 1999 and 2003, the fuel tax on gasoline and diesel was increased by 3.07 cents (6 Pfennig) per liter. This led to a total tax increase of 15.35 cents per liter for gasoline and diesel and is hereafter referred to as the eco-tax.

The law was updated in 2002, when some tax rates were increased and special rules implemented (Bundesgesetzblatt I, S. 2432., 1999; Bundesgesetzblatt I, S. 4602, 2002). Due to economic and social concerns, the eco-tax was exempted for many areas; thus it only affected the price of fuels and the use of electricity for less energy-intensive industries (Knigge and Görlach, 2005; Bach, 2009). For this reason, we focus our analysis on the German transport sector only instead of total economy-wide emissions. Since then, it has not been changed, implying that nominal taxes on transport fuels have remained the same since 2003 up until the introduction of an explicitly labeled CO_2-price in January 2021. Interestingly, the revenue generated by the eco-tax overwhelmingly goes toward the German pension fund as reducing the statutory payments toward the pension fund was one of the key goals of the tax reform (Beuermann and Santarius, 2006). Out of the 18.7 billion euros that were raised by the eco-tax in 2003, 16.1 billion euros went to the pension fund (Kohlhaas, 2005).

We report some descriptive statistics to provide context on the German transport sector before and after the implementation of the eco-tax. Figure A.1 plots total fuel consumption by fuel type over time whereas Figure A.2

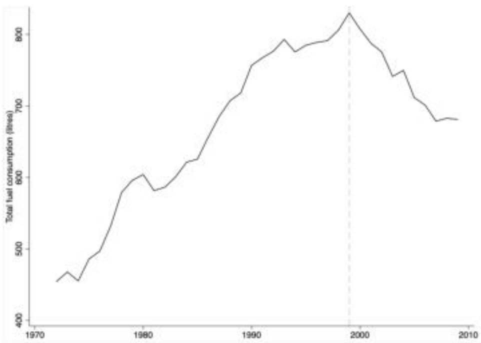
shows the nominal mineral oil tax from 1939 to 2009 for gasoline and diesel. For real values and other tax rates, please refer to Figure A.3. Over time, this law was changed frequently until its name was eventually changed to energy taxation law in 2006 Bundesministerium der Finanzen (2014). This is why we refer to the mineral oil tax as "energy tax" henceforth.

As mentioned in the main text, the German eco-tax is not a direct carbon tax, however, it can be interpreted as one. As of 2020, the total energy tax per liter of gasoline is 65.45 cents (Bundesministerium der Finanzen, 2014). The combustion of one liter of gasoline emits 2.325 kg of CO_2 (US EPA, 2005). If this is taken as a base, the energy tax on gasoline indirectly amounts to 281.51€ per ton of CO_2. The numbers are slightly different for diesel with 2.660 kg of CO_2 emitted as a result of the combustion of one liter and an energy tax of 47.04 cents per liter (US EPA, 2005; Bundesministerium der Finanzen, 2014). Still, this amounts to a price of 176.84€ per ton of CO_2. Prior to the eco-tax reform, the energy tax resulted in an indirect carbon tax of 215.53€ per ton of CO_2 for gasoline and 119.17€ for diesel. This means, that the eco-tax increased the effective carbon price by 57.67€ ($65.17) for diesel and 65.98€ ($74.56) for gasoline between 1999 and 2003. Thereby the eco-tax effectively represented the second highest tax on CO_2 in the world at that time.[42] Figure A.4 compares the evolution of fuel-specific tax rates in Germany to the OECD average to put magnitudes into perspective in relation to the donor pool of countries employed for the synthetic control methods (SCMs).

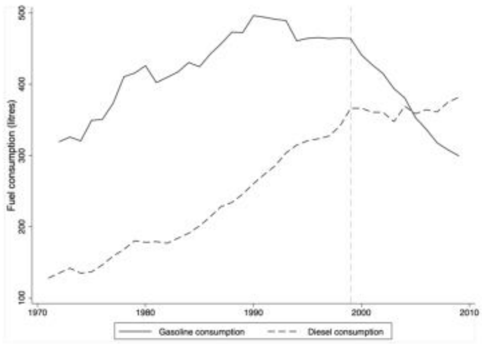
[42]The World Bank (2020) counts seven CO_2 taxes in 2003, with the highest in Sweden ($89.65), followed by Norway ($44.53). The German eco-tax is not classified.

Figure A.1: Fuel consumption over time

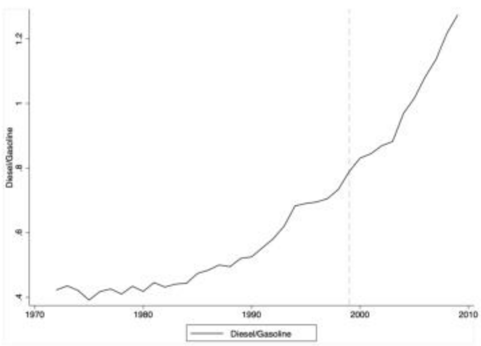
(a) Total fuel use



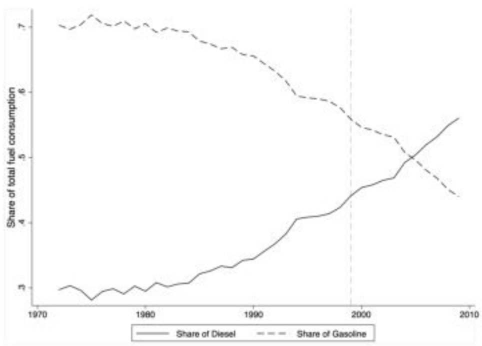
(b) Total fuel use by fuel type



(c) Diesel-to-gasoline ratio

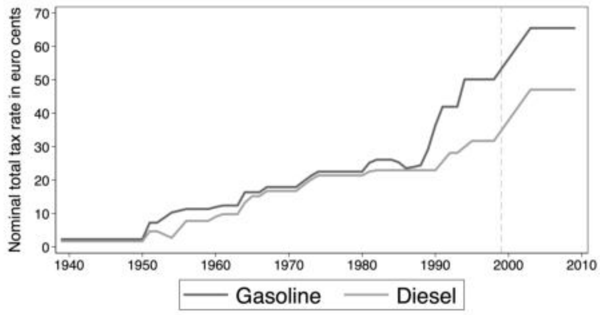


(d) Share of diesel and gasoline consumption



Notes: Data on fuel consumption is expressed in liters per capita or percentage terms, as denoted on the y-axis.

