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Cars, Carbon Taxes and CO_2 Emissions

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Abstract

Is a carbon tax effective in reducing emissions of greenhouse gases, and thereby mitigating climate change? This paper is one of the first empirical analyses of this question and the first to find a significant causal effect on emissions, using a quasi-experimental study of the implementation of a carbon tax and a value added tax on transport fuel in Sweden. The results show that, after the introduction of the taxes in the early 1990's, carbon dioxide emissions from the Swedish transport sector are reduced by around 11 percentage points in an average year relative to a comparable synthetic control unit, with a 6 percentage points reduction from the carbon tax alone. Importantly, I also find that the carbon tax elasticity of demand for gasoline is three times larger than the price elasticity. This finding suggests that ex-ante policy evaluations of carbon taxes, which use existing price elasticities of demand to simulate emission reductions, may significantly underestimate their true effect.

JEL classification: Q58, H23

Keywords: Carbon tax, transport sector, synthetic control method, climate change

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1 Introduction

In Paris in 2015, countries renewed their commitment to address climate change. As part of the Paris Agreement, each country put forward a ”nationally determined contribution” (NDC) towards the common goal of limiting global warming. This bottom-up approach of voluntary pledges will likely shift the focus away from international mitigation policies, such as the Kyoto Protocol, to national policies. At the centre of these national mitigation policies should be an effort to put a price on greenhouse gas (GHG) emissions such as carbon dioxide (CO_2), indirectly by issuing tradeable emission permits or directly through a carbon tax[1] (Arrow et al., 1997; Howard and Sylvan, 2015; IMF, 2016a). Comparing the two instruments, most economists favour a carbon tax over tradeable permits (see e.g. Nordhaus 2008, 2013 and Weitzman 2015, 2016). Public support for carbon taxes, however, are generally low and people tend not to believe that they are environmentally efficient, although when provided with evidence that they indeed reduce emissions, the support for carbon taxes increases (Murray and Rivers, 2015; Carattini et al., 2016). However, few countries have implemented carbon taxes and there are, surprisingly, even fewer ex-post empirical studies of their causal effect on emissions to draw from (Davis and Kilian, 2011; Baranzini and Carattini, 2014; Sterner, 2015). The lack of empirical studies of carbon taxes are unfortunate given the urgency of tackling climate change, and relying on less efficient measures may make it hard to reach current targets (the NDCs), not to mention the even more ambitious abatement targets that are needed if we are serious about curbing warming to no more than 2°C above pre-industrial levels. Correctly estimating the effectiveness of carbon taxes empirically is thus important for shoring up much needed public support, as well as ensuring that environmentally and economically efficient mitigation policies are adopted across countries by the diffusion of lessons from national climate policies worldwide (Carraro et al., 2015)

I investigate empirically the environmental efficiency of carbon taxes by analysing the Swedish experience of introducing a carbon tax and a value-added tax (VAT) on transport

[1] The purpose of a carbon tax is to reduce emissions by equalizing the private and social cost of releasing carbon.

fuels in the early 1990s. Sweden was one of the first countries in the world to implement a carbon tax in 1991. It was introduced at the level of US$30 per ton of CO_2 and then successively increased to today's rate of US$132, currently the highest carbon tax in the world (Kossoy et al., 2015). In the year prior, in March of 1990, Sweden also added VAT of 25% to the price of gasoline and diesel (Swedish Parliament, 1989-1990). The VAT is applied to all components of the retail price: the production cost of the transport fuel, producer margin, and any added excise taxes.

Since Sweden implemented a carbon tax as early as 1991, we are provided with an excellent opportunity to analyse its effect by using ex-post data, and the size of the tax makes it easier to clearly identify its impact on emissions using empirical methods. In the first half of this paper, I show that the introduction of the carbon tax and the VAT had a significant effect on CO_2 emissions from the Swedish transport sector in the years 1990 to 2005; the chosen post-treatment period of interest in this paper.

Although the Swedish carbon tax was implemented quite broadly, some sectors of the economy, especially industry and agriculture received a lower rate in 1993 and onwards due to concerns of international competitiveness, and fuels used for electricity production are fully exempted from paying the tax (Johansson, 2000). Consequently, when evaluating the environmental efficiency of the tax it is not advisable to look at *total* CO_2 emissions since many units in the economy do not receive the 'treatment'.[2] Fortunately, the transport sector, Sweden's largest source of CO_2 emissions, is fully covered[3] by the carbon tax and thus a suitable sector to analyse. From 1990 to 2005 the sector was responsible for close to 40% of annual CO_2 emissions (Ministry of the Environment and Energy, 2009).

I estimate empirically the reduction of CO_2 emissions using panel data and two separate identification strategies: a differences-in-differences (DiD) approach and the synthetic control method (Abadie and Gardeazabal, 2003; Abadie, Diamond, and Hain-

[2]Two underlying assumptions in analyses of causal effects are (1) no interference between units, and (2) all treated units receive the same dose of the treatment. If total CO_2 emissions are the dependent variable in our analysis, then clearly assumption (2) is violated.

[3]Fuels used for domestic aviation is exempt from energy and carbon taxation as well as VAT. However, domestic aviation is only responsible for 3.5% of transport's CO_2 emissions (Hammar and Åkerfeldt, 2011).

mueller, 2010, 2015). The DiD approach constructs the counterfactual using an unweighted average of CO_2 emissions from transport from a carefully chosen control group of OECD countries. The synthetic control method uses the same donor pool of OECD countries but creates instead a synthetic Sweden: a comparable unit consisting of a weighted combination of countries that did not implement carbon taxes, or similar policies, but had similar pre-treatment trajectories of CO_2 emissions in the transport sector. The DiD approach provides an estimated emission reduction from the transport sector of 8.1%, or 1.9 million metric tons in an average year during 1990 to 2005. The synthetic control method provides a larger estimate, a 10.9%, or 2.5 million metric tons reduction. As will be evident later, there are multiple reasons to why we would prefer to use the synthetic control method over the DiD framework in this case.

Not relying on empirical ex-post data, most studies of the environmental effect of carbon taxes are instead ex-ante (or ex-post) simulations, using available price elasticities of demand to estimate reductions in consumption of transport fuel and energy, two major sources of emissions (Andersen, Dengsøe, and Pedersen, 2001; Baranzini and Carattini, 2014). There are however a number of problems with these simulation analyses. Firstly, there is growing evidence that consumers respond more strongly to tax changes than prices changes, especially in the gasoline market (Davis and Kilian, 2011; Li, Linn, and Muehlegger, 2014; Rivers and Schaufele, 2015; Antweiler and Gulati, 2016). That tax elasticities of demand are larger than corresponding price elasticities are often referred to as the 'salience' or 'persistence' of taxes. Simulations that use price elasticities of demand thus underestimate the true causal effect of carbon taxes on CO_2 emissions. Secondly, existing analyses of transport markets focus only on changes in demand for one type of fuel and don't account for substitution between fuels, most notably from gasoline to diesel. A failure to capture this substitution will bias the results (Davis and Kilian, 2011). Lastly, simulations (and earlier ex-post empirical studies) have struggled with creating a convincing counterfactual – the emission level that would have existed in the absence of taxes (Bohlin, 1998; Bruvoll and Larsen, 2004; Lin and Li, 2011).

In the second half of the paper, I analyse the question of 'salience' by estimating tax and price elasticities of demand for gasoline in Sweden.[4] To this end, I use time-series analysis of the consumption and price of gasoline in Sweden during 1970 to 2011. Exploiting yearly changes to the carbon tax rate and the carbon tax-exclusive price of gasoline (the total gas price minus the carbon tax) I find that the carbon tax elasticity of demand is around three times larger than the price elasticity.

