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Exiting the fossil world: The effects of fuel taxation in the UK

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Abstract

Carbon taxes remain economists favoured policy tool to curb emissions, but are unpopular among segments of the populations. Theoretical and numerical work tends to show the effectiveness of carbon taxes, but ex-post empirical analyses are still rare. In this paper we attempt to bridge this gap. We construct a theoretical general equilibrium model with dirty and clean transportation to show the static and dynamic effects of a fuel tax on transportation and consumption by deriving closed-form solutions. We take the predictions of the model to data on the UK Fuel Tax Escalator, and estimate the impact of the tax on CO2 emissions, GDP, and transport behaviour. With a potential control pool of OECD countries, we use the synthetic control method to estimate the difference between the observed outcome in the UK and a synthetic counterfactual UK. We find that the tax has a large and significant impact on CO2 emissions from traffic, while there is no discernable impact on GDP or growth. We do not find large changes in driving behaviours, but the available evidence points to a possible switch to rail travel from road travel.

Keywords: fuel tax, synthetic control method, climate policy, transport, level and growth effects.
JEL Classification: Q43, O47, Q56, O41

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1 Introduction

Taxation of carbon is the policy usually preferred by economists to combat climate change (Weitzman, 2014, Stiglitz, 2019). Yet, there are widespread concerns that fuel taxes are not very effective to curb emissions in important sectors such as transportation, where the transformation to a fossil-free system involves changing large networks on a global scale. Alternatives for road transportation lack attractiveness, and consumers have a tendency to persist in their mobility habits. Public protests have shown the public's dissatisfaction with what it considers unfair taxation, reflected in various studies (Hammar *et al.*, 2004; Baranzini & Carattini, 2017; Douenne & Fabre, 2019). For policy makers, supporting greener types of traffic often appears more attractive than taxation. In terms of policy effectiveness, the empirical estimates of price elasticities for fuel demand may be insufficient as a guideline for policy (Rivers & Schaufele, 2015). There is evidence that estimated elasticities vary with general economic circumstances and may thus not reflect the impact achieved by a policy under real conditions. What is more, carbon taxes are often seen as critical with respect to aggregate consumption, domestic production, and long-run economic growth, relating to the macroeconomic consequences of environmental policy (Bretschger, 2015).

Using the example of the UK fuel tax, the paper addresses the concerns about lacking or even negative impact of carbon taxes theoretically and empirically. The UK is a prime example as it relatively early adopted a rather strict approach to price-based environmental policy. Carbon emissions were peaking in the early 1990s and have declined since then by around 40%. It may be that for decarbonization, factors like structural change or international trade have been equally or even more important than policies. Hence, to obtain robust conclusions about the impact of taxation, it is necessary to compare development in one country with an appropriate control group, which we highlight in the main part of the paper.

We first construct a theoretical general equilibrium model with dirty and clean transportation to show the static and dynamic effects of a fuel tax by deriving closed-form solutions. We then present a broad empirical analysis of the different effects of a fuel tax, using the synthetic control method (SCM). Addressing the issue of a missing control group, this method is a quasi-experimental study of a carbon tax implementation with a synthetic control group of countries. Our results for the UK show that fuel taxes are a very efficient instrument to reduce fossil-based transportation and that they support public transport. We also show that there is no significant impact on consumption level and income growth.

The present paper complements the small but growing literature on ex-post evaluation of carbon taxes (Davis & Kilian, 2011). Several papers have explored the effects of the British Columbia tax. Xiang & Lawley (2019) find that the tax reduced residential gas consumption; Rivers & Schaufele (2015) find that the tax reduced gasoline consumption, and more so than other price changes would have. Addressing the concern that carbon taxes negatively affect employment, Yamazaki (2017) finds that while the tax indeed reduced employment in dirty sectors, it had an overall positive impact on jobs in the province. Several other papers similarly conclude that the BC carbon tax has been largely a success (Antweiler & Gulati, 2016). Other papers have explored the effect of the Swedish carbon tax (Andersson *et al.* (2015) looks at the effect on emissions from transport), the UK Carbon tax (Abrell *et al.* (2019) look at the effect on power plant emissions), gasoline taxes in the US (Li *et al.*, 2014). Lin & Li (2011) find that carbon taxes lowered emissions in Finland, but not in Norway, Sweden or Denmark.

As Andersson (2019), Yamazaki (2017) and Xiang & Lawley (2019), our paper relies on the synthetic control method (SCM) for identification. This method has been used for impact evaluation of taxes in several settings, including waste pricing (Bueno & Valente, 2019), tobacco taxation (Abadie *et al.*, 2010), international environmental protocols (Isaksen, 2018). To our knowledge, there has been no ex-post analysis of the fuel tax escalator. We also add to the literature by relating our empirical results to a general equilibrium model where the policy effects are derived from first principles.

The chapter is organized as follows. Section 2 examines the effects of a fuel tax by developing a theoretical model. Section 3 carries out an econometric analysis of the model, using the UK Fuel Duty escalator as a case study. Section 4 discusses the results, and section 5 concludes.

2 Theoretical Model

2.1 Model setup

The economy is populated by households who maximize utility U over an infinite time horizon which depends positively on a consumption bundle C and negatively on pollution stock P according to

$$U_t = \int_0^{+\infty} e^{-\rho t} \left[\frac{C_t^{1-\varepsilon}}{1-\varepsilon} - \phi P_t \right] dt, \tag{1}$$

where $\rho > 0$ is the rate of pure time preference, $-\varepsilon$ the elasticity of marginal utility of consumption ($1/\varepsilon$ the elasticity of intertemporal consumption substitution), $\phi > 0$ the pollution impact parameter, and t the time index. Consumption is composed of regular goods (X) and transportation (T) which is an aggregate of fossil-driven (F) and green (G) transportation. We write

$$C_t = X_t^{\alpha} T_t^{1-\alpha} = X_t^{\alpha} \left[\lambda F_t^{\frac{\sigma-1}{\sigma}} + (1-\lambda) G_t^{\frac{\sigma-1}{\sigma}} \right]^{\frac{(1-\alpha)\sigma}{\sigma-1}} \tag{2}$$

so that the elasticity of substitution between X and T is unity and the elasticity of substitution between F and G is $\sigma > 0$ while λ is the distribution parameter in the CES subfunction. Emissions E are caused by F with $E_t = \theta F_t$ ($\theta > 0$) and pollution stock is built up following $P_t = \int_0^{+\infty} (E_t - \Delta_t)\, dt$ where Δ_t is natural decay.

Households own capital stock K which earns an interest rate r; capital income and consumption expenditures determine the budget constraint. By combining Eqs. (1) and (2) and writing p_i for the price of good i, we obtain the Hamiltonian for the optimization, which we present in the Appendix, complemented by the first-order conditions. By combining these conditions and using g_C and g_P for the growth rate of consumer goods and their prices as well as $s \equiv \frac{p_F F}{p_T T}$, we obtain

$$g_C + g_P = \frac{1}{\varepsilon}(r - \rho) \tag{3}$$

$$\alpha = \frac{p_X X}{p_C C};\ 1 - \alpha = \frac{p_T T}{p_C C} \tag{4}$$

$$\frac{F}{G} = (\frac{\lambda}{1-\lambda})^{\sigma} \left(\frac{p_F}{p_G}\right)^{-\sigma} \tag{5}$$

$$\frac{p_F F}{p_G G} \equiv \frac{s}{1-s} = (\frac{\lambda}{1-\lambda})^{\sigma} \left(\frac{p_F}{p_G}\right)^{1-\sigma} \tag{6}$$

For the growth rate of aggregate (nominal) consumption we find the standard Keynes-Ramsey rule in Eq. (3). Once households have determined the intertemporal consumption pattern, they decide on disaggregated expenditures in each point of time. Following (4) the consumption expenditure share of regular goods is α and the share of transportation is also constant, $1-\alpha$. The modal split in transportation, F/G, is determined by the relative price of the two transport modes and the elasticity of substitution σ, see Eq. (5). Expression (6) shows that expenditure shares for fossil-based transport (s) and green transport ($1-s$) are determined by relative prices and the factor $1-\sigma$ which says that the expenditure share for a mode of transportation grows (shrinks) with its price when $\sigma < 1$ ($\sigma > 1$).

Firms produce regular goods by combining capital K and public services Q according to

$$X_t = K_t^{\beta} Q_t^{1-\beta} \tag{7}$$

with $0 < \beta < 1$. First-order conditions of profit maximization yield

$$\beta = \frac{rK}{p_X X},\ 1 - \beta = \frac{p_Q Q}{p_X X} \tag{8}$$

For simplicity, fossil-driven transportation (F) is supplied perfectly elastically at a price determined by the tax rate τ so that $p_{Ft} = \tau$,[2] while green transportation (G) is supplied perfectly elastically at a price which is given by the (exogenous) costs of green technology (solar, wind, batteries) i.e. $p_{Gt} = \bar{p}_G$.