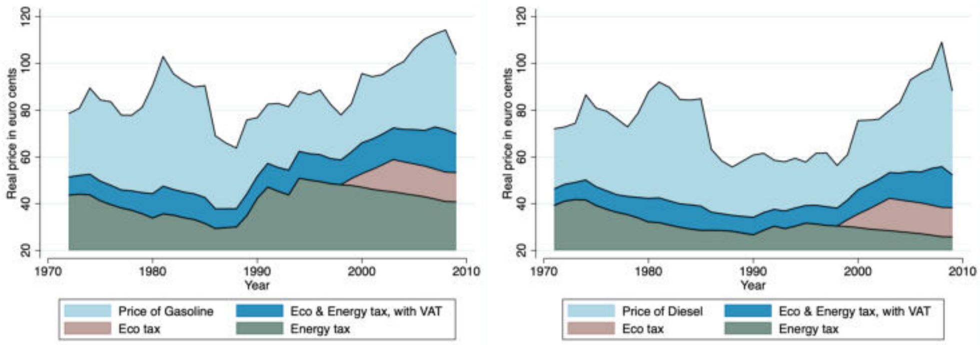
Figure A.2: Nominal taxes of gasoline and diesel over time



Notes: The figure above plots nominal taxes of gasoline and diesel from 1939 to 2009 as reported by the Bundesministerium der Finanzen (2014). Note that whenever a tax changes throughout a year, the average tax is calculated and shown here. Numbers are in cents.

Figure A.3: Real fuel prices and their tax components over time

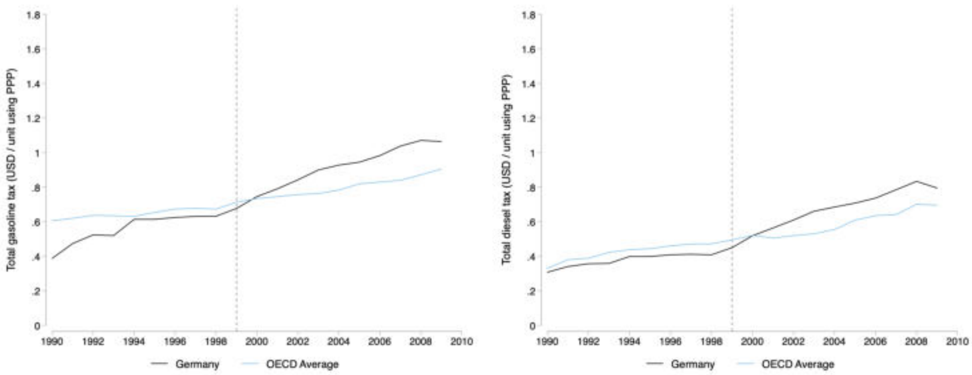
(a) Gasoline **(b)** Diesel



Notes: Prices are in 1995€. Own calculations.

Figure A.4: Fuel taxes in Germany and the OECD average

(a) Gasoline **(b)** Diesel



Notes: Prices are in USD using PPP. Source: IEA Energy Prices and Taxes Statistics.

Table A.1: Data Sources

Variable	Source
Share of CO_2 emissions from transport	Data downloaded from World Bank
CO_2 emissions from fuel combustion	IEA
$PM_{2.5}$ ad NO_X emissions from EDGAR	EDGAR
Population	World Bank
Expenditure-side real GDP at current PPPs (in mil. 2011 US$)	Penn World Tables
Urban population (% of total population)	World Bank
Road sector diesel (1) and gasoline (2) fuel consumption per capita (kg of oil equivalent)	World Bank (1), World Bank (2)
Road sector gasoline fuel consumption per capita (kg of oil equivalent)	Mineralwirtschaftsverband
Consumer price index for Germany (1995=100)	Statistisches Bundesamt (Destatis)
Consumer price index for Germany (2015=100)	Statistisches Bundesamt (Destatis)
Strategic Reserve for Gasoline and Diesel in DM/t	Erdölbevorratungsverband
Energy Tax for diesel and gasoline in cents per litre	Bundesminesterium für Finanzen
Eco Tax for diesel and gasoline in cents per litre	Bundesminesterium für Finanzen
Value-added tax rate	Statista
Unemployment Rate	Bundesagentur für Arbeit
U.S. Crude Oil First Purchase Price (Dollars/Barrel)	EIA
Euro/ECU exchange rates - annual data	Eurostat
Vehicles ownership per 1,000 people	Received from Prof. Gately (Dargay et al., 2007).
Low-carbon patents related to transportation: triadic patent families (1) and total (2)	OECD (1), OECD (2)
Newspaper-specific article frequency counts	Factiva (Commercial data)
Road passenger transport (pkm)	OECD
Vehicle registrations by age	UNECE
Road casualties	OECD

Appendix B Synthetic Control Method: Additional results

This section of the Online Appendix provides additional supporting material and results related to the synthetic control methods (SCMs) employed in the study. Specifically, this section contains the following material: Tables B.1 - B.3 report country-specific weights used for the construction of our synthetic counterfactuals in Figure 1. The three panels in Figure B.2 plot in-time placebo tests when we assign a fake treatment to Germany in 1995. Figure B.3 reports our results leveraging the standard SCM when we do not impose any of the sample restrictions discussed in Section 3. Figure B.4 reports leave-one-out tests (c.f. Abadie et al., 2015) for our *Baseline* (i.e., Panels a, c and e) and *No covariates* specifications (i.e., Panels b, d and f). The former is in line with the recommendations in Kaul et al. (2022), while the latter follows Ferman et al. (2020). Finally, Figure B.4 plots the dynamic treatment effects estimated for each of our GSCM specifications presented in Section 4.2.

Table B.1: SCM for CO_2: Pre-Treatment Predictor Means for Germany, Baseline Synthetic Germany and the Sample Average

Variables	Germany	Synthetic	Sample Mean
GDP per capita	22,197.42	23,615.94	17,972.24
Diesel consumption per capita	185.23	185.27	130.29
Gasoline consumption per capita	332.55	332.77	343.23
Share of urban population	0.73	0.73	0.73
Number of vehicles per 1,000 people	410.34	410.48	290.14
CO2 from transport in 1998	2.10	2.10	2.12

All variables except lagged CO_2 per capita are averaged from 1971-1998. GDP per capita is measured at current PPPs in million 2011 USD. Gasoline and diesel consumption is measured in kg of oil equivalent. Share of urban population is measured as a percentage of total population. CO2 emissions are measured in metric tons per capita and are retrieved from the IEA.