Using the estimated tax and price elasticities I then disentangle the effect of the carbon tax on emissions from the effect of the VAT. From the carbon tax alone I estimate a post-treatment reduction of 6.3%, or 1.5 million metric tons of CO_2 emissions in an average year. This result is in contrast to earlier empirical studies that find no effect from the Swedish carbon tax on domestic transport CO_2 emissions (Bohlin, 1998; Lin and Li, 2011), and the estimated reduction is 40% larger than an earlier simulation study finds (Ministry of the Environment and Energy, 2009). In fact, my finding differs from all the earlier empirical studies which find that carbon taxes have had very small to no impact on CO_2 emissions in the countries that implemented them (Bohlin, 1998; Bruvoll and Larsen, 2004; Lin and Li, 2011). This is thus the first quasi-experimental study to find a significant causal effect of a carbon tax.

The evidence from Sweden indicates that there is a significantly larger behavioural response to changes to the carbon tax rate than to equivalent gasoline price changes. This finding is in line with previous empirical evidence of the salience/persistence of gasoline taxes, where changes to tax rates have been found to create two and a half to four times larger demand responses (Davis and Kilian, 2011; Li, Linn, and Muehlegger, 2014; Rivers and Schaufele, 2015; Antweiler and Gulati, 2016), a difference observed to persist over the long run (Li, Linn, and Muehlegger, 2014). Multiple explanations have been given to account for this finding. Davis and Kilian (2011) and Li, Linn, and Muehlegger (2014) discuss 'salience', the fact that tax changes often are accompanied by media coverage, thereby notifying consumers about the change in price; and 'persistence', the fact that tax changes are more long-lasting (and upwards-trending (Hammar, Löfgren, and Sterner, 2004)) than oil-induced changes to the price of transport fuel. Furthermore, Antweiler

[4] I focus on gasoline since 95% of CO_2 emissions in the transport sector come from road transport (Ministry of the Environment and Energy, 2009), where gasoline is the main fuel used (see Figure 2).

and Gulati (2016) suggests that it might be due to the difference between making buying decisions under certainty versus uncertainty – the tax part of the gasoline price being stable and certain compared to the volatile and uncertain part driven by fluctuations in crude oil prices. Lastly, Rivers and Schaufele (2015) refer to other-regarding preferences and a resentment of free-riding – the carbon tax eliminates the opportunity to free-ride on an environmental public good provision – to explain the larger behavioural response that the carbon tax produces.

If changes to carbon tax rates induce larger demand responses than equivalent price changes – at least in the transport market – this has an impact on climate change policies, as well as numerical calibrations of optimal gasoline taxes (see e.g. Parry and Small 2005). More generally, this finding affects a central assumption in public economics: that agents "optimize fully with respect to tax policies" (Chetty, Looney, and Kroft, 2009, p. 1145) and thus respond in the same way to a tax change as to a price change. The differentiated demand response indicates that simulation analyses may underestimate the true effect of carbon taxes, and the empirical analysis in this paper clearly shows that a carbon tax can successfully fulfil its main purpose of substantially reducing CO_2 emissions.

The reminder of the paper is organised as follows. Section 2 presents the Swedish carbon tax. Section 3 presents the data and methods used for the estimation of emission reductions. Section 4 presents the results of the empirical analysis as well as several robustness checks. Section 5 analyses the salience issue, disentangles the carbon tax effect from the VAT and compares the paper's findings with earlier studies. Finally, section 6 concludes.

2 The Swedish Carbon Tax

Sweden is a small, open economy with a population of 9.5 million and a nominal GDP per capita that ranked it as the eleventh richest county in the world in 2015 (IMF, 2016b; The World Bank, 2016). With regards to climate change policies, it was one of the first countries in the world to implement a carbon tax in 1991. The tax was first suggested by the Social Democrats in 1988, citing the threat of climate change, and signed into law by the Social Democratic government in 1990 (Collier and Löfstedt, 1997; Swedish Parliament, 1989-1990). Although measures to combat climate change had broad political support in the late 80's and early 90's, the Conservative-led government, in 1993, concerned about the international competitiveness of Swedish industry and the effects of the Swedish domestic recession that started in 1991[5], lowered the rate for industry to 25 percent of the rate levied on other sectors of the economy. This differential have since decreased – industry paid from 21 to 50 percent of the general CO_2 tax rate in the years 1993 to 2005 – and today industry pays 80 percent of the general rate. The carbon

(a) Tax components (b) Total tax

Figure 1: Gasoline price components

[5]Sweden's economic problems in the early 1990s started in the housing and financial sector but soon affected the economy as a whole. An earlier expansion of credit (and debt), coupled with an overvalued currency, had made the economy vulnerable to adverse shocks. From mid 1990 to mid 1993, GDP dropped by a total of 6% and unemployment went from 3 to 10% of the labor force. The economy and the banking sector eventually stabilised in the summer of 1993, following the decision in late 1992 to move from a fixed to a floating exchange rate.

tax was introduced at US$30 per ton of CO_2 and increased slightly during the 1990's to US$44 in 2000. Then, from 2001 to 2004, the rate was increased in a step-by-step manner to US$109. Today, in 2017, the rate is US$132 per ton of CO_2, the world's highest CO_2 tax imposed on non-trading sectors and households. The final tax rates applied to fossil fuels are set in accordance with their carbon content. For example, the combustion of one litre of gasoline releases 2.323 kilos of CO_2. The carbon tax rate of 0.25 SEK per kg of CO_2 (1 SEK=US$0.12) in 1991 thus equated to an addition to the consumer price of gasoline of 0.58 SEK per litre.

When the carbon tax was implemented, it complemented an existing energy tax that was added to the price of gasoline as early as 1924 (Speck, 2008). With the addition of a VAT of 25% in 1990, the retail price of gasoline and diesel today consist of a tax-exclusive price p_t, an energy tax $\tau_{t,energy}$, a carbon tax $\tau_{t,CO2}$ and a value-added tax:[6]

$$p_t^* = (p_t + \tau_{t,energy} + \tau_{t,CO_2})VAT \tag{1}$$

Figure 1(a) shows that the real (inflation-adjusted) energy tax applied to gasoline was fairly constant from 1960 to 2000, before decreasing in the years 2001-2005[7]. This decrease was counteracted by a simultaneous increase in the carbon tax rate, sustaining the upward trend in the total tax, as evident in Figure 1(b). The total tax rate increased by 39% in 1990 and more than 82% between 1989 and 2005 – from 4 SEK to over 7 SEK per litre. That the introduction of a carbon tax and VAT had an impact on consumption of transport fuel is evident from Figure 2 that plots per capita consumption of gasoline and diesel during 1960-2005.

Revenues from the Swedish carbon tax (from all taxed sectors) comprised 1.75% of total government revenues in 2006, and are not ear-marked for any specific purpose when entering the governmental budget. Furthermore, the administrative cost for the tax authority is low, around 0.1% of total revenues from the tax (Withana et al., 2013).

[6]The VAT doesn't have a time subscript since its rate is constant during the entire time period of our analysis; acting as a multiplier of movements in the other price components – thus taking the value of 1 for years prior to 1990, and 1.25 thereafter.

[7]In section 5, I estimate how much larger total emission reductions would likely have been if the energy tax rate had not decreased between 2001 to 2005.