Using the Cobb Douglas price index for consumption goods and applying the Wong-

[2]Cross-country data show that country price differences in fossil fuels are determined almost one hundred percent by the differences in taxes.

Viner envelope theorem for utility maximization in the transport sector, the percentage change in consumer price (denoted by a hat) as a function of percentage changes in fuel tax becomes

$$\hat{p}_C = (1-\alpha)s\hat{\tau}. \tag{9}$$

When revenues of fuel taxes are not redistributed in a lump-sum fashion to households, they have an impact on the allocation in the economy. Following the practice in the UK we posit that tax revenues are used by the government in the general budget to provide public services. Abstracting from taxes and public expenditures other than those related to fuels,[3] the budget constraint of the government reads

$$p_Q Q_t = \gamma \tau F_t \tag{10}$$

where p_Q is the price of services and $\gamma < 1$ denotes costs and inefficiencies of public service provision.

2.2 Policy impacts

We first derive the effect of a percentage change in fuel tax $\hat{\tau}$ on the change in fossil transports $\hat{F}$ in a static economy ($\dot{K}_t = 0$; $r = \rho$). Taking log differentials of the cost share s and of Eq. (6) we obtain $\hat{F} = [-\sigma(1-s) - s]\,\hat{\tau}$ which shows a negative effect of taxes as expected. But we also need to consider that expenditures for transports, $p_T T$, do not remain constant in general. With given prices for green goods, transports become more expensive with the tax so that prices for consumption rise. This reduces total consumption and, with it, the use of transport goods. Including Eqs. (A.2), (4), and (9) the total tax effect on fossils amounts to

$$\hat{F} = \left[-\sigma(1-s) - s\frac{1-\alpha(1+\varepsilon)}{\varepsilon}\right]\hat{\tau}. \tag{11}$$

The expression shows the well-known substitution effect i.e. it says that the higher is the substitution elasticity σ the greater is the negative effect of fuel taxes on fuel use. It also features the income effect: higher consumer prices reduce consumption

[3] Adding lump sum taxes and additional public spending to the model would not change the results and is thus omitted here.

with the negative effect depending on the elasticity of marginal utility of consumption, $-\varepsilon$. The sign of the term in square brackets on the rhs of Eq. (11) is unambiguously negative. Invoking Eq. (5) we find the effect of a percentage change in fuel tax $\hat{\tau}$ on green transports $\hat{G}$ to be

$$\hat{G} = \left[s \left(\sigma - \frac{1 - \alpha(1 + \varepsilon)}{\varepsilon} \right) \right] \hat{\tau} \tag{12}$$

showing that the substitution effect is weighted by the share of fossil-based transport s and the (negative) income effect is identical to the one for dirty transport F. Green transport increases in the fuel tax when substitution in the transport sector σ is high and the income effect is low, so that the expression in the round brackets becomes positive. The percentage change of consumption $\hat{C}$ is the net income effect of fuel taxes which amounts to $-\frac{1-\alpha}{\varepsilon}s$; it is unambiguously negative. With a lump-sum redistribution of tax revenue the negative income effect would be the aggregate effect on consumption. However, in the present model there is a supply effect in addition to the demand effect: tax revenues have a positive effect on public services which increases X-production (see Eq. (10)). Adding the supply effect by taking log differentials of Eq. (7) and using Eq. (6), the overall (static) effect of fuel tax change on consumption becomes

$$\hat{C} = \left[\alpha \left(1 - \beta\right) \Omega - \frac{1 - \alpha}{\varepsilon} s \right] \hat{\tau} \tag{13}$$

where $\Omega = (1 - s)(1 - \sigma) - (1 - 1/\varepsilon)(1 - \alpha)s$. The sign of Ω depends on the elasticity of substitution σ. Ω may become positive when the elasticity of substitution σ is smaller than unity, which supports raising public revenues from the fuel tax. $\sigma > 1$ is equivalent to $\Omega < 0$, which entails lower tax revenues, lower public services, and thus an unambiguously negative impact of carbon tax on output and income level.

We now turn to a dynamic economy ($\dot{K}_t > 0$; $r > \rho$). By employing Eqs. (3), (7), (8), and (10), we find consumption growth as

$$g_C = \frac{1}{\varepsilon} \left[\frac{\gamma \tau F_t}{K_t} - \rho \right] \tag{14}$$

so that, for any given $K > 0$, consumption growth g_C increases (decreases) with fuel tax revenues, τF_t, which increase with the fuel tax rate when we have $\hat{\tau} > -\hat{F}_t$ $\left(\hat{\tau} < -\hat{F}_t\right)$;

this is realised when the expression in square brackets in Eq. (13) is positive. It crucially depends on the size of Ω as above, so that an elasticity of substitution smaller than unity, $\sigma < 1$, supports the growth effects through an increase in public spending with a tax increase. Higher growth does not necessarily mean higher welfare because (i) with positive discounting and decreasing marginal utility of consumption, growth may become too high and (ii) we would have to include the negative impact of pollution stock on utility as given in Eq (1).

2.3 Hypotheses from theory

Equipped with the theoretical foundations of the last subsection, we can now proceed with the empirical estimations. Summarizing our findings on the significance of fuel tax impacts on transportation and on income and growth, we have the following relationships we want to carry to the data:

- $\partial F/\partial \tau < 0$, based on Eq. (11),
- $\partial G/\partial \tau > 0$, based on Eq. (12),
- $\partial C/\partial \tau \gtreqless 0$, based on Eq. (13),
- $\partial g_C/\partial \tau \gtreqless 0$, based on Eq. (14).

In the first two cases we test whether the empirics confirm the theoretical model with respect to the signs, while in the other two cases empirics should help us to establish the direction of the effects, which turn out to be ambiguous in theory.

With respect to the size of the different effects, we will relate the estimated results for transportation quantities F and G to recent empirical literature, while using the results with respect to consumption level C and consumption growth g_C to discuss the magnitude of central model parameters, such as the elasticity of substitution in the transport sector.

3 Empirical Evidence

Based on our theoretical predictions, we want to present evidence on the effect of a carbon tax on emissions, GDP, and transportation behaviour. This section will start by introducing the policy we based the case study on, i.e. the UK fuel tax escalator. We will then describe the synthetic control method used, before we present the results of testing the four hypotheses: first, the impact of the tax on emissions from dirty transport, second the impact on output (GDP) and growth, and finally on transport choices (road and rail travel).

3.1 Background on The Fuel Duty Escalator

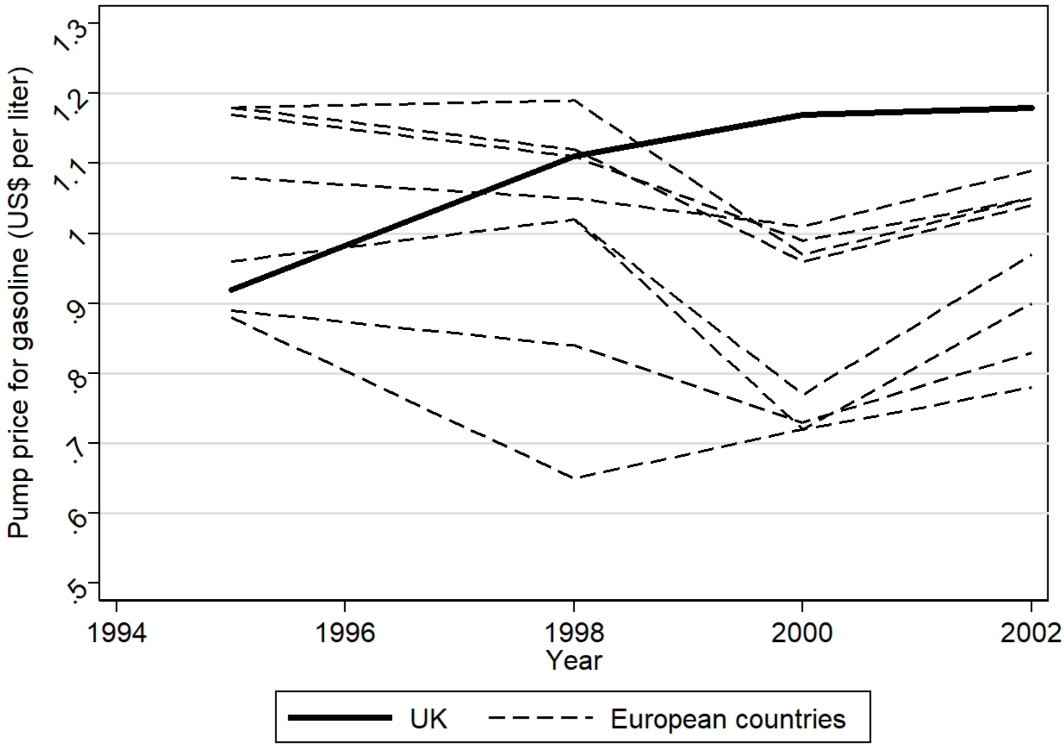
The fuel duty escalator was introduced by the conservative government in 1993, in response to rising air pollution. In order to reduce pollution and congestion, the tax on fuel was increased by 10% in 1993. Additionally, the government committed to an escalator of the tax - they would increase the fuel tax by 3% more than inflation per year. The increase in tax was substantial; between 1993 and 2000, UK gasoline prices went from among the lowest in Europe to the highest (BBC, 2017). Gasoline prices for the UK and other OECD countries from 1995 are shown in figure 1, where the black line shows the increase in the UK price. The UK is one of the few countries with consistently rising prices in the period we have data for.