Table B.2: SCM for $PM_{2.5}$: Pre-Treatment Predictor Means for Germany, Baseline Synthetic Germany and the Sample Average

Variables	Germany	Synthetic	Sample Mean
GDP per capita	22,197.42	22,346.93	17,972.24
Diesel consumption per capita	185.23	170.25	130.29
Gasoline consumption per capita	332.55	367.82	343.23
Share of urban population	0.73	0.75	0.73
Number of vehicles per 1,000 people	410.34	410.39	290.14
$PM_{2.5}$ from transport in 1998	0.58	0.61	0.58

All variables except lagged $PM_{2.5}$ per capita are averaged from 1971-1998. GDP per capita is measured at current PPPs in million 2011 USD. Gasoline and diesel consumption is measured in kg of oil equivalent. Share of urban population is measured as a percentage of total population. $PM_{2.5}$ emissions are measured in kg per capita and are retrieved from the EDGAR v6.1 database.

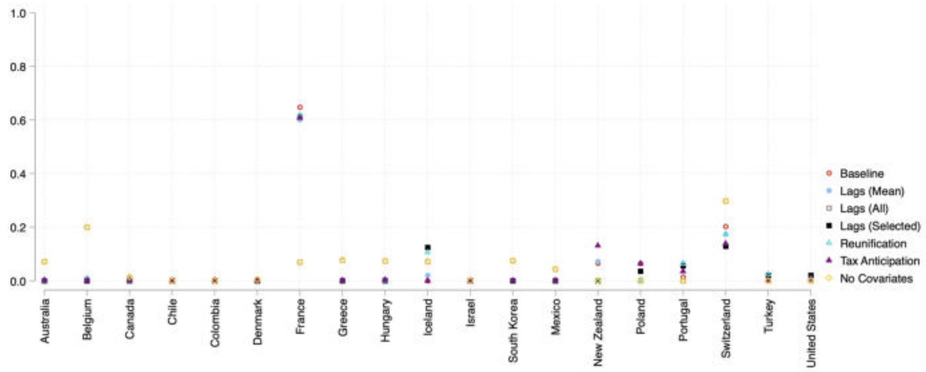
Table B.3: SCM for NO_X: Pre-Treatment Predictor Means for Germany, Baseline Synthetic Germany and the Sample Average

Variables	Germany	Synthetic	Sample Mean
GDP per capita	22,197.42	22,199.20	17,972.24
Diesel consumption per capita	185.23	179.35	130.29
Gasoline consumption per capita	332.55	303.51	343.23
Share of urban population	0.73	0.76	0.73
Number of vehicles per 1,000 people	410.34	360.88	290.14
$PM_{2.5}$ from transport	0.50	0.50	0.42
NO_X from transport in 1998	14.13	14.26	16.72

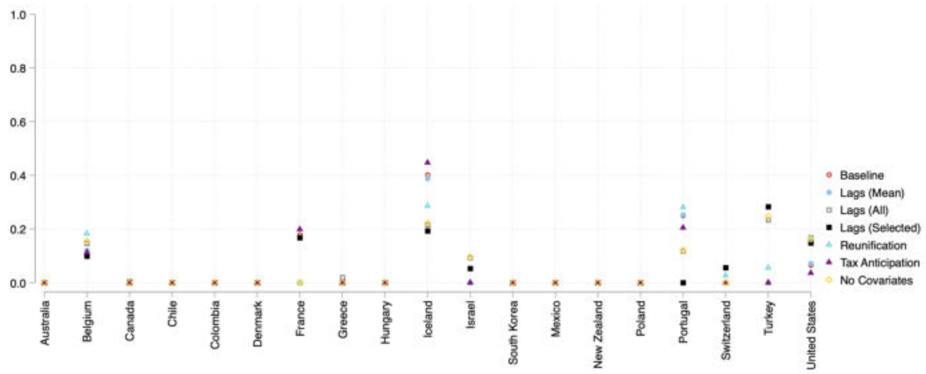
All variables except lagged NO_X per capita are averaged from 1971-1998. GDP per capita is measured at current PPPs in million 2011 USD. Gasoline and diesel consumption is measured in kg of oil equivalent. Share of urban population is measured as a percentage of total population. NO_X emissions are measured in kg per capita and are retrieved from the EDGAR v6.1 database.

Figure B.1: Comparing donor pool weights across SCM specifications

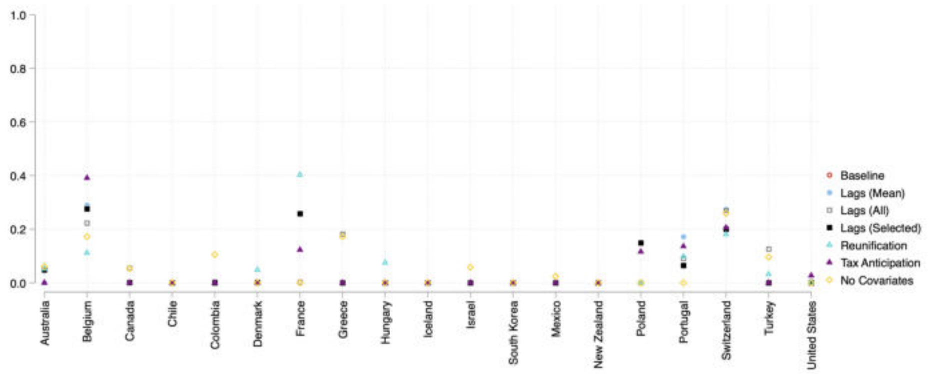
(a) Synthetic Germany: CO_2



(b) Synthetic Germany: $PM_{2.5}$



(c) Synthetic Germany: NO_X

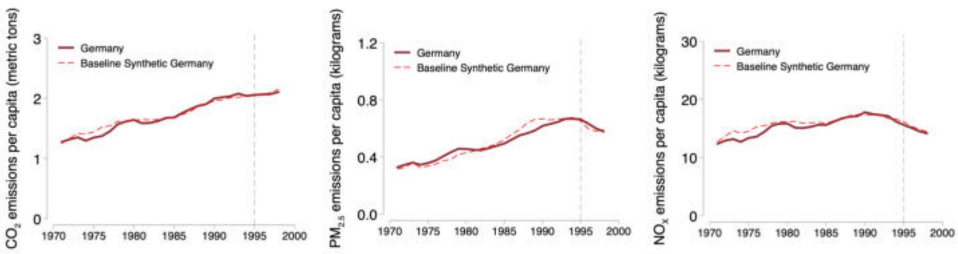


Notes: The figure plots the estimated country-specific weights assigned by the synthetic control algorithms across our set of SCM specifications (c.f. Table 1).