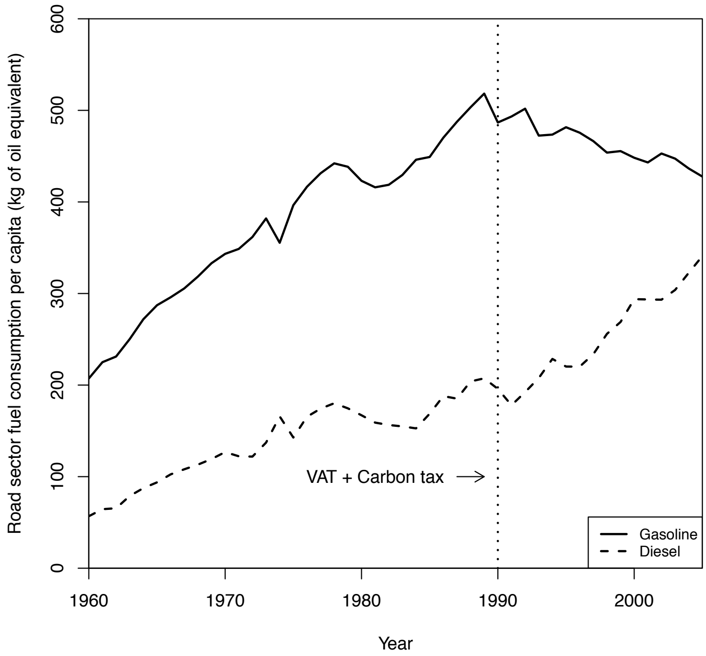


Figure 2: Road fuel consumption 1960-2005

2.1 Tax Incidence

An important question for our subsequent analysis of the effect on emissions is to what extent fuel taxes are borne by consumers. If the carbon tax is fully passed through to consumers this will result in higher prices at the fuel pump, and higher prices reduce demand and thus fuel use, resulting in lower CO_2 emissions from the transport sector. Furthermore, if tax changes are fully passed on to consumers, we can view estimated tax elasticities as demand elasticities.

I analyse empirically the question of tax incidence by decomposing the Swedish retail price of gasoline into oil prices and excise taxes. Using first-differences I regress the nominal tax-inclusive price of gasoline during time-period t on the crude oil price, and excise taxes:

$$\Delta p_t^* = \alpha_0 + \alpha_1 \Delta\theta_t + \alpha_2 \Delta\tau_t + \epsilon_t \tag{2}$$

where p_t^* is the retail price of gasoline, θ_t is the crude oil price, and τ_t is the sum of the energy and carbon tax (I exclude VAT and the producer margin from the model). Using yearly data from 1970 to 2015 ($N = 45$) I find an estimate for the coefficient on taxes of 1.15 (95% confidence interval of [0.76-1.54]). The coefficient is statistically indistinguishable from 1 and the data thus indicate that tax changes are borne heavily by consumers. To check the robustness of this result, I re-ran the model using monthly seasonally adjusted data for 2000-2015 ($N = 191$). The tax coefficient is now 1.00 [0.80-1.20] and not statistically different from 1, again showing that taxes are borne by consumers. Lastly, I split up the total tax into its energy and carbon tax part. The result stays unchanged, the coefficients being 1.04 [0.76-1.30] for the nominal energy tax and 0.97 [0.80-1.15] for the nominal carbon tax, both statistically indistinguishable from 1. The Swedish energy and carbon taxes are thus both fully passed through to consumers, a result similarly found in studies of US gasoline taxes by, among others, Marion and Muehlegger (2011), Davis and Kilian (2011), and Li, Linn, and Muehlegger (2014).

3 Empirical Methodology

3.1 Data

To empirically analyse the effect on emissions from the environmental tax reform in 1990-1991, I use annual panel data on per capita CO_2 emissions from transport for the years 1960 to 2005 for 25 OECD countries (including Sweden)[8]. The outcome variable is measured in metric tons, and the data, obtained from the World Bank, contains emissions from the combustion of fuel from road, rail, domestic navigation, and domestic aviation, excluding international aviation and international marine bunkers.

I choose 2005 as the end date because that year was the start of the EU Emissions Trading System (EU ETS), one of the main building blocks of the EU's climate change policy, and also because many countries in the sample implemented carbon taxes or made marked changes to fuel taxation from 2005 and onwards. The sample period hence gives me thirty years of pre-treatment data and sixteen years of post-treatment data, which is sufficient to construct a viable counterfactual and enough time post-treatment to evaluate the effect of the policy changes.

From this initial sample of 25 OECD countries I exclude countries that during the

[8] Included are the 24 countries that were OECD members in 1990 plus Poland that became a member in 1996 and is geographically close to Sweden.

sample period enacted carbon taxes that cover the transport sector, in this case: Finland, Norway, and the Netherlands, or made large changes to fuel taxes, which exclude Germany, Italy, and the UK.[9] Additionally, I exclude Austria and Luxembourg due to "fuel tourism" distorting their emissions data. Austria's emissions data is skewed from the year 1999 and onwards. This is due to Austria lowering fuel taxes in 1999, while neighbouring Germany and Italy increased their fuel taxes the same year. Austria is a major transit country and large trucks in particular tend to fill up in countries with low diesel prices on their way through Europe. In 2005, diesel sales in Austria were 150% higher than a decade earlier, a clear indication that "fuel tourism" had taken place. Luxembourg has had lower fuel taxes than neighbouring European countries for many years, which explains them having five to eight times higher per capita consumption of fuel than their neighbours (European Federation for Transport and Environment, 2011), and thus more than two times higher per capita CO_2 emissions from transport than the next highest emitter in the sample. Similarly, I omit Turkey which had average per capita emissions in the pre-treatment period way below the other countries in the sample. Lastly, I exclude Ireland due to their unique economic expansion in the 1990s – the "Celtic Tiger" – which more than doubled their GDP per capita and CO_2 emissions per capita from transport during the post-treatment period. This rapid economic expansion is very dissimilar to Sweden's and the other donor countries' development during the same time period. Note, however, that my main results from using the synthetic control method are identical and unaffected by whether or not Austria, Luxembourg, Turkey, and Ireland are included in the sample, since these four countries all obtain zero weight in synthetic Sweden. Furthermore, as will be evident in the result section, the estimated emission reductions from comparing Sweden with its synthetic counterpart are never driven by any one single country in the donor pool.

In the end, my donor pool consists of 14 countries: Australia, Belgium, Canada, Denmark, France, Greece, Iceland, Japan, New Zealand, Poland, Portugal, Spain, Switzerland, and the United States.

[9]Denmark also implemented a carbon tax, in 1992. However, their tax level is set relatively low – US$24 in 2015 (Kossoy et al., 2015) – and, more importantly, the transport sector is exempted.

3.2 Differences-in-Differences

The differences-in-differences (DiD) estimator constructs the counterfactual using an unweighted average of CO_2 emissions from transport during 1960 to 2005 from our final control group of fourteen OECD countries. An estimate of the emission reduction (the 'treatment' effect) is gained by comparing the change in the outcome variable pre- and post-treatment, for Sweden and the control group. What makes the DiD estimator attractive for comparative studies is that, by taking time differences, it can eliminate the influence of unobserved covariates that predict the outcome variable, assuming that the effects on the outcome variable do not change over time. A further assumption is that any macroeconomic shocks, or other time effects, are common to the treated unit and the control group. Together, these two assumptions are usually referred to as the 'parallel trends assumption': implying in our case that, in the absence of a carbon tax and VAT, CO_2 emissions from the transport sector in Sweden and our control group would have followed parallel trajectories.

I use the DiD method to estimate the following fixed-effects, panel data regression model:

$$Y_{it} = \delta_t + \lambda\mu_i + \alpha D_{it} + \epsilon_{it} \tag{3}$$

where i is country identifier and t is year. Y_{it} is per capita CO_2 emissions from transport, δ_t are (common) time fixed effects, μ_i are country fixed effects with a time-invariant parameter λ, D_{it} is the treatment indicator, taking the value of 1 for Sweden in the years after treatment and 0 otherwise, α measures the effect of the treatment and is thus our main coefficient of interest, and finally, ϵ_{it} are country-specific shocks with mean zero.