The tax applied to all gasoline, with no exemptions for professional drivers. The sharp increase in prices was not well received by the public, particularly those employed in the transport sector, and large scale national protests erupted in 2000. This so-called “lorry strike”, lead by truck drivers, led the government to freeze the escalator in 2001. No subsequent government has opted to reinstate the escalator, and the tax has remained frozen at the 2001 level ever since.

3.2 Method

In order to create a counterfactual for the UK, we use the Synthetic Control Method introduced by Abadie & Gardeazabal (2003) and further developed by Abadie *et al.* (2010) and Abadie *et al.* (2015). The synthetic control method is a data driven approach to choosing the unit(s) to compare to the unit of interest. While a difference-in-difference approach is commonly used in cases like these, it has the disadvantage that it leaves it up to the researcher to pick suitable control units. In cases like ours, where we have one treated unit and several untreated ones, this can be problematic. No single country

Figure 1: Pump price of gasoline, UK and donor countries



Gasoline price in the UK bold line, donor countries grey lines (Source: World Bank)

recreates the pre-intervention path of the UK, nor does the average of the donors. Figure 2 shows the path of the UK compared to the average of the OECD countries. The pre-treatment emissions do not have the same trend, and thus the assumption of parallel trends needed for identification in a difference-in-difference framework fails. However, as we will show, the SCM allows us to use a weighted combination of countries to recreate the pre-intervention paths of the UK. Further, other methods attempt to difference out unobserved heterogeneity, whereas SCM uses matching on observables in an attempt to recreate the unobserved heterogeneity in the control unit. The method proceeds as follows.

Let $J+1$ be the number of countries in the sample. Let J=1 be the UK, and following Abadie *et al.* (2010) we will refer to the J other countries as the "donor pool" which we will use to create the synthetic UK.

In our case, we have $i = 1, ..., J+1$ countries and $t = 1, ..., T$ time periods. The number of pre-intervention periods is given by T_0, with $1 \leq T_0 \leq T$. The CO_2 emissions from transport in the UK under no treatment are given by Y_{1t}^N, while the emissions with treatment are given by Y_{1t}^{TAX}. We are interested in the treatment effect on the treated, which is given by $\alpha_t = Y_{1t}^{TAX} - Y_{1t}^{N}$. However, as these two quantities cannot be observed for the same t, we have to use the synthetic control method to construct an observable counterfactual Y_{1t}^{N}.

We construct the Synthetic UK with a convex combination of the untreated countries by assigning a vector of weights $\boldsymbol{W} = (w_2, ..., J+1)'$ where $0 \leq w_j \leq 1$ and $w_2 + ... + w_{J+1} = 1$. Each value of $\mathbf{W}$ represents a potential synthetic UK. We use the algorithm developed by Abadie *et al.* (2010) to choose the best fitting $\mathbf{W}$ based on pre-treatment characteristics of the UK and the donor pool.

Let $\boldsymbol{X_1} = (\boldsymbol{Z_1'}, Y_{11}, ..., Y_{1T_0})'$ denote a $(k \times 1)$ vector of pre-treatment characteristics, where Y here is emissions and Z are predictors of emissions. Let $\boldsymbol{X_0}$ denote a $(k \times J)$ matrix of pre-treatment characteristics for the donor pool countries. $\mathbf{W^*}$ is then chosen to minimize the distance between $\boldsymbol{X_1}$ and $\boldsymbol{X_0 W}$ using the following calculation:

$$||\boldsymbol{X_1} - \boldsymbol{X_0 W}||v = \sqrt{(\boldsymbol{X_1} - \boldsymbol{X_0 W})'\boldsymbol{V}(\boldsymbol{X_1} - \boldsymbol{X_0 W})} \quad (15)$$

where $\mathbf{V}$ is some $(k \times k)$ symmetric and positive semidefinite matrix. V assigns weights to the predictors so that more important predictors are given more weight. We follow Abadie *et al.* (2010), and allow for a data driven approach to choosing $\mathbf{V}$ among the set of positive definite and diagonal matrices which minimizes the Mean Squared Error (MSE) for the pre-treatment periods.

Large sample inferential techniques are not suitable for this type of comparative case study. Instead, we assess the significance of the impact through placebo tests where we use SCM on the other countries in our sample. Finding a large effect for the treated country relative to the non-treated lets us conclude that the Fuel Tax had an effect on the outcome variable.

3.3 Data

First, we want to test the effect of the tax on dirty transportation (hypothesis 1). The main variable of interest is CO_2 emissions from the transport sector. We use data from the World Bank on total CO_2 emissions and combine it with data on the fraction of emissions coming from the transport sector. This data is available for a large range of countries and time periods. Further, in order to guide the creation of counterfactual UK, we match on other variables that contribute to the level of CO_2 emissions. We include the level of human capital and GDP per capita, as we assume these indicate a certain type of economy correlated with emissions. Further, we include driving related indicators, namely the percent of population living in urban areas and gasoline consumption per capita. All variables are collected from the World Bank. Between these four variables we believe that we capture important elements contributing to CO_2 emissions, and will be able to recreate the path of the UK reasonably well. Following Abadie *et al.* 2010, we also include lagged values of the outcome variable - 1975, 1980, 1985 and 1990.

3.3.1 Choice of donor pool

We start by compiling a donor pool of countries similar to the UK. We start from OECD countries, as these are generally high-income democratic countries that should be similar to the UK. This list is somewhat shortened by the availability of data for gasoline consumption. We further exclude the countries that has introduced any carbon limiting policies: Norway, Sweden, Finland, and the Netherlands all introduced carbon- and/or fuel taxes in the 1990s, so including them would put a downward bias on our treatment effect. Following Andersson, 2019, we also exclude countries that are likely to have skewed emissions calculations due to fuel tourism, namely Luxembourg and Austria. This leaves us with 14 OECD countries in the final pool.

3.4 Results

In order to test the predictions from the theoretical model, we start by examining the impact the tax had on emissions from the transport sector. We relate this to the dirty transport in the model.

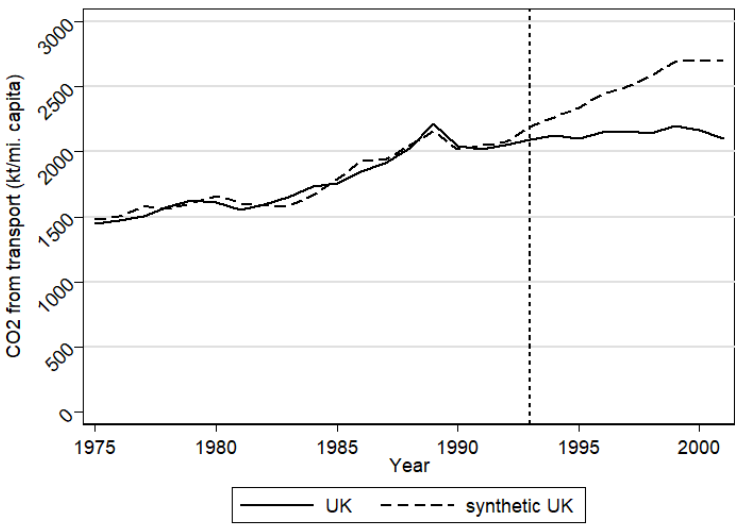
3.4.1 Hypothesis 1 & 2: The effect of the tax on CO2

The results of applying the SCM to the UK Fuel Tax Escalator are shown in figure 3. The figure shows the observed path of the UK (solid line) compared to the counterfactual

Figure 2: CO_2 from transport: UK vs OECD average

CO2 emissions per million capita from transport in kilotons

Figure 3: CO_2 from transport: UK vs Synthetic UK



CO2 emissions per million capita from transport in kilotons

Table 1: Weights, synthetic UK

Country	Weight
US	0
Canada	0
Ireland	.197
Belgium	0
France	0
Spain	0
Portugal	0
Italy	0
Greece	.253
Denmark	0
Japan	.176
Australia	0
New Zealand	.375

synthetic UK (dotted line), which is a linear combination of the J control countries. It is clear from the figure that synthetic UK does very well in recreating the pre-treatment path of the UK, indicating that the synthetic control estimator is indeed unbiased and captures the treated-specific unobserved heterogeneity from the UK.