B.1 Placebo in time

Figure B.2: In-time placebos

(a) CO_2 **(b)** $PM_{2.5}$ **(c)** NO_x

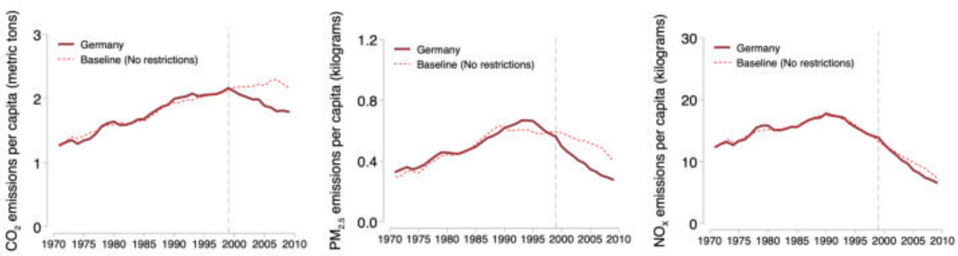


Notes: The figure plots the in-time placebo for our results on (a) CO_2, (b) $PM_{2.5}$, and (c) NO_X emissions where a placebo treatment is assigned in 1995.

B.2 No sample restrictions

Figure B.3: Results with no donor pool restrictions

(a) CO_2 **(b)** $PM_{2.5}$ **(c)** NO_x

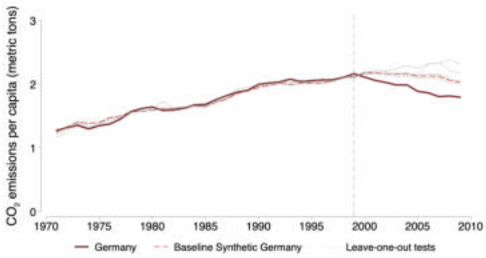


Notes: The figure plots our Baseline SCM results without applying the sample description described in Section 3.

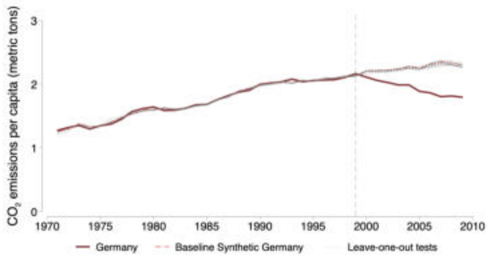
B.3 Leave-one-out tests

Figure B.4: Leave-one-out tests

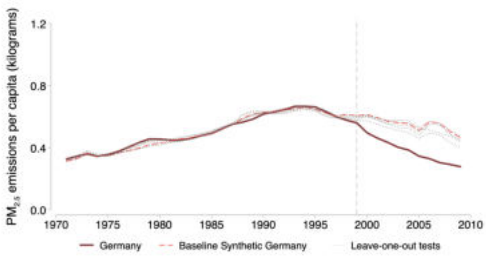
(a) CO_2: Baseline results



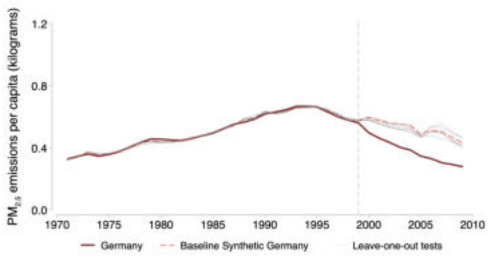
(b) CO_2: No covariates results



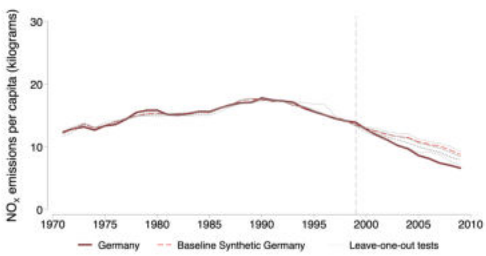
(c) $PM_{2.5}$: Baseline results



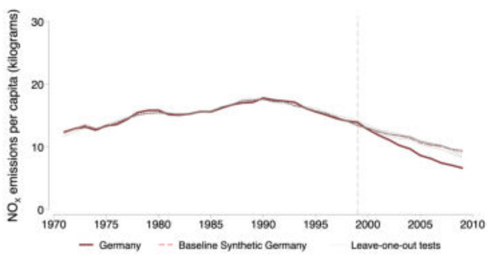
(d) $PM_{2.5}$: No covariates results



(e) NO_x: Baseline results



(f) NO_x: No covariates results

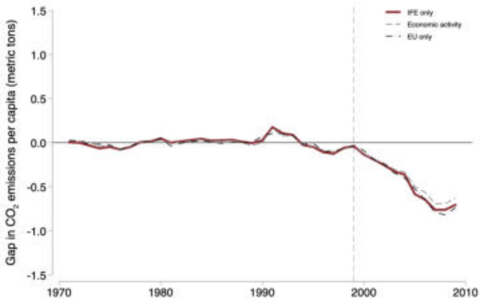


Notes: The figure plots leave-one-out tests following Abadie et al. (2015) where we iteratively exclude countries that receive at least a 1% in the construction of the synthetic counterfactual. More details can be found in Section 4.2.