The parallel trends assumption in the DiD framework is difficult to verify, which is a drawback for this method. It is sometimes possible pre-treatment by analysing the trends of the outcome variable, but obviously not possible after treatment. In case the treated unit and the control group do not follow a common trend, the DiD estimator will be biased. Therefore, finding a method that relaxes this assumption is preferable for comparative case studies. The synthetic control method does just this by allowing the effects of unobserved confounders on the outcome variable to vary over time (λ_t) (Abadie, Diamond, and Hainmueller, 2010). The synthetic control method constructs a comparison unit consisting of a time-invariant weighted average of all potential comparison units that prior to intervention resemble Sweden on a number of key predictors of CO_2 emissions in the transport sector and had similar trajectories of these emissions, but did not implement carbon taxes or similar policies. The synthetic counterpart is thus able to produce the counterfactual outcome, the level and trajectory of emissions we would see in the absence of treatment.

3.3 The Synthetic Control Method

Let[10] $J+1$ be the number of OECD countries in my sample, indexed by j, and let $j=1$ denote Sweden, the "treated unit". The units in the sample are observed for time periods $t=1,2,\dots,T$. It is important to have data on a sufficient amount of time periods prior to treatment $1,2,\dots,T_0$ as well as post treatment $T_0+1,T_0+2,\dots,T$ to be able to construct a synthetic Sweden *and* evaluate the effect of the treatment.

Next we define two potential outcomes: Y_{jt}^I refers to CO_2 emissions from transport when exposed to treatment for unit j at time t and Y_{jt}^N is CO_2 emissions without treatment. The goal of the analysis is to measure the post-treatment effect on emissions in Sweden, formalised as $\alpha_{1t} = Y_{1t}^I - Y_{1t}^N = Y_{1t} - Y_{1t}^N$. However, since we cannot observe Y_{1t}^N for $t > T_0$ we need to construct it using a synthetic control.

Synthetic Sweden is constructed as a weighted average of control countries $j = 2,\dots,J+1$, and represented by a vector of weights $W = (w_2,\dots,w_{J+1})'$ with $0 \leq w_j \leq 1$ and $w_2 + \cdots + w_{J+1} = 1$. Each choice of W gives a certain set of weights and hence characterises a possible synthetic control. We want the synthetic control to not only be able to reproduce the trajectory of CO_2 emissions but also to be similar to Sweden on a number of pre-treatment predictors of the outcome variable. Hence, let Z_j denote the vector of observed predictors for each unit in the sample. Now suppose that we find

[10]The description here follows the structure in Abadie, Diamond, and Hainmueller (2010, 2011).

$W = W^* = (w_2^*, \ldots, w_{J+1}^*)$ such that for the pre-treatment period $t \leq T_0$ we have that:

$$\sum_{j=2}^{J+1} w_j^* Y_{j1} = Y_{11}, \sum_{j=2}^{J+1} w_j^* Y_{j2} = Y_{12}, \cdots, \sum_{j=2}^{J+1} w_j^* Y_{jT_0} = Y_{1T_0}, \quad \text{and} \quad \sum_{j=2}^{J+1} w_j^* Z_j = Z_1 \qquad (4)$$

then, as proved in Abadie, Diamond, and Hainmueller (2010), for the post-treatment period $T_0 + 1, T_0 + 2, \ldots, T$ we can use the following as an unbiased estimator of α_{1t}:

$$\hat{\alpha}_{1t} = Y_{1t} - \sum_{j=2}^{J+1} w_j^* Y_{jt} \qquad (5)$$

To find W^* we need to define a measurable difference between Sweden and its control units which we then minimize. Let $X_1 = (Z_1', Y_{11}, \ldots, Y_{1T_0})'$ denote an (kx1) vector of pre-treatment values for the key predictors of the outcome variable and the outcome variable itself for Sweden, and let the (kxJ) matrix X_0 contain similar variables for the control countries.[11] We then choose W^* so that the distance $\|X_1 - X_0 W\|$ is minimized for the pre-treatment period, subject to the above (convexity) constraints on the weights. In this paper I solve for a W^* that minimizes:

$$\|X_1 - X_0 W\| \, v = \sqrt{(X_1 - X_0 W)' V (X_1 - X_0 W)} \qquad (6)$$

where V here is the (kxk) symmetric and positive semidefinite matrix that minimizes the mean squared prediction error (MSPE) of the outcome variable over the entire pre-treatment period.[12]

The purpose of introducing V is to weight the predictors and allow a larger weight being given to more important predictors of the outcome variable. Here, V is chosen through a data-driven procedure but other methods are possible, for instance, assigning weights based on empirical findings in the literature on the main drivers of CO_2 emissions, or cross-validation methods (Abadie, Diamond, and Hainmueller, 2015).

As key predictors I use GDP per capita, number of motor vehicles (per 1000 people),

[11] Note that the main analysis does not use all pre-treatment values for the outcome variable, only three distinct years.

[12] To find V (which here is diagonal) and W^* I used a statistical package for R called Synth (Abadie, Diamond, and Hainmueller, 2011).

gasoline consumption per capita, and percentage of urban population (see Appendix for details and sources). The level of GDP per capita is shown in the literature to be closely linked to emissions of greenhouse gases (Neumayer, 2004), and OECD countries that are less urbanized have a higher usage of motor vehicles and hence higher emissions from transport. I average the four key predictors over the 1980-1989 period. Finally, to the list of predictors I add three lagged years of CO_2 emissions: 1970, 1980, and 1989.

With a large number of pre-intervention periods, an accurate prediction of the outcome during these years makes it more plausible that unobserved and time-varying confounders affect the treated unit and the synthetic counterpart in a similar way (Kreif et al., 2015). The intuition is that synthetic Sweden is only able to reproduce the level and trajectory of CO_2 emissions from the transport sector in Sweden for the thirty years before treatment, if it is true that the two units are similar when it comes to observed ($\sum w_j^* Z_j = Z_1$) and unobserved ($\sum w_j^* \mu_j = \mu_1$) predictors and the effects of these predictors on emissions. Thus, by relaxing the parallel trends assumption the synthetic control method improves on the DiD estimator in our case.

There are additional reasons to why we should prefer the synthetic control method for our analysis. With DiD there is often an ambiguity in the choice of comparison units (see e.g. Card 1990), whereas the synthetic control method chooses them using a data-driven method. Furthermore, with the inclusion of predictors of the outcome variable we weight the units in the control group so as to create a comparison unit that more resembles Sweden. Addition of these covariates, such as level of urbanisation and number of motor vehicles per capita, is not possible in the DiD regression as they are likely affected by the treatment - themselves being outcome variables - and are thus considered "bad controls." Lastly, as we will see in the next section, the relative contribution of each control unit is made explicit, and we can analyse the similarities, or lack thereof, between our selected synthetic control group and the treated unit on the pre-intervention outcomes and (observable) predictors of the post-intervention outcomes (Abadie, Diamond, and Hainmueller, 2010, 2015).

Table 1: DiD estimate of the treatment effect

Dependent variable	CO_2 emissions from transport
Treatment	-0.214**
	(0.085)
Year fixed effects	Yes
Country fixed effects	Yes
Observations	690
R^2 (within)	0.806

Note: Robust standard errors in parenthesis (clustered by country).
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

4 Results

Table 1 presents the result from the DiD estimator. The estimated treatment effect from the implementation of VAT and a carbon tax is an emission reduction from the Swedish transport sector of 8.1%, or 0.214 metric tons of CO_2 per capita in an average year post-treatment.

To see if the underlying parallel trends assumption holds, I analyse the trend in emissions before the policy changes. Figure 3 shows the trajectory of emissions from transport in Sweden and the OECD average during the sample period[13]. Overall, they seem to follow a similar trend but the fit is poor in the 1980's. A statistical analysis shows that on average, from 1960 to 1989, emissions in Sweden and the OECD average grew at a similar pace. However, between 1980 and 1989, emissions in Sweden grew twice as fast, a difference in trend that is statistically significant. This result indicates that the common trends assumption is violated and that the result from using the DiD framework is biased. So, let's turn to our second model, the synthetic control method, and see if it produces more promising results.