The optimal weights, $\boldsymbol{W}$, are estimated by the algorithm developed by Abadie *et al.* 2010 and implemented using the SYNTH package (Abadie *et al.*, 2014). The weights are reported in table 1. We see that synthetic UK is a combination of three island states, Ireland, Japan and New Zealand, as well as Greece. Table 2 shows the mean values of the predictors for the observed UK, synthetic UK and the sample average, i.e. when all weights in $\boldsymbol{W}$ are equal. We see that Synthetic UK is generally closer to the UK than the sample average is, indicating a good fit.

Figure 3 shows that the fuel tax seems to have had a strong effect on emissions from transport: while the emissions in synthetic UK continue to grow, emissions in the UK hardly grow at all in the period. The gap between the UK and the synthetic UK is shown in figure 4. When the policy ends, the UK has emissions that are more than .500 metric ton lower than synthetic UK per capita. The average treatment effect in the treated time frame is 0.352 metric tons of CO_2 per capita.

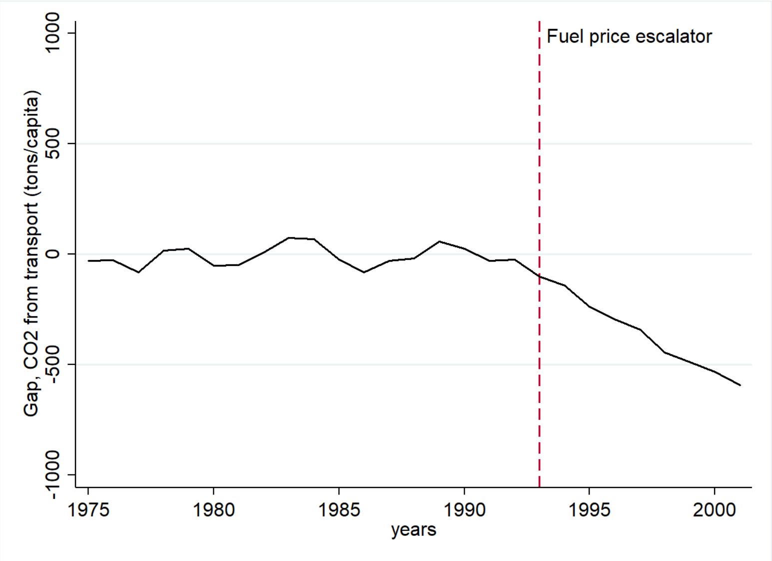
3.4.2 Inference: Placebo tests

SCM does not allow for traditional large sample inference methods. Instead, inference can be done by running placebo tests in space and time (Abadie *et al.*, 2010). The

Table 2: Predictor means for CO2 from transport

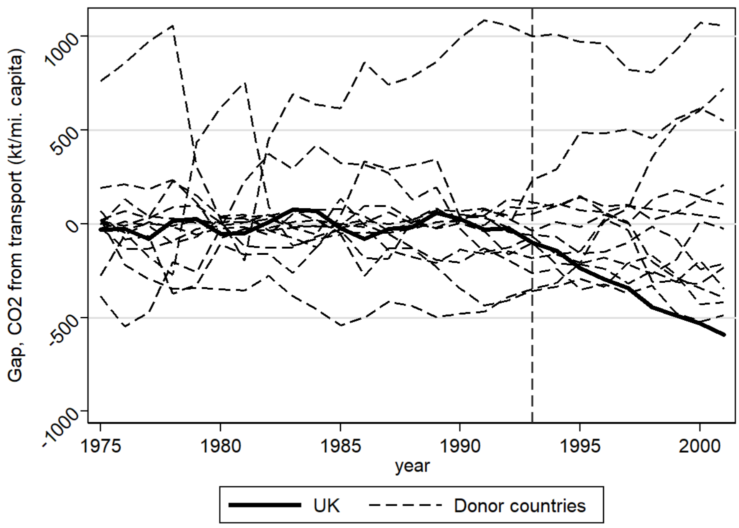
	Treated	Synthetic	Sample
Gasoline consumption per capita	6543.2	5866.1	7787
GDP per capita	21633.7	21187.2	27266
Urbanization rate	78.2	73.7	75.1
Human capital	3.1	2.9	2.9
CO2 from transport(1975)	1450.9	1480.7	1967.1
CO2 from transport(1980)	1610.9	1663.7	2233.5
CO2 from transport(1985)	1762.4	1787.4	2245.8
CO2 from transport(1990)	2043.0	2018.7	2451.4

Figure 4: CO_2 from transport: Gap between UK vs Synthetic UK



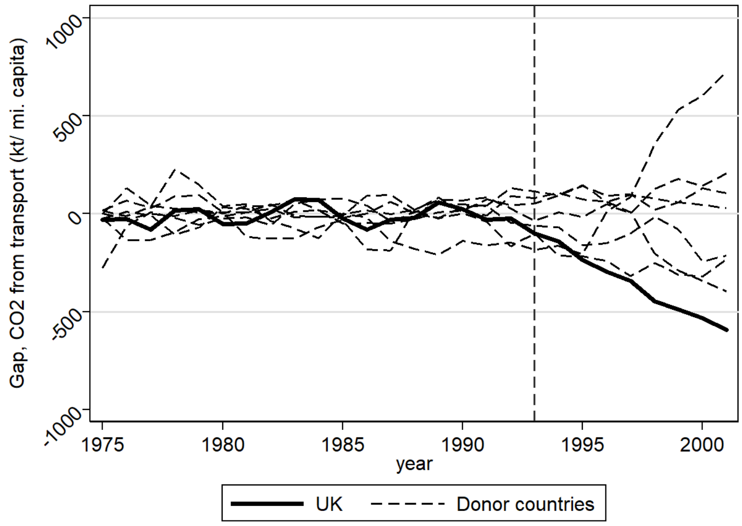
CO2 emissions per million capita from transport in kilotons

Figure 5: CO_2 from transport: Placebo tests in space, UK vs Donor countries



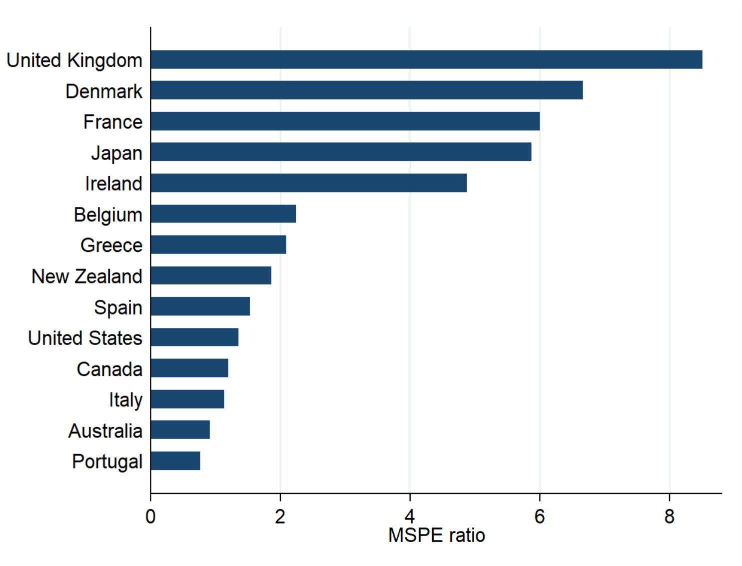
CO2 emissions per million capita from transport in kilotons

Figure 6: CO_2 from transport: Placebo tests in space, UK vs Donor countries (no outliers)



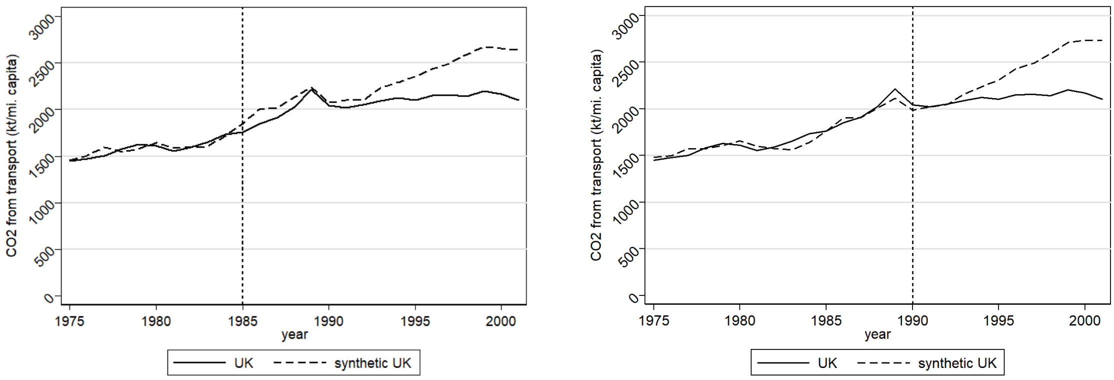
CO2 emissions per million capita from transport in kilotons, without countries with MSPE 5x of UK