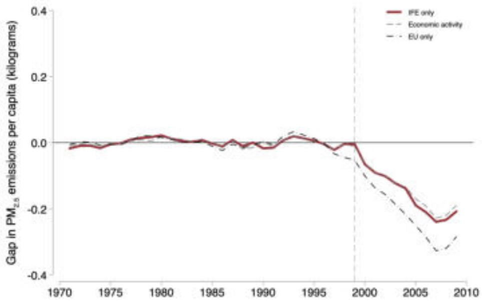
B.4 Generalized Synthetic Control Method (GSCM)

Figure B.5: GSCM with Interactive Fixed Effects Models

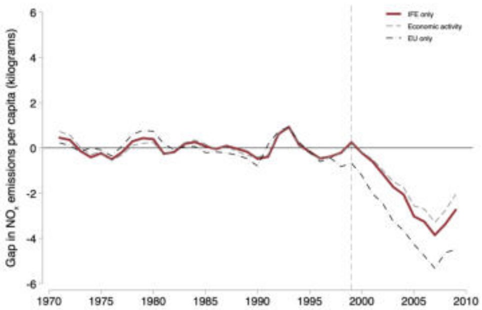
(a) Change in CO_2 over time



(b) Change in $PM_{2.5}$ over time



(c) Change in NO_x over time



Notes: The figure plots the estimated gaps in emissions relative to a synthetic counterfactual development based on a Generalized Synthetic Control Method with interactive fixed effects models Xu (2017). More details on the GSCM specifications can be found in Section 4.2.

Appendix C Elasticities

This Section is structured as follows. First, we provide evidence of tax pass-through to prove that taxes are noticeable to consumers in our setting. Second, Tables C.1a - C.1b provide a host of robustness tests for our real and eco-tax elasticity results presented in Section 5. Figure C.1 plots our elasticity results when employing a distributed lag model with one lead to account for anticipatory behaviour (Coglianese et al., 2017; Kilian and Zhou, 2023).[43] Table C.3a and C.3b provides evidence of gasoline-to-diesel substitution in our setting again leveraging the semi-elasticity models presented in Section 2.2. Figure C.2 displays predicted NO_X emissions under different taxation scenarios complementing Figure 5 in the main text. Figure C.3 compares the dynamic treatment effects across all the different empirical strategies employed in our study, namely the (a) SCM, (b) the generalized SCM and (c) the simulation approach.[44] Finally, Figure C.4 leverages again the semi-elasticity models to provide some complementary suggestive evidence on the average effects of the eco-tax on road casualties (i.e., considering fatalities and injuries).

Tax pass-through. Before computing fuel-specific price and tax elasticities, we check if the tax increases get effectively passed through to the retail price of fuel to ensure that changes in taxation are noticeable to consumers (c.f. Andersson, 2019). We use first-differencing to regress the crude oil price i and the combined nominal energy and eco tax $\tau^{eco,energy}$ on the retail fuel price p^* of gasoline and diesel, respectively:

$$\Delta p_t^* = \alpha_0 + \alpha_1 \Delta\sigma_t + \alpha_2 \Delta\tau_t^{eco,energy} + \epsilon_t \tag{9}$$

[43]We additionally run first-differences models including different sets of leads and lags of the normalized tax change, as in Kilian and Zhou (2023). We produce a distribution of p-values for testing the null of equal effects between tax-exclusive and eco-tax price changes: Across all the different specifications, we reject the null hypothesis of equal effects between tax-exclusive and tax-only price changes in our setting. Results are available upon request.

[44]Note that simulated $PM_{2.5}$ emissions are not directly comparable to our SCMs results as the former do not account for non-exhaust emissions.

The p-values of a linear Wald test show that for both regressions, the tax coefficient α_2 is not significantly different from unity.[45] For gasoline, α_2 equals 0.94 (with a 95% confidence interval of [0.79; 1.08]). The result is comparable for diesel, where the coefficient is 0.86 [0.54; 1.17]. We repeat the estimation with the tax rates being formally separated into energy and eco-tax in the model:

$$\Delta p_t^* = \alpha_0 + \alpha_1 \Delta\sigma_t + \alpha_3 \Delta\tau_t^{energy,VAT} + \alpha_4 \Delta\tau_t^{eco,VAT} + \epsilon_t \qquad (10)$$

Again, we are not able to reject the hypothesis that there is full pass-through.[46] This indicates that fuel taxes have been noticeable for consumers and that we can interpret our estimates of fuel-specific tax elasticities as price elasticities of demand.

[45] The p-value of the linear Wald test for $\Delta\alpha_2 = 1$ is equal to 0.38 for gasoline and 0.34 for diesel.

[46] For gasoline, α_3 equals 0.92 [0.75; 1.09] and α_4 1.02 [0.83; 1.20]. While the eco-tax coefficient for diesel is similar at 0.96 [0.49; 1.43], the one for the energy tax is slightly lower at 0.64 [0.02; 1.25]. The p-values of the linear Wald tests for $\Delta\alpha_3 = 1$ are 0.34 for gasoline and 0.24 for diesel, and 0.84 and 0.87 for $\Delta\alpha_4 = 1$, respectively.

Table C.1: Comparing real price, aggregate tax and eco-tax elasticities by fuel

(a) Gasoline consumption

	Real price	Aggregate tax	Eco-tax
Real price of Gasoline	-0.00603**		
	(0.00278)		
Raw price of Gasoline (only VAT)		-0.00584*	-0.00357*
		(0.00331)	(0.00204)
Energy + Eco Tax		-0.00798**	
		(0.00375)	
Energy Tax on Gasoline			-0.00242
			(0.00497)
Eco Tax on Gasoline			-0.0306***
			(0.00773)
Dummy Eco Tax	-0.154	-0.144	0.104**
	(0.131)	(0.126)	(0.0393)
Trend	0.00158	-0.00328	0.0240
	(0.0138)	(0.0118)	(0.0210)
GDP per capita	0.000174	0.00893	-0.0245
	(0.0116)	(0.0168)	(0.0318)
Unemployment rate	0.0292	0.0311*	0.00902
	(0.0176)	(0.0177)	(0.0239)
Observations	38	38	38

(b) Diesel consumption

	Real price	Aggregate tax	Eco-tax
Real price of Diesel	-0.00440***		
	(0.00103)		
Raw price of Diesel (only VAT)		-0.00384***	-0.00346***
		(0.000908)	(0.00104)
Energy + Eco Tax		-0.0111***	
		(0.00141)	
Energy Tax on Diesel			-0.00729**
			(0.00292)
Eco Tax on Diesel			-0.0143***
			(0.00359)
Dummy Eco Tax	-0.0205	0.0574*	0.0794***
	(0.0564)	(0.0315)	(0.0174)
Trend	0.0189***	0.0104**	0.0187**
	(0.00587)	(0.00456)	(0.00774)
GDP per capita	0.0177***	0.0287***	0.0201**
	(0.00528)	(0.00702)	(0.00753)
Unemployment rate	0.0107*	0.0104*	0.00651
	(0.00558)	(0.00538)	(0.00816)
Observations	39	39	39