[13] The slump in emissions in Sweden and the OECD countries in the years following 1979 is a response to what is commonly called the "second oil crisis", prompted by the Iranian Revolution in 1979. It wasn't until around 1986 that the price of oil was back down at pre-1979 levels. This increase in the oil price hence acts as a 'natural experiment' that shows that increased prices of fuel leads to reductions in CO_2 emissions from transport

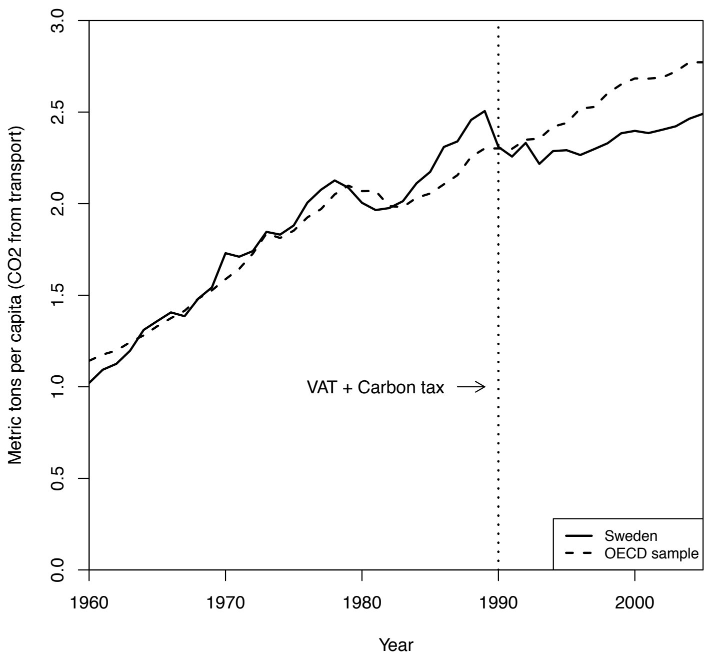


Figure 3: Trajectory of CO_2 emissions from transport in Sweden vs. the OECD average of my 14 donor countries

4.1 Sweden vs. Synthetic Sweden

If synthetic Sweden is able to track CO_2 emissions from transport in Sweden in the pre-treatment period and reproduce the values of the key predictors, it lends credibility to our identification assumption: that the synthetic control unit provide the trajectory of emissions from 1990 to 2005 in the absence of taxes.

Figure 4 shows that, prior to treatment, emissions from transport in Sweden and its synthetic counterpart track each other closely; an average (absolute) difference of only around 0.03 metric tons of CO_2 (or 1.79%). Hence, the synthetic control doesn't underestimate the treatment effect in the way that the DiD estimator do by failing to capture the trend in the last ten years before treatment. Furthermore, Table 2 compares the values of the key predictors for Sweden prior to 1990 with the same values for synthetic Sweden and a population-weighted average of the 14 OECD countries in the donor pool. For all predictors, except gasoline consumption per capita, Sweden and its synthetic version have almost identical values and a much better fit compared to the OECD average. It is especially encouraging to see the good fit on GDP per capita.

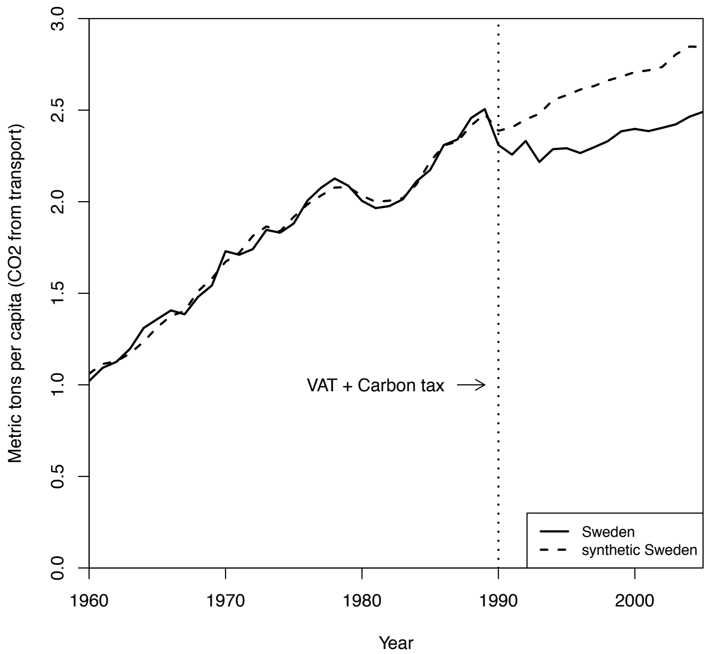


Figure 4: Path plot of per capita CO_2 emissions from transport during 1960-2005: Sweden vs. synthetic Sweden

Table 2: Predictor means for CO_2 emissions from transport

Variables	Sweden	Synth Sweden	OECD Sample
GDP per capita	20121.5	20121.2	21277.8
Motor vehicles (per 1000 people)	405.6	406.2	517.5
Gasoline consumption per capita	456.2	406.8	678.9
Urban population (%)	83.1	83.1	74.1
CO_2 from transport per capita 1989	2.5	2.5	3.5
CO_2 from transport per capita 1980	2.0	2.0	3.2
CO_2 from transport per capita 1970	1.7	1.7	2.8

Note: All variables except lagged CO_2 are averaged for the period 1980-1989. GDP per capita is Purchasing Power Parity (PPP)-adjusted and measured in 2005 U.S. dollars. Gasoline consumption is measured in kg of oil equivalent. CO_2 emissions are measured in metric tons. The values for the OECD sample are population-weighted averages.

The predictors are weighted (the V matrix) as follows: GDP per capita (0.219); Motor vehicles (0.078); Gasoline consumption (0.010); Urban population (0.213); and, CO_2 emissions from transport in 1989 (0.183); 1980 (0.284); and, 1970 (0.013).[14] The small weight assigned to gasoline consumption per capita may explain the poor fit between Sweden and its synthetic version on this variable.

Lastly, The W weights reported in Table 3 shows that CO_2 emissions from transport in Sweden is best reproduced by a combination of Denmark, Belgium, New Zealand, Greece, the United States, and Switzerland. The rest of the countries in the donor pool get either a weight of zero, or very close to zero. The large weight given to Denmark (0.384) seems reasonable considering that Sweden and Denmark are similar in many social and economic dimensions. Belgium and Sweden have had a similar level and growth rate of GDP per capita – a major predictor of GHG emissions – from 1960 to 2005, whereas New Zealand and Sweden have a comparable geography (low population density) and urbanisation pattern (both level and trend is remarkably alike). Together, Denmark, Belgium, and New Zealand make up three fourths of Synthetic Sweden.

Table 3: Country weights in synthetic Sweden

Country	Weight	Country	Weight
Australia	0.001	Japan	0
Belgium	0.195	New Zealand	0.177
Canada	0	Poland	0.001
Denmark	0.384	Portugal	0
France	0	Spain	0
Greece	0.090	Switzerland	0.061
Iceland	0.001	United States	0.088

Note: With the synthetic control method, extrapolation is not allowed so all weights are between $0 \leq w_j \leq 1$ and $\sum w_j = 1$.

[14] I tried different combinations of lagged CO_2 – e.g. (1989, 1981, 1969) and (1980-89, 1970-79, 1960-69) – but none gave a better fit pre-treatment nor changed the W weights and estimated emission reductions substantially. Additionally, I also switched to lags of GDP instead of CO_2, which again produced a similar result as the main analysis.