Figure 7: CO_2 from transport: MSPE ratios, UK vs Donor countries



MSPE ratios pre/post treatment from placebo tests

Figure 8: CO_2 from transport: Placebo tests in time



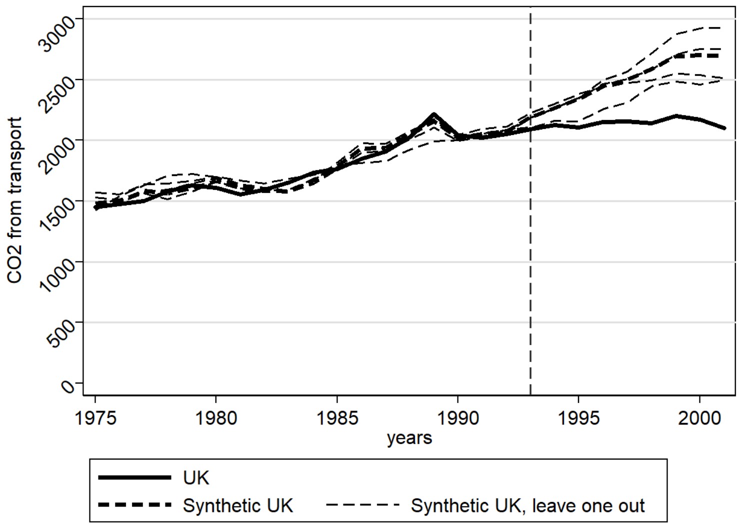
Treatment 1985 Treatment 1990

placebo in time is done by assigning the treatment to a date before it was actually assigned. If there was a large difference between the synthetic and observed UK before 1993, this would cast doubt on the validity of our results. Results are shown in figure 8, and, as expected, show no significant impact of the placebo treatment.

In the placebo tests, we run the same algorithm on all the countries in the sample, as this lets us see whether the gap between the UK and synthetic UK is particularly large. If other countries show the same or larger differences between their observed and synthetic outcome compared to the UK, that would indicate that the results may be driven by other things than the tax. The results are shown graphically in figure 5. We see that the UK has the largest negative gap to its synthetic counterpart.

In order to compare to standard hypothesis testing, we look at how big the pre-treatment to post-treatment MSPE ratio is compared to the rest of the sample. That is, we compare the effect in the UK to a randomly assigned treatment. If the gap in the UK is in the top percentiles of the sample, this indicates that a gap of this size is unlikely if the treatment is assigned randomly. As shown in figure 7, the UK has the largest post-treatment to pre-treatment MSPE ratio of all the countries. This places the UK in the top 7.1% of the sample, the highest percentile possible in the sample. This is comparable to a p-value of 0.071, and thus our results are statistically significant at the usual levels (see Abadie *et al.* (2010)).

Figure 9: CO_2 from transport: Leave-one-out



3.4.3 Robustness: Leave one out

In order to check the sensitivity of our results, we redo the analysis leaving out one of the countries that makes up synthetic UK. If the results are highly sensitive to the exclusion of one donor country, that could indicate that the results are driven by developments in this donor country. We plot the results in figure 9. The mean average treatment effect over the four permutations is a reduction of 325 tons/capita per year, which is just a little lower than in the main results.

3.4.4 Robustness: Difference-in-difference estimate

As a robustness check we also estimate the effect of the policy using the difference in difference (DiD) estimator. Table 3 presents the results of the DiD estimator. We see that the effect shown using DiD shows the same direction of the effect of the tax, i.e. it lowers emissions, but the estimate is smaller than the one we found using the SCM. This is likely due to the bias in the estimator from the failure of the matching pre-treatment trend assumption.

3.4.5 Hypothesis 3 & 4: The effect on GDP and growth

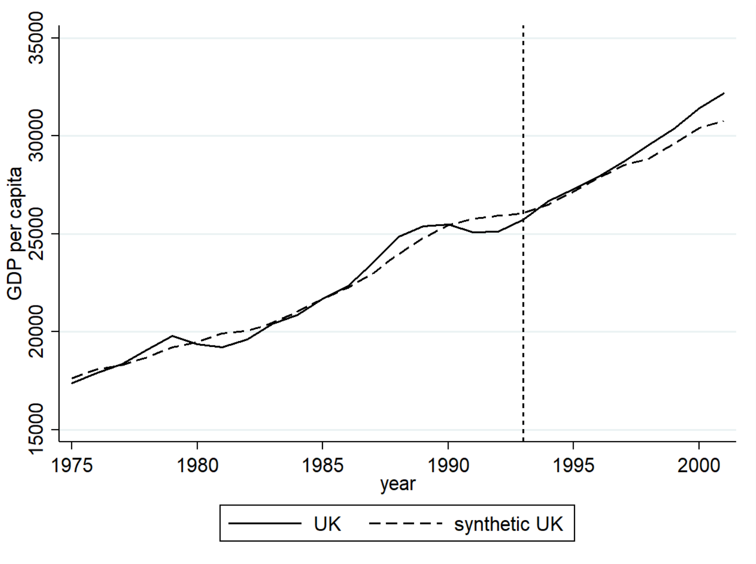
The model does not predict the direction of the effect of the tax on GDP, so we test this with data. Evidence on this effect is important, as one of the main criticisms of

Table 3: CO_2 from transport: DiD regression estimates (1975-2004)

VARIABLES	(1) CO2 from transport
Treatment dummy	-168.8*
	(82.80)
GDP per capita	0.0131
	(0.00799)
Gasoline consumption per capita	0.236***
	(0.00960)
Human capital	-432.9***
	(115.7)
Urbanization rate	11.69***
	(2.678)
Constant	263.6
	(152.2)
Time effects	Yes
Observations	420
R-squared	0.979

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

Figure 10: GDP per capita: UK vs Synthetic UK



carbon taxes is that they decrease growth and output.

We therefore run the SCM on GDP levels and growth for the UK. We use the same predictors as for emissions, and include four lags of GDP per capita instead of the lags of emissions. The results are shown in figure 10. The graph indicates a good pre-treatment fit. The effect of the tax on GDP appears negligible, but slightly positive. The average difference between the UK and its synthetic counterpart in the post treatment period is $511 per capita.

For inference, we again preform the placebo tests in space, shown in figure 11 and in time, in figure 12. We can see from the graph that the UK is somewhere in the middle of the sample, indicating that no unique changes in GDP were observed following the introduction of the tax. The placebo in time indicates a slightly worse fit for GDP than CO2, but no large impact in 1993 (figure 12). The MSPE ratio (not reported) shows that the effect in the UK is the fourth largest in a sample of 13. This means the effect is not statistically significant at any commonly used values.

We have shown that the level of GDP is not affected. As we also want to look at the effect the tax had on growth, we run the same SCM analysis as above on growth rates. The results are reported in figure 13. The figure reveals that this specification does not have a very good pre-treatment fit. Post-treatment it appears that there was no effect of the tax. Certainly, we find no evidence of the depressing effect of carbon taxes on GDP as often cited by opponents. The placebo tests further indicate no large effect on the UK (figure 14), and the MSPE ratio test ranks the effect on the UK as the fourth smallest out of all the countries. In appendix 6.2 we use the weights from section 3.4.1.

Between the two measures, we find no evidence that output or consumption growth were impacted by the tax. Further, that lets us conclude that emissions reductions were not driven by a fall in GDP. Rather, it appears that the tax triggered a change in the transport behaviour of consumers, prompting more environmentally friendly transportation choices. We explore this choice more in the next section.

3.4.6 Mechanisms for hypothesis 1 & 2: Transportation choices

The model predicts a substitution from dirty to clean transportation. The reduction in CO_2 emissions we found in section 3.4.1, combined with the results from section 3.4.5 of no significant effect on GDP, shows that this must have happened. We want to find the exact mechanism through which this happened. In order to test if people substituted private transport with public, we will use data on passenger kilometres travelled by rail and by road. Rail travel is considered as the clean, public transport, whereas road travel is considered as the dirty transport. While some road traffic could be clean (e.g. electric cars, bus), we assume that most road traffic is polluting.

Unfortunately, the data availability restricts us to only 8 countries. This means that even if the UK sees the largest effect in the sample, the amount of placebo tests we are able to run will not be sufficient for a p-value below the normal cutoff. However, SCM can still be informative as bias in the estimator decreases in the number of pre-treatment periods rather than in J, and we proceed with the analysis.