Notes: The dependent variable is the log of fuel consumption in liters per capita, which refers to total fuel consumption or either gasoline or diesel consumption (as indicated by the column heading). Prices are in 1995€. Results for gasoline consumption refer to 1972-2009 due to missing price data prior to 1972. Unemployment is measured as percentage of total labor force. Newey-West standard errors in parentheses are heteroskedasticity and autocorrelation robust. Standard errors are calculated relying on the automatic bandwidth selection procedure following Newey and West (1994). * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table C.2: Real price elasticities for transport fuels after 1991

(a) Gasoline consumption

	(1) OLS	(2) OLS	(3) OLS	(4) IV: Brent Crude
Real price of Gasoline	-0.00698***	-0.00693***	-0.00510***	-0.00531***
	(0.00142)	(0.00150)	(0.000592)	(0.000640)
Dummy Eco Tax	0.105**	0.106***	0.106***	0.106***
	(0.0371)	(0.0354)	(0.0164)	(0.0135)
Trend	-0.0237***	-0.0217*	-0.0336***	-0.0332***
	(0.00703)	(0.0111)	(0.00544)	(0.00505)
GDP per capita		-0.00311	0.00795	0.00793
		(0.00686)	(0.00636)	(0.00575)
Unemployment rate			0.0181***	0.0178***
			(0.00309)	(0.00268)
N	19	19	19	19

(b) Diesel consumption

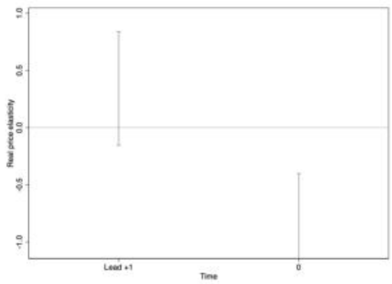
	(1) OLS	(2) OLS	(3) OLS	(4) IV: Brent Crude
Real price of Diesel	-0.00404**	-0.00456***	-0.00358***	-0.00317***
	(0.00161)	(0.00112)	(0.000318)	(0.000315)
Dummy Eco Tax	0.0687***	0.0635***	0.0634***	0.0632***
	(0.0151)	(0.0167)	(0.0111)	(0.00961)
Trend	0.0206***	0.0108	0.00457	0.00384*
	(0.00596)	(0.00670)	(0.00264)	(0.00227)
GDP per capita		0.0172***	0.0217***	0.0211***
		(0.00388)	(0.00355)	(0.00235)
Unemployment rate			0.0104**	0.0113***
			(0.00388)	(0.00378)
N	19	19	19	19

Notes: The dependent variable is the log of fuel consumption in liters per capita, which refers to total fuel consumption or either gasoline or diesel consumption (as indicated by the column heading). Columns (4) use the brent crude oil price as an instrumental variable for the real fuel price. Prices are in 1995€. Unemployment is measured as percentage of total labor force. Newey-West standard errors in parentheses are heteroskedasticity and autocorrelation robust. Standard errors are calculated relying on the automatic bandwidth selection procedure following Newey and West (1994). * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

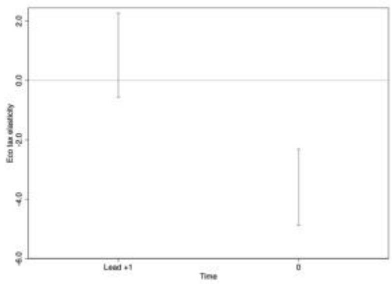
C.1 Elasticities with a distributed lag model

Figure C.1: Fuel-specific real price and eco tax elasticities with a lead

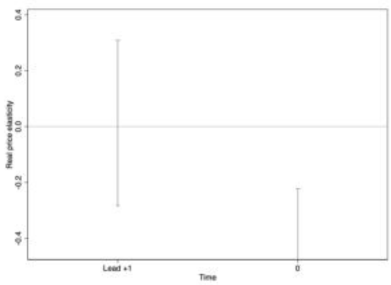
(a) Gasoline: Real price elasticity



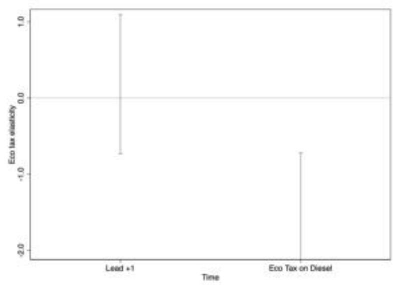
(b) Gasoline: Eco tax elasticity



(c) Diesel: Real price elasticity



(d) Diesel: Eco tax elasticity



Notes: The figure plots the estimated fuel-specific elasticities of gasoline and diesel demand by amending our log-level semi-elasticity models with the introduction of a lead (c.f. Section 2.2). Specifically, Panel (a) and (c) show the real price elasticity of gasoline and diesel demand respectively (c.f. Table 3b and 3a). Panel (b) and (d) display the gasoline and diesel eco tax elasticities (c.f. Table 4b and 4a). Prices are in 1995€. Results for gasoline consumption refer to 1972-2009 due to missing price data prior to 1972. Unemployment is measured as percentage of total labor force. Confidence intervals are based on Newey-West standard errors are heteroskedasticity and autocorrelation robust. Standard errors are calculated relying on the automatic bandwidth selection procedure following Newey and West (1994). * $p < 0.05$, ** $p < 0.01$, ***

C.2 Fuel substitution due to the eco-tax

Table C.3: Fuel substitution

(a) Diesel-to-Gasoline ratio

	(1) Diesel/Gasoline	(2) Diesel/Gasoline	(3) Diesel/Gasoline
Raw price of Gasoline (only VAT)	0.00187	0.00185	0.00184
	(0.00241)	(0.00124)	(0.00126)
Energy Tax on Gasoline	0.00471***	-0.000316	0.000991
	(0.00123)	(0.00263)	(0.00237)
Eco Tax on Gasoline	0.0175***	0.0157***	0.0126**
	(0.00634)	(0.00465)	(0.00482)
Dummy Eco Tax	-0.0108	-0.0619**	-0.0377
	(0.0276)	(0.0296)	(0.0242)
Trend	0.0126***	-0.00700	0.00671
	(0.00306)	(0.00700)	(0.0152)
GDP per capita		0.0372**	0.0214
		(0.0149)	(0.0187)
Unemployment rate			-0.0142
Observations	38	38	38