4.2 Emission Reductions

The post-treatment distance between Sweden and synthetic Sweden in Figure 4 measures the reduction in CO_2 emissions. This distance is further visualised in the gap plot of Figure 5. The introduction of the VAT and the gradual increase of the carbon tax create larger and larger reductions during the post-treatment period. In the last year of the sample period, 2005, emissions from transport in Sweden are 12.5%, or -0.35 metric tons per capita, lower than they would have been in the absence of treatment. The reduction in emissions for the 1990 to 2005 period is 10.9%, or -0.29 metric tons of CO_2 per capita in an average year. Aggregating over the total population gives an emission reduction of 3.2 million tonnes of CO_2 in 2005 and an average for the 1990-2005 period of 2.5 million tonnes of CO_2. The total cumulative reduction in emissions for the post-treatment period is 40.5 million tonnes of CO_2.

Due to the reduction of the energy tax rate in the years 2001 to 2005 (see Figure 1(a)), the simultaneous increase of the carbon tax rate is cancelled out during this period, leaving a flat combined real tax rate. Consequently, we can be more confident in stating that the emission reductions from 1990 to 2000 is due to the introduction of the carbon

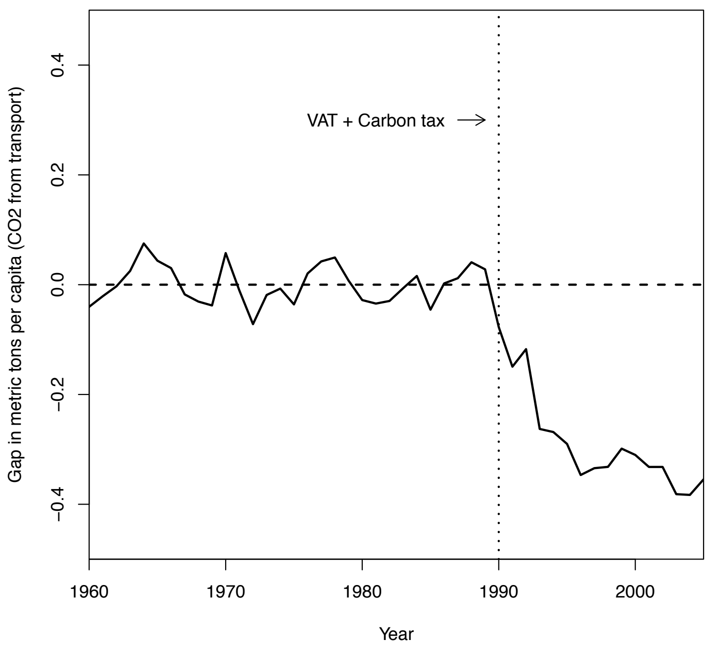
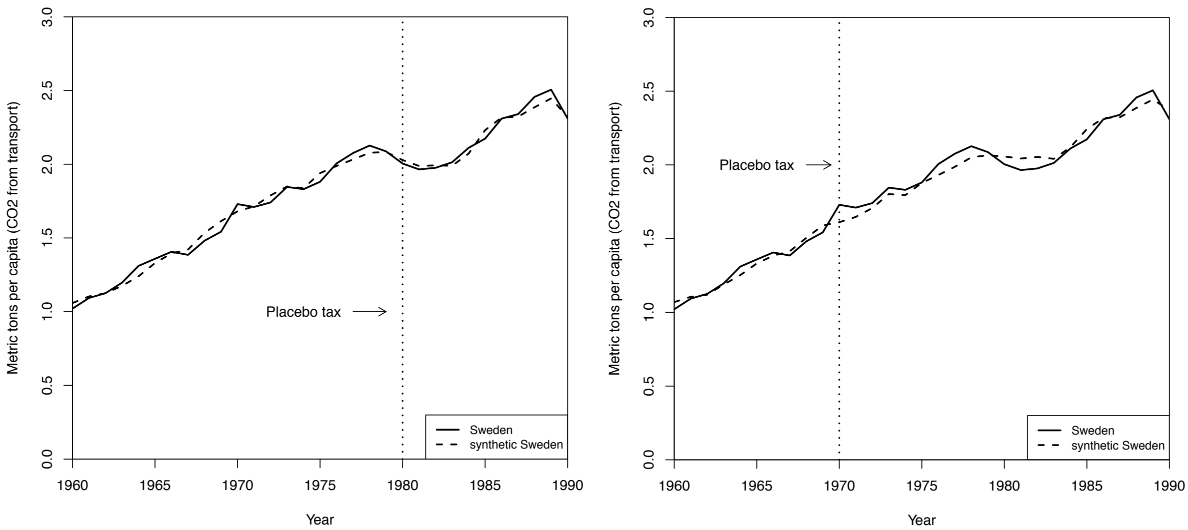


Figure 5: Gap in per capita CO_2 emissions from transport between Sweden and synthetic Sweden

tax and VAT alone, whereas for 2001 to 2005 the reductions is due to changes in all three tax components - assuming that a similar reduction in the energy tax rate did not take place in the countries that make up synthetic Sweden. In 2000, the last year before the energy tax was lowered, emissions from transport were reduced by 11.5%, or -0.31 metric tons per capita.

4.3 Placebo Tests

To further test the validity of the results I performed a series of placebo tests: "in-time", "in-space" and "leave-one-out". For the in-time tests the year of treatment is shifted to 1970 and 1980, years that are both prior to the actual environmental tax reform. For the two tests, the choice of synthetic control is based only on data from 1960 to 1969, and 1960 to 1979 respectively. We want to find that this placebo treatment doesn't result in a post-placebo-treatment divergence in the trajectory of emissions between Sweden and its synthetic control. A large placebo effect casts doubt on the claim that the result illustrated in Figure 4 and 5 is the actual causal effect of the carbon tax and the VAT. Encouraging, Figure 6 shows that no such divergence is found.



(a) 1980 (b) 1970

Figure 6: Placebo in-time tests

Note: In (a) the placebo tax is introduced in 1980, ten years prior to the actual policy changes. In (b) the placebo tax is introduced in 1970.

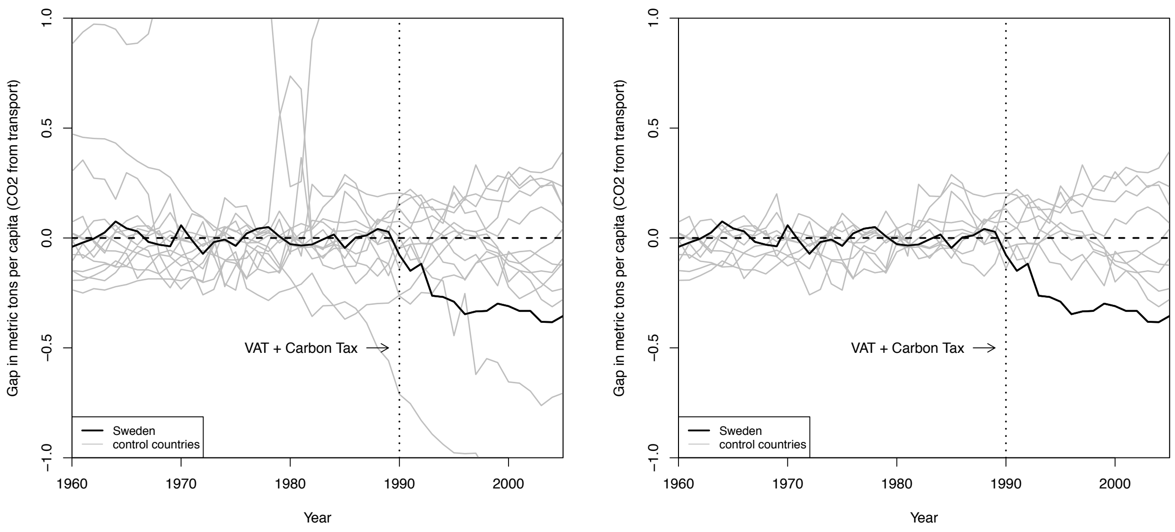


Figure 7: Permutation test: Per capita CO_2 emissions gap in Sweden and placebo gaps for the control countries

For the in-space placebo test the treatment is iteratively reassigned to every country in the donor pool, again using the synthetic control method to construct synthetic counterparts. This gives us a method to establish if the result obtained for Sweden is unusually large, by comparing that result with the placebo results for all the countries in the donor pool. This form of permutation test allows for inference and the calculation of p-values: measuring the fraction of countries with results larger than or as large as the one obtained for the treated unit (Abadie, Diamond, and Hainmueller, 2015, p. 6).