The data is only available from 1980 and onwards. We use human capital, urbanization rates, GDP per capita and emissions from transport, along with three lags of the dependent variable (1980, 1985, and 1992) as predictors.

The results for rail travel are shown graphically in figure 15. The results indicate that rail travel in the UK increased significantly compared to the synthetic UK. However, the placebo test reveals that Portugal, when assigned the same treatment, saw a larger increase. The post- to pre-MSPE ratio is also higher for Portugal, which means the effect on the UK is in the 25th percentile of the sample. Therefore we cannot conclude that the tax had a statistically significant effect on rail travel.

Further, the UK started large scale restructuring and privatization of the rail system in 1995, so we cannot confidently say that the results are not driven at least in part by this reform. Considering the difference in scale of the two transportation modes, it is unlikely that the rail policy had a large impact on CO_2 from transport.

We also look at the effect the policy had on road travel, reported graphically in figure 17. The pre-treatment fit is fairly good. The post-treatment effect is negligible; there is no evidence that road traffic was significantly reduced. The placebo tests also indicate that nothing significant happened in driving behaviour in the UK following the tax. Again, the small sample size makes these results less reliable than the other results.

Note that road travel is much more common that rail travel. The observed 30% increase in rail travel only constitutes 200 passenger km per capita; tiny relative to the

12000 annual passenger km by road.

The mechanism that decreased the emissions from transport is not shown conclusively in these results. It is interesting to note that the evidence from the road kilometres travelled does not indicate a significant drop relative to the synthetic UK; it does not appear that the tax made people reduce the distance travelled by road. It seems the emission reductions would be due to more environmentally friendly driving and/or more efficient vehicles, rather than large scale restructuring of travel habits.

4 Discussion

The impact of fuel taxes on emissions is negative as expected and significant in magnitude; the reduction for the considered years amounts to 0.352 metric tonnes per capita. The study on the Swedish transport sector of a tax of roughly similar magnitude by Andersson (2019) found a comparable number – an average reduction of 0.29 metric tonnes per capita – which makes us confident that the magnitude derived in this study is reasonable.

The empirical test of the impact of carbon taxes on non-dirty transportation has been less successful because of the lack of sufficient data. Nevertheless, we were able to detect an apparent increase in public transportation as a consequence of the launching of carbon taxation which corresponds to general expectations and the findings of the theoretical model.

The lack of evidence supporting an effect of carbon taxes on income is important for the political debate; it is often claimed that there is a negative impact. The net impact of zero can be interpreted in terms of the model parameters as expressing that supply and demand effects of taxation cancel. Comparing this to our model and especially to Eq. (13), it would mean that $\alpha\,(1-\beta)\,\Omega = \frac{1-\alpha}{\varepsilon}s$ which depends on elasticity of substitution in the transport sector being below unity, i.e. $\sigma < 1$. Otherwise, a substantial supply side effect does not emerge to counteract the negative demand effect. Of course, the smaller the demand effect, the lower is the required productivity effect via fuel taxation.

In a system with redistribution of tax revenues directly to households, a similar neutrality of fuel taxes on total consumption could emerge, but the mechanism would be different from the one in the UK that we have described in this paper.

Interestingly, according to our results, the UK fuel tax had no impact on the economic growth rate – despite the importance of transportation and the significant tax rate. Again, this indicates that the negative demand effect was compensated by a positive supply effect, i.e. the increase in public services financed by fuel tax revenue was able to counterbalance the loss in purchasing power of households. It points to the important issue of tax revenue spending when evaluating carbon taxes. When revenue is used to increase productive activities, the economy benefits from a higher capital return, which supports savings and investment. On the contrary, when revenue is redistributed to the public, e.g. on a per capita basis, the possibly negative distributional impacts of environmental policy can be addressed in a powerful manner.

5 Conclusion

In this paper we have explored the effect of a carbon tax on transportation theoretically and empirically. In a general equilibrium model we derived the effects of the tax on dirty transport, GDP, and transport mode choice. The results indicated that a switch from dirty to clean(er) transportation lowered emissions, but remained agnostic on the effect on output and consumption growth. We tested this using SCM on CO_2 emissions from the transport sector, finding that the tax reduced emissions by about 0.3 tonnes per capita relative to the synthetic UK in an average treated year. Using the same method on the level and growth rate of GDP, showed that the tax succeeded in lowering emissions without impacting output. We attempted to further test whether the tax caused a shift from polluting road travel to rail travel, and found that the data does indicate this but that the results are not statistically significant.

Our paper thus provides evidence to support implementing carbon taxes. Using ex-post empirical analysis founded in a theoretical model, we have shown that the Fuel Tax escalator fulfilled its purpose - it lowered emissions. Thus we have addressed a common grievance related to carbon taxes: if the tax is substantial enough to have a significant impact on emissions, it will negatively affect output and growth. Our results show that for the UK Fuel Duty Escalator this does not hold. The tax did lower emissions, and did so without negatively affecting the macro-economy.

Figure 11: GDP per capita: Placebo tests in space, UK vs donor countries GDP level

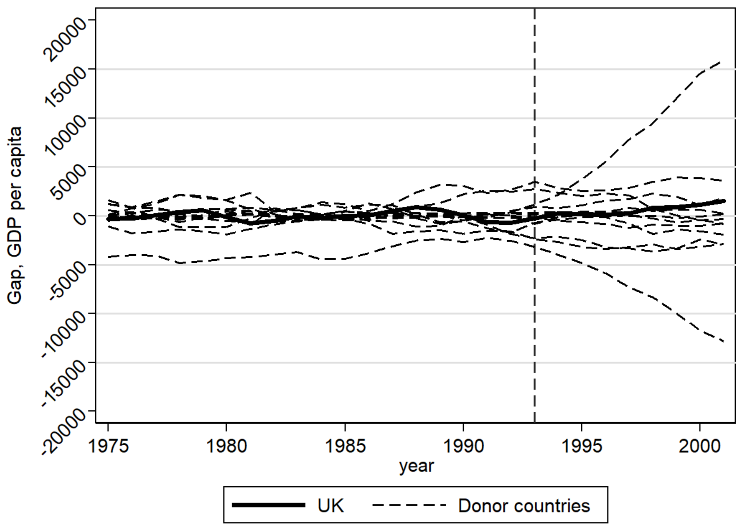
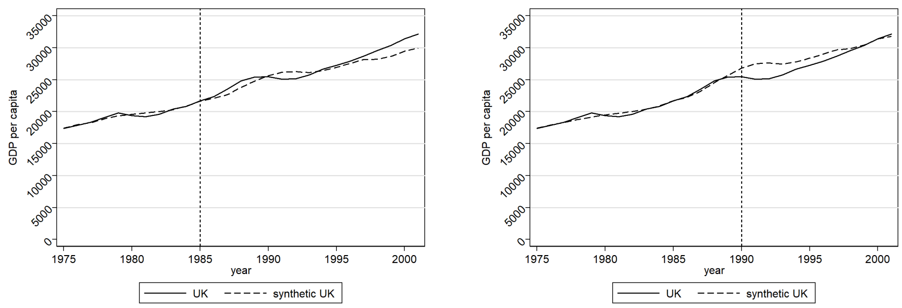


Figure 12: GDP per capita: Placebo tests in time, UK vs donor countries GDP level