(b) Share of Diesel

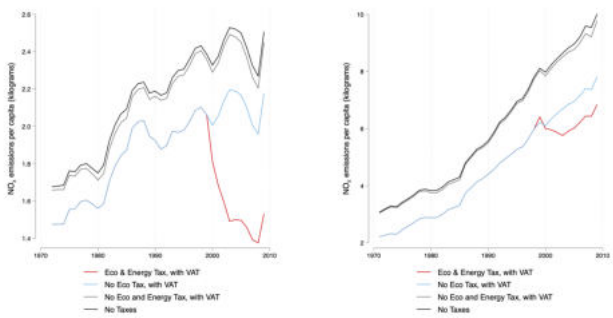
	(1) Share of Diesel	(2) Share of Diesel	(3) Share of Diesel
Raw price of Gasoline (only VAT)	0.000255	0.000250	0.000248
	(0.000565)	(0.000314)	(0.000317)
Energy Tax on Gasoline	0.00179***	0.000697	0.000917
	(0.000396)	(0.000658)	(0.000721)
Eco Tax on Gasoline	0.00415***	0.00376***	0.00325***
	(0.00144)	(0.00110)	(0.00108)
Dummy Eco Tax	0.00367	-0.00746	-0.00339
	(0.00645)	(0.00747)	(0.00630)
Trend	0.00482***	0.000554	0.00286
	(0.000731)	(0.00168)	(0.00378)
GDP per capita		0.00810**	0.00546
		(0.00352)	(0.00491)
Unemployment rate			-0.00239
			(0.00420)
Observations	38	38	38

Notes: The dependent variable is either (a) the ratio of diesel-to-gasoline consumption in litres per capita or (b) the share of diesel of total fuel consumption in percentage terms (as indicated by the column heading). Prices are in 1995€. Results for gasoline consumption refer to 1972-2009 due to missing price data prior to 1972. Unemployment is measured as percentage of total labor force. Newey-West standard errors in parentheses are heteroskedasticity and autocorrelation robust. Standard errors are calculated relying on the automatic bandwidth selection procedure following Newey and West (1994). * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

C.3 NO_X emission under different taxation regimes

Figure C.2: Predicted NO_X emissions by fuel under different tax scenarios

(a) Gasoline consumption **(b)** Diesel consumption

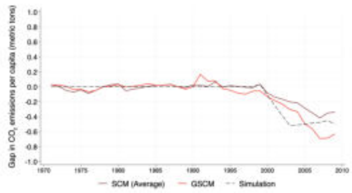


Notes: The figures above plot predicted emissions from the eco-tax specification of our log-level semi-elasticity models (c.f. Section 2.2) under different taxation scenarios. We rely the estimated fuel-specific price and tax elasticities computed from our estimates from column (3) in Tables 4a and 4b. Panel (a) refers to predicted emissions from gasoline consumption, while Panel (b) covers diesel consumption. In each panel the y-axis refers to per capita NO_X in kilograms. The top black line displays predicted emissions when the eco and energy tax elasticities are set to zero, and VAT is deducted from the fuel price. For the gray line, the eco and energy tax elasticities are set to zero but VAT is included. The light blue line shows how predicted emissions change when the eco tax is set to zero, but we include the energy tax and VAT. The red line provides predicted emissions using the full model with differentiated tax and price elasticities.

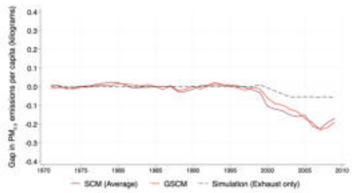
C.4 SCMs and the Simulation Approach

Figure C.3: Gap in per capita emissions: SCMs vs Simulation Approach

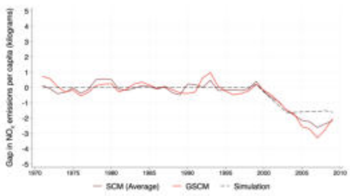
(a) CO_2 emissions (t)



(b) $PM_{2.5}$ emissions (kg)



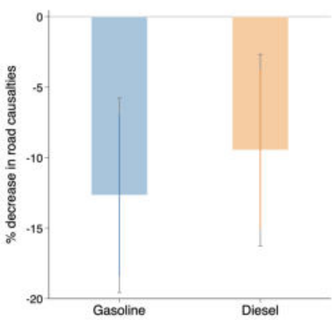
(c) NO_X emissions (kg)



Notes: The figures above plot the estimated average gap in per capita emissions from our synthetic control experiments (c.f. Section 2.1) and the simulation approach based on our log-level semi-elasticity models (c.f. Section 2.2). Nationwide reductions in emissions in the simulation approach have been computed by accounting for predicted emission reductions from both gasoline and diesel. Note that simulated $PM_{2.5}$ emissions are not directly comparable to our SCMs results as the former do not account for non-exhaust emissions.

C.5 Impacts of the eco-tax on road casualties

Figure C.4: Effects of the eco-tax on road casualties



Notes: The dependent variable is the number of road casualties (i.e., including fatalities and injuries) in logarithmic terms. The estimated effects refer to the average eco-tax rate of 13 cents. All regressions control for the fuel raw price, the energy tax rate, GDP per capita (in 1995€), the unemployment rate, and include a time trend as well as a dummy for the post-treatment period (i.e., equal to 1 after 1999). We use Newey-West standard errors that are heteroskedasticity and autocorrelation robust following Newey and West (1994).

Appendix D Salience analysis

The following section provides additional information on the salience analysis conducted in Section 5.4. This section of the Online Appendix is structured in three parts. First, we report the different search strategies that were used to extract frequency counts of newspapers' articles from Factiva. Second, we provide a detailed description of the construction of our set of newspaper-based indices that were employed in the empirical analysis. Finally, we present a set of robustness checks for our empirical analysis of salience effects presented in Section 5.4.