Figure 7 shows the results of the in-space placebo test. The plot on the left indicates that for some countries in the donor pool, the synthetic control method is not able to find a convex combination of countries that can simulate the path of emissions in the pre-treatment period. This is especially true for the United States, Poland and Portugal. This is not surprising since the United States has the largest CO_2 emissions during all the pre-treatment years and Poland and Portugal have the lowest. Therefore, in the plot on the right, all the countries with a pre-treatment MSPE at least twenty times larger than Sweden's are excluded, which leaves nine countries in the donor pool. Now the gap in emissions for Sweden in the post-treatment period is the largest of all remaining countries. The p-value of estimating a gap of this magnitude is thus $1/10 = 0.10$.

However, the choice of a particular cut-off threshold for the MSPE value when doing

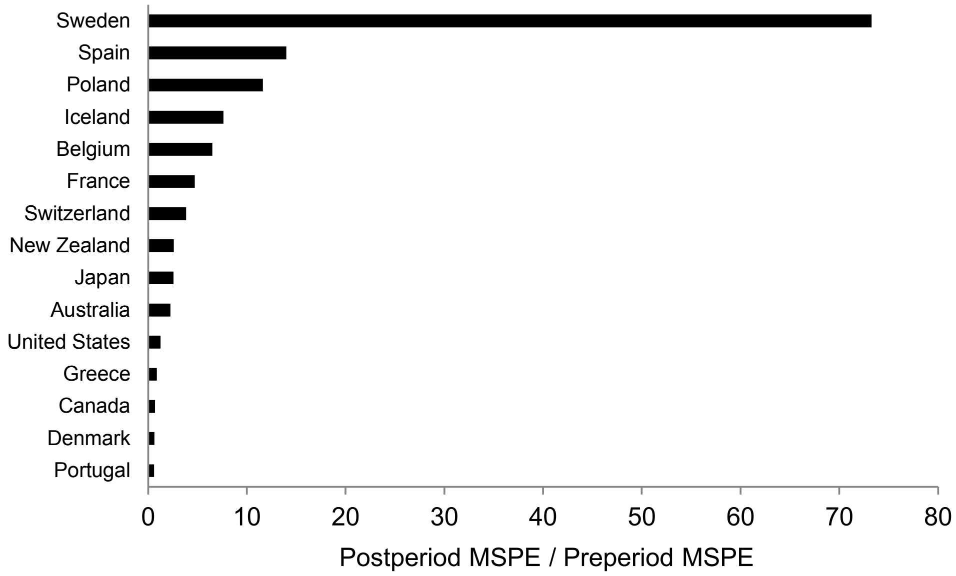


Figure 8: Ratio test. Ratios of post-treatment MSPE to pre-treatment MSPE

permutation testing is arbitrary. A better inferential technique is to look at the ratio of post-treatment MSPE to pre-treatment MSPE (Abadie, Diamond, and Hainmueller, 2010), with the assumption that a large ratio is indicative of a true casual effect from treatment. With the ratio test we do not have to discard any of the countries in the donor pool based on an arbitrarily chosen cut-off rule, and thus the ratio test is advantageous when you have a small number of control units.

Figure 8 show that Sweden by far has the largest ratio of all the countries in the sample. If one was to assign the treatment at random, the probability of finding a ratio this large is $1/15 = 0.067$, the smallest possible p-value with my sample size.

The last robustness check I perform is the "leave-one-out" test (Abadie, Diamond, and Hainmueller, 2015). Here I iteratively eliminate one of the six control countries that got a W weight larger than 0.001 (0.1%) to check if the results are driven by one or a few influential controls. As we can see from Figure 9, the main results are robust to the elimination of one donor pool country at a time. We get slightly larger reductions when we eliminate Denmark, slightly smaller reductions when we eliminate Switzerland or the US, and basically unchanged results for the others. This test thus provides us with a range for the estimated emission reduction, from an average post-treatment reduction of 13.0% (when eliminating Denmark) to the most conservative estimate of an 8.8% reduction

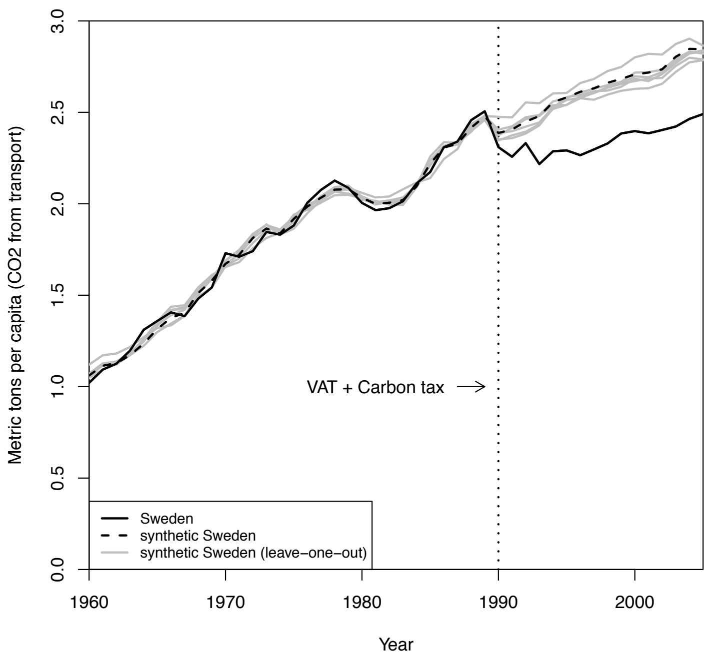


Figure 9: Leave-one-out: Distribution of the Synthetic Control for Sweden

(omitting Switzerland). The average of the six iterations gives an emission reduction of 10.4%. Note also that the conservative estimate is still larger than the DiD estimate of a 8.1% reduction.

4.4 Possible Confounder

A common argument against carbon taxation is that it may hurt economic growth. We also find in the literature clear evidence of a link between GDP growth and growth in CO_2 emissions. Could it thus be that the introduction of the carbon tax reduced the level of GDP in Sweden post-treatment, and that this is the actual driver behind the emission reductions? Or, alternatively, could it be the exogenous shock of the domestic financial and economic crisis in the early 1990s that is driving the results?