Treatment 1985

Treatment 1990

Figure 13: GDP growth: UK vs Synthetic UK

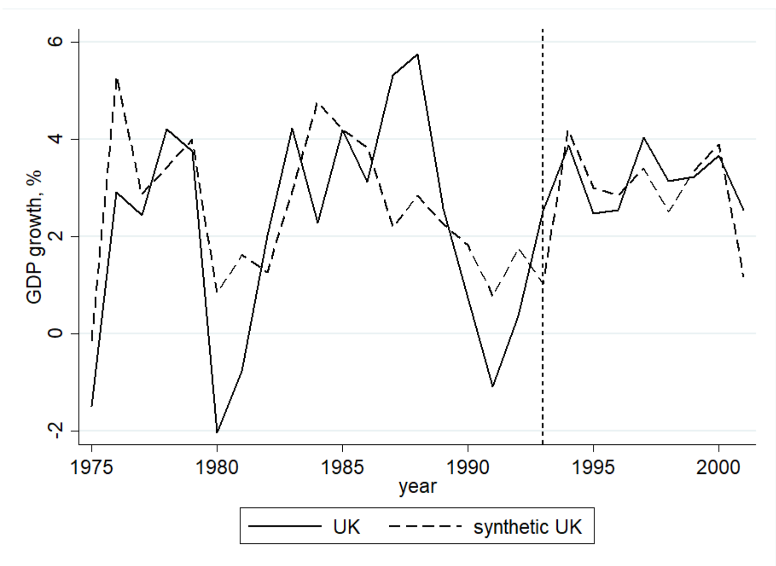


Figure 14: GDP growth: Placebo tests in space, UK vs donor countries GDP growth

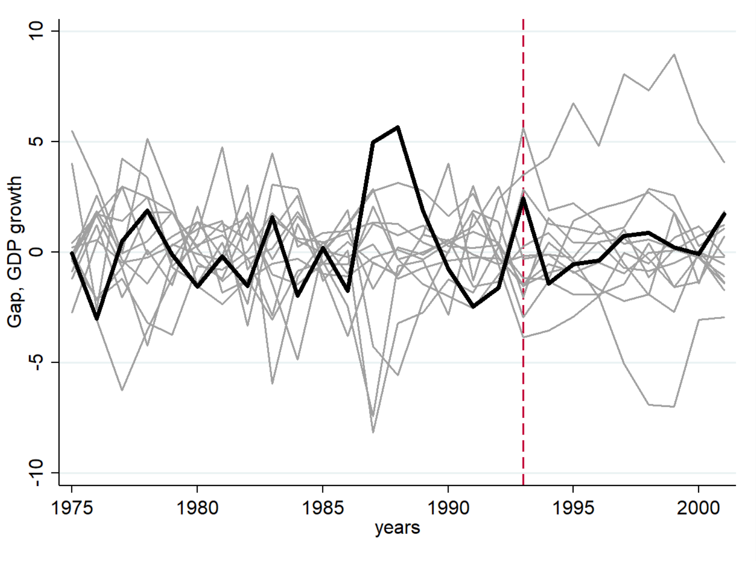


Figure 15: Passenger km travelled by rail: UK vs Synthetic UK

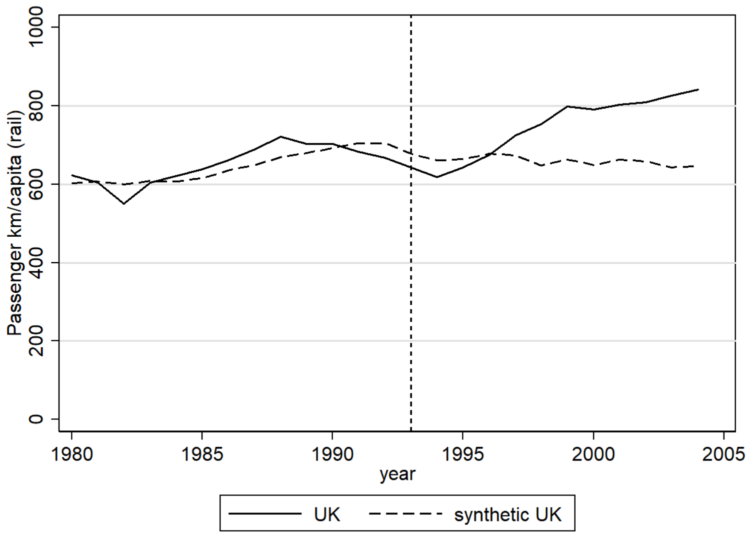


Figure 16: Passenger km travelled by rail: Placebo tests in space, UK vs donor countries

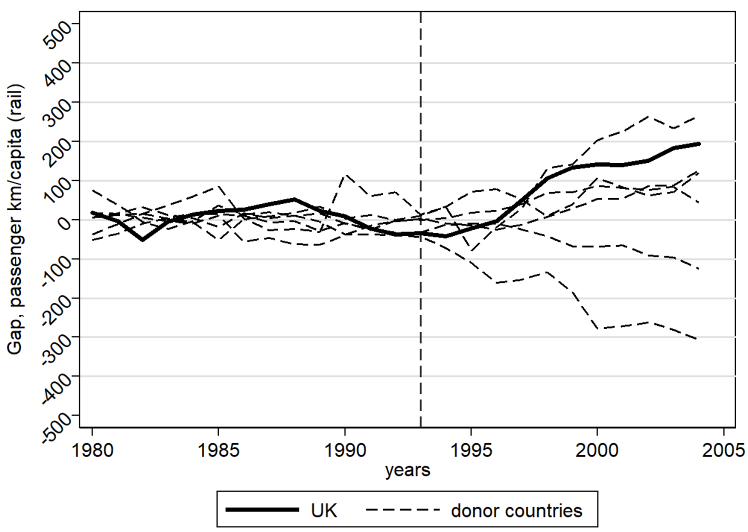


Figure 17: Passenger km travelled by road: UK vs Synthetic UK

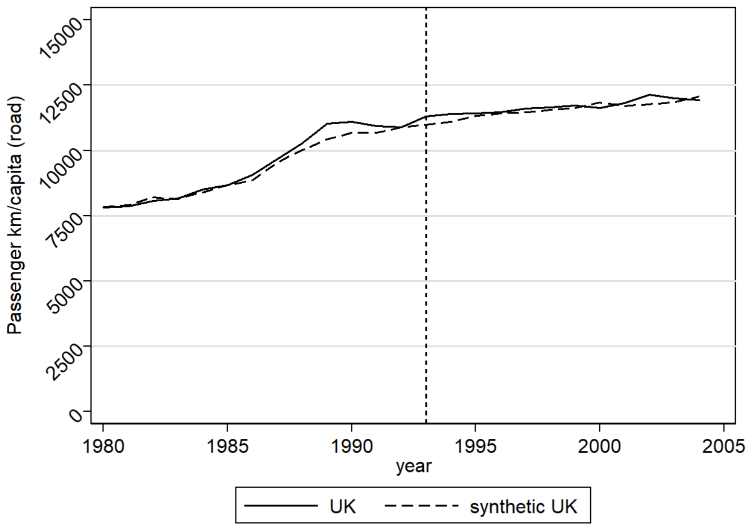
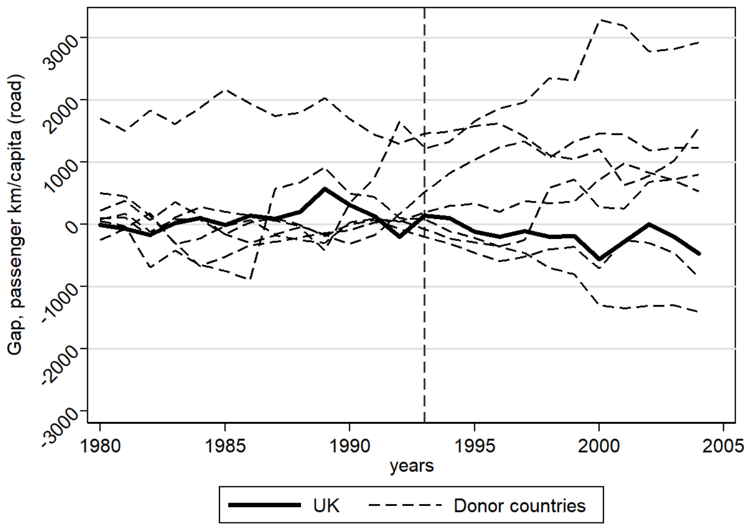


Figure 18: Passenger km travelled by road: Placebo tests in space, UK vs donor countries



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6 Appendix

6.1 Household optimization

The current-value Hamiltonian for the optimization of the households

$$H = \frac{X_t^{\alpha(1-\varepsilon)}}{1-\varepsilon}\left[\lambda F_t^{\frac{\sigma-1}{\sigma}} + (1-\lambda) G_t^{\frac{\sigma-1}{\sigma}}\right]^{\frac{(1-\varepsilon)(1-\alpha)\sigma}{\sigma-1}} - \phi P + \mu\left[rK - p_C C\right] \tag{A.1}$$

which includes the state variable K and the control variables X, F, and G and where $p_C C = p_X X + p_F F + p_G G$; μ is the costate variable. In the decentralized equilibrium, the impact of fossil-based transportation on pollution stock is not considered by the households. Using the aggregates C and T and by denoting by s the expenditure share of F in terms of expenditures for T goods ($s = p_F F / p_T T$) the first-order conditions of this problem read

$$H'(C) = 0 \Longleftrightarrow C^{-\varepsilon} = \mu p_C \tag{A.2}$$

$$H'(X) = 0 \Longleftrightarrow -\varepsilon\alpha X^{\alpha-1} T^{1-\alpha} = -\varepsilon\alpha\frac{C}{X} = \mu p_X \tag{A.3}$$

$$H'(T) = 0 \Longleftrightarrow -\varepsilon\left(1-\alpha\right) X^{\alpha} T^{-\alpha} = -\varepsilon\left(1-\alpha\right)\frac{C}{T} = \mu p_T \tag{A.4}$$

$$H'(F) = 0 \Longleftrightarrow -\varepsilon\left(1-\alpha\right) X^{\alpha} T^{-\alpha}(\partial T/\partial F) = \mu p_F \tag{A.5}$$

$$H'(G) = 0 \Longleftrightarrow -\varepsilon\left(1-\alpha\right) X^{\alpha} T^{-\alpha}(\partial T/\partial G) = \mu p_G \tag{A.6}$$

$$H'(K) = \rho\mu - \dot{\mu} \Longleftrightarrow r\mu = \rho\mu - \dot{\mu} \tag{A.7}$$