D.1 Search strategies

Here below, we report the three different search strategies that were developed to download articles' count used in the construction of our indices. A brief description of each strategy will follow. *Strategy # 1* restricts our search to articles talking about environmental/ecological taxation. This provides us with a clearer idea of publishing trends directly related to environmental taxation and will be used to scale frequency counts of a more targeted search strategy that specifically captures price salience. Finally, *Strategy # 2* is employed to identify articles talking about environmental/ecological taxation *and* resulting in increases in fuel prices. Here, we use a double AND operator to impose that at least one keyword from each of the brackets that come after the operator must appear in the article.

Strategy #1: Environmental taxation trends. (Ökosteuer* or "Ökologische Steuerreform" or Umweltsteuer* or "Ökologische Finanzreform" or Umweltabgabe*)

Strategy #2: Eco tax price salience. (Ökosteuer* or "Ökologische Steuerreform" or Umweltsteuer* or "Ökologische Finanzreform" or Umweltabgabe*) AND (Dieselpreis or Benzinpreis) AND (Preissteigerung or Preisanstieg or Preiserhöhung or Anstieg or ansteigen or steigen or zunehmen or Zunahme or Erhöhung or erhöhen or anheben or aufschlagen or Aufschlag or angestiegen or zugenommen or erhöht* or angehoben or aufgeschlagen)

D.2 Using information in newspaper articles as an indicator of salience

For each newspaper, we separately downloaded the annual count of articles that are picked up by our search strategies. To account for publishing trends specific to the topic of environmental taxation, we begin by computing a simple newspaper-specific ratio of articles matching Strategy #2 over the frequency counts from Strategy #1. A challenge with these raw article ratios is that the number of articles varies a lot across newspapers and time, making it difficult to simply average the ratios across several newspapers. We, therefore, apply the standardization approach of Baker et al. (2016) to obtain our salience index.

We begin with the simple ratio of articles matching Strategy #2 divided by the total article counts for Strategy #1 for each newspaper, and then divide this ratio by the newspaper-specific standard deviation across all years. This creates a newspaper-specific time series with a unit standard deviation across the entire time interval, which ensures that the volatility of the index is not driven by the higher volatility of a particular newspaper. We then average these standardized series across all newspapers within each year. Lastly, we normalize the yearly series to a mean of 100 over the entire time interval to develop our main salience index. This procedure allows us to explicitly capture variation over time in the price salience of the eco-tax while accounting for newspaper-specific publishing trends concerning the topic of environmental taxation.

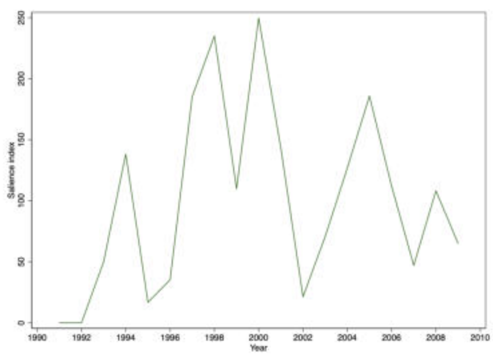


Figure D.1: Evolution of the salience index over time

D.3 Salience analysis: Robustness checks

Table D.1: Effects of salience on fuel cconsumption

(a) Gasoline consumption

	(1)	(2)	(3)	(4)
Raw price of Gasoline (only VAT)	-0.00266	-0.00282	-0.00280	-0.000497
	(0.00242)	(0.00179)	(0.00176)	(0.00130)
Energy Tax	-0.00610**	-0.00243	-0.00338	-0.00717
	(0.00234)	(0.00505)	(0.00489)	(0.00427)
Eco Tax	-0.00656	-0.0103	-0.00773	0.00947
	(0.00492)	(0.00632)	(0.00557)	(0.0105)
Eco Tax x Salience Index	-0.00531***	-0.00433**	-0.00441**	-0.00199**
	(0.00132)	(0.00203)	(0.00190)	(0.000739)
L.Eco Tax x Salience Index				-0.000459
				(0.00197)
L2.Eco Tax x Salience Index				-0.00622***
				(0.00208)
Dummy Eco Tax	-0.0227	0.0323	0.0135	-0.195
	(0.0399)	(0.0868)	(0.0738)	(0.116)
Trend	0.0153***	0.0296**	0.0198	0.0135
	(0.00391)	(0.0143)	(0.0221)	(0.0206)
GDP per capita		-0.0000274	-0.0000161	0.00000913
		(0.0000310)	(0.0000316)	(0.0000298)
Unemployment rate			0.0101	-0.00325
			(0.0256)	(0.0213)
N	38	38	38	37

(b) Diesel consumption

	(1)	(2)	(3)	(4)
Raw price of Diesel (only VAT)	-0.00306***	-0.00318***	-0.00326***	-0.00197***
	(0.000766)	(0.00103)	(0.000900)	(0.000620)
Energy Tax	-0.00103	-0.00537	-0.00723**	-0.00773**
	(0.00293)	(0.00337)	(0.00348)	(0.00342)
Eco Tax	-0.0119***	-0.00998***	-0.00818***	0.000528
	(0.00129)	(0.00232)	(0.00275)	(0.00367)
Eco Tax x Salience Index	-0.000999*	-0.00123	-0.00120*	0.000337
	(0.000497)	(0.000732)	(0.000689)	(0.000440)
L.Eco Tax x Salience Index				-0.00166*
				(0.000891)
L2.Eco Tax x Salience Index				-0.00187*
				(0.000971)
Dummy Eco Tax	0.0821***	0.0647**	0.0558*	-0.0411
	(0.0209)	(0.0309)	(0.0306)	(0.0343)
Trend	0.0356***	0.0262***	0.0184*	0.0177
	(0.00176)	(0.00611)	(0.00955)	(0.0105)
GDP per capita		0.0000131	0.0000210**	0.0000272**
		(0.0000101)	(0.00000995)	(0.0000106)
Unemployment rate			0.00636	0.00131
			(0.00894)	(0.00931)
N	39	39	39	37

Notes: The dependent variable is the log of fuel consumption in liters per capita, which refers to total fuel consumption or either gasoline or diesel consumption (as indicated by the column heading). Prices are in 1995€. Results for gasoline consumption refer to 1972-2009 due to missing price data prior to 1972. Unemployment is measured as percentage of total labor force. Newey-West standard errors in parentheses are heteroskedasticity and autocorrelation robust. Standard errors are calculated relying on the automatic bandwidth selection procedure following Newey and West (1994). * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

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