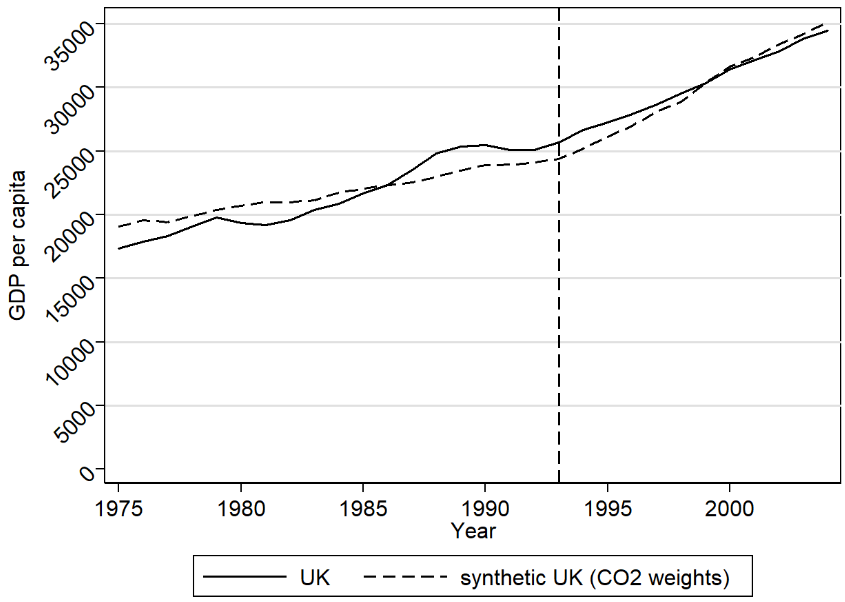
6.2 Robustness checks

6.2.1 GDP with weights from the CO2 estimation

In the main text we reesitmated the weights for the synthetic UK in order to get the best pre-treatment fit. We did this as we are interested in the effect the tax had on GDP in its own right. However, as a robustness check we also show the results when using the weights from the previous estimation. GDP can be a confounding factor in the previous section. If there were a simultaneous drop in GDP and emissions immediately following the introduction of the tax, this could cast doubt on the validity of the estimates from the previous section.

Results are reported in figure 19, and show that the synthetic UK may have grown at a slightly higher rate than the UK. This may mean that the results of the main analysis are somewhat overestimated. However, as the relative difference in the emissions are much larger than in GDP, we remain convinced that the tax was effective.

Figure 19: Effect of tax on GDP, using weights from CO2



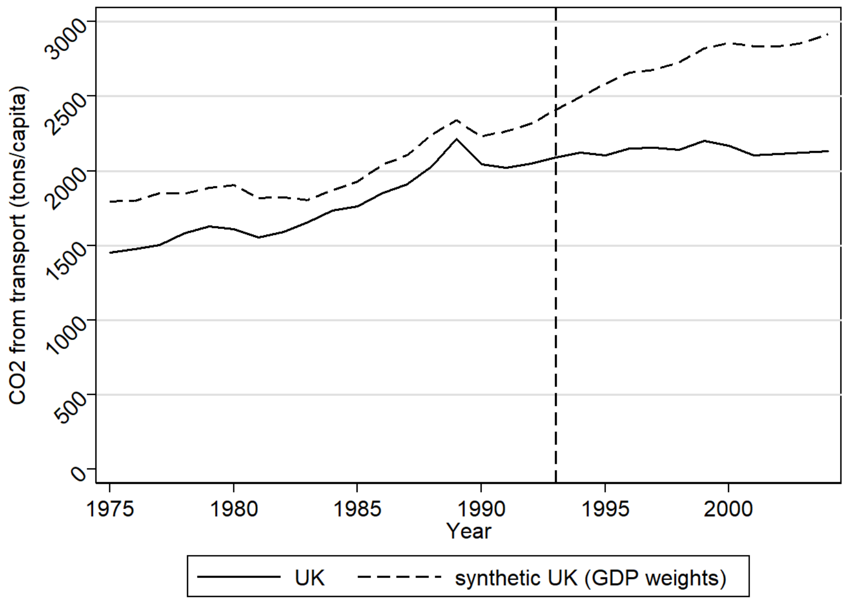
6.2.2 CO2 from transport with weights from the GDP estimation

We further check whether using the weights calculated from the GDP estimations show different results. The results are reported in figure 20. They show a worse fit for emissions, but show that from 1980 to 1992 the UK had a similar trend to synthetic UK, and that after 1993 the trend flattened out for the UK but not for the synthetic UK. These results are thus similar to our main estimation, indicating that the tax indeed reduced emissions relative to the synthetic control.

6.2.3 Gasoline consumption

We have shown that the fuel tax reduced emissions from road transport. As this should correspond to a roughly similar reduction in gasoline consumption per capita, we apply the weights calculated in the main analysis to gasoline consumption per capita. Results are reported in figure 21. The graph indicates that the gasoline consumption in the UK was reduced after the Fuel Tax Escalator was implemented, while that of the synthetic

Figure 20: Effect of tax on CO2 emissions from transport, using weights from GDP



control continued growing. However, the fit for gasoline consumption is worse than for emissions. The trends for the UK and its synthetic control do not appear to be similar until 1985, and then around 1990, the UKs gasoline consumption flattens out. This may be due to an increase in the fuel levy in 1990 which was similar to that of the escalator, but not a part of the same policy. While these results appear less robust than the main ones, they do not contradict that the policy had an effect on gasoline consumption. We thus do not revise our main conclusion that the tax had a negative effect on CO2 emissions from traffic.

6.3 Data sources

Data sources reported in table 4.

Figure 21: Effect of tax on gasoline consumption, using weights from CO2

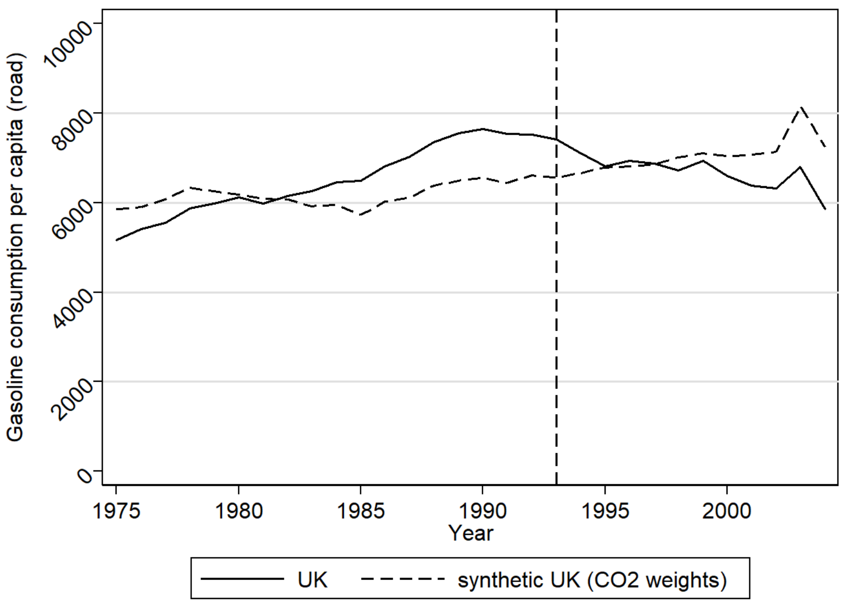


Table 4: Data sources

Variable	measured in	source	available at
Pump price for gasoline	USD	GIZ & World Bank	https://data.worldbank.org/indicator/EP.PMP.SGAS.CD
CO2 emissions from transport	Metric tons per capita	World Bank WDI Database	https://data.worldbank.org/indicator/EN.CO2.TRAN.ZS
GDP per capita	millions of 2011 USD	Penn World Tables	https://data.worldbank.org/indicator/NY.GDP.MKTP.CD
Urbanization rate	Percentage of total population	World Bank WDI Database	https://data.worldbank.org/indicator/SP.URB.TOTL
human capital	Index	Penn World Tables	
Passenger km travelled by rail	Millions of passenger-kilometres	International Transport Forum	https://doi.org/10.1787/g2g5557f-en
Passenger km travelled by road	Millions of passenger-kilometres	International Transport Forum	https://doi.org/10.1787/g2g5557f-en
Gasoline consumption	Kg of oil equivalent	World Bank WDI Database	https://data.worldbank.org/indicator/IS.ROD.SGAS.PC

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