Figure 10 show that GDP per capita in Sweden and its synthetic counterpart track each other quite well during the 30 years before and 16 years after treatment. Yes, there is a reduction in real GDP per capita from 1990 to 1993, which is not matched by a similar reduction in Synthetic Sweden, but already by 1995 the two series are closely aligned again. If the recession in Sweden drove the reduction in emissions we would expect to see a "bounce back" in emissions once economic growth started to catch up again, and

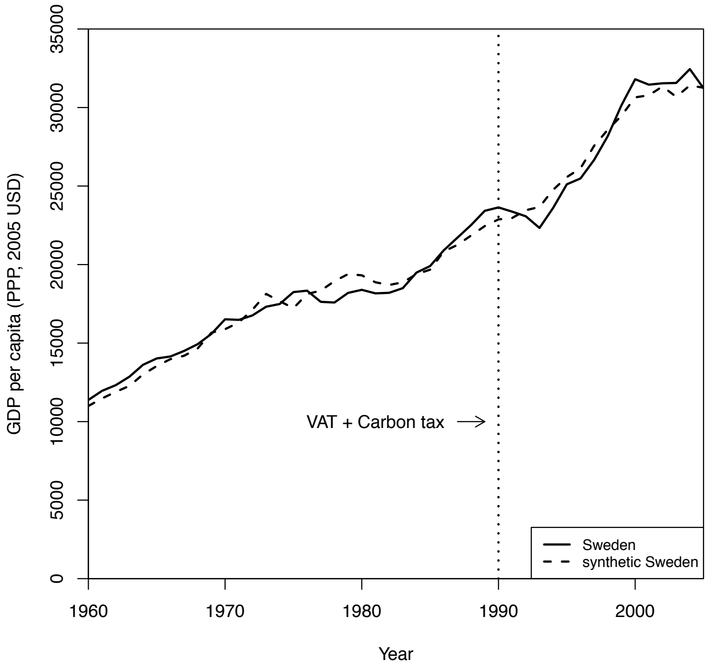


Figure 10: GDP per Capita: Sweden versus Synthetic Sweden

this we do not see. There is hence no indication that the domestic recession is driving emissions post-treatment and no observable (long-term) negative impact on GDP from the taxes. In fact, average GDP per capita in Sweden during the post-treatment period of 1990-2005 is 0.1% higher compared to GDP in synthetic Sweden.

To conclude, Figure 10 together with the gap plot in Figure 5 gives an indication that, since the introduction of the carbon tax, the (positive) correlation between GDP growth and emissions in the transport sector has weakened considerably. There is tentaive evidence that this might hold for the economy as a whole: during 1990 to 2011, total greenhouse gas emissions fell by 16% in Sweden while real GDP increased by 58% (Åkerfeldt, 2013).

5 Carbon Tax Salience

The effect I find on transport emissions from the Swedish carbon tax and the VAT is larger than earlier empirical analyses of carbon taxes would suggest and larger than a simulation analysis found that looked specifically at the effect on Swedish transport emissions from the introduction of the carbon tax in 1991 (Ministry of the Environment and Energy, 2009). Possible explanations for this result could be that the carbon tax induces a larger behavioural response than we assume from just looking at price elasticities of demand, or that the VAT accounts for the largest part of the total emission reductions. To examine this result further, we turn now to the paper's second (but complementary) empirical analysis: comparing the behavioural response from changes to the carbon tax rate and equivalent gas price changes. I analyse this issue by using annual time-series data of the consumption and real price of gasoline in Sweden from 1970 to 2011. I decompose the retail price of gasoline into its carbon tax-exclusive price component, $p_t^v = (p_t + \tau_{t,energy})VAT$, and the carbon tax, $\tau_{t,CO_2}^v = (\tau_{t,CO_2})VAT$. Since the VAT is constant, and a multiplier, it is perfectly correlated with all price components. The VAT is hence added to each respective price component and not treated separately. I set up the following log-linear (static) model:

$$ln(x_t) = \alpha + \beta_1 p_t^v + \beta_2 \tau_{t,CO_2}^v + \beta_3 D_{t,CO_2} + X_t \gamma + \epsilon_t \tag{7}$$

where x_t is gasoline consumption per capita, D_{t,CO_2} is a dummy that takes the value of 1 for years from 1991 and onwards and zero otherwise, X_t is a vector of control variables: GDP per capita, urbanisation, the unemployment rate, and a time trend, and finally, ϵ_t is idiosyncratic shocks.

The results from the OLS regression of our log-linear model, specifications (1) to (4) in Table 4, shows that the tax elasticity is around 3.1 to 4.5 times larger than the corresponding price elasticity, a difference that is statistically significant in all cases.

There is a risk, however, that the results are biased due to omitted variables or the endogeneity of gasoline prices: that gasoline consumption affects the gasoline price and

Table 4: Estimation Results from Gasoline Consumption Regressions

	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) IV(EnTax)	(6) IV(OilPrice)
Gas price with VAT	-0.0575***	-0.0598***	-0.0612***	-0.0603***	-0.0620***	-0.0641***
	(0.019)	(0.018)	(0.016)	(0.014)	(0.020)	(0.014)
Carbon tax with VAT	-0.260***	-0.232***	-0.234***	-0.186***	-0.186***	-0.186***
	(0.050)	(0.063)	(0.065)	(0.059)	(0.038)	(0.038)
Dummy carbon tax	0.109*	0.0604	0.0633	0.0999	0.0977	0.0949
	(0.057)	(0.088)	(0.087)	(0.079)	(0.070)	(0.059)
Trend	0.0207***	0.0253***	0.0244***	0.0341***	0.0342***	0.0344***
	(0.003)	(0.005)	(0.005)	(0.007)	(0.003)	(0.003)
GDP per capita		-0.00108	-0.00105	-0.00366**	-0.00367***	-0.00368***
		(0.001)	(0.001)	(0.002)	(0.001)	(0.001)
Urban population			0.0127	0.0301	0.0313	0.0329
			(0.056)	(0.052)	(0.064)	(0.058)
Unemployment rate				-0.0242***	-0.0242***	-0.0242***
				(0.008)	(0.005)	(0.005)
Constant	6.228***	6.407***	5.372	4.407	4.313	4.198
	(0.129)	(0.197)	(4.616)	(4.141)	(5.152)	(4.693)
Observations	42	42	42	42	42	42
R^2	0.72	0.73	0.73	0.76	0.76	0.76

Note: Newey-west standard errors in parentheses, heteroscedasticity and autocorrelation robust.
Real prices are in 2005 Swedish kronor.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

not just the other way around. Endogeneity is arguably a lesser risk for a small country such as Sweden, compared to larger oil consumers such as the US, since crude oil prices are set in a global market and changes in demand in Sweden will thus have a negligible impact on the world price. The issue still needs to be addressed though since domestic producers (at the retail and refinery level) may adjust their margin, and hence affect the pump price, as a response to local changes in demand. In specifications (5) and (6), the carbon tax-exclusive gasoline price is instrumented using the energy tax rate and the (brent) crude oil price respectively. The energy tax rate comprises a large part of the carbon tax-exclusive price and thus satisfies the instrument relevance condition. At the same time, changes to the energy tax level occur with a considerable lag and is often driven by exogenous changes to environmental policies, and thus also satisfies the instrument exogeneity condition. Taken together, the energy tax rate is arguably a valid instrument.

Comparing the estimated coefficients for specification (4) with (5) and (6) we see that they are almost identical; thus, endogeneity of gasoline prices is likely not a problem in our model. Running the Durbin-Wu-Hausman test also indicates that the carbon tax-exclusive gasoline price is indeed exogenous to gasoline consumption. Additionally, the Stock and Yogo (2005) test for weak instruments indicate that the energy tax is a weak instrument, but not the crude oil price. If we still believe that the carbon tax-exclusive price may be endogenous we should thus use the results from specification (6) that have the crude oil price as an instrument.

The earlier analysis of tax incidence in section 2 indicated that tax changes are fully passed through to consumers, and we can thus view the estimated elasticities as demand elasticities. The results in specification (4) give a price elasticity of demand of -0.51 and a tax elasticity of demand of -1.57, a ratio in the demand response of just over 3. The model specification I use is a static model, no lags are included. Each observation of the outcome variable is hence modelled as depending only on contemporaneous values of the explanatory variables. Elasticity estimates using yearly data and a static model often fall in-between the short- and long-run elasticities found when using lagged models (Dahl and Sterner, 1991), and could therefore be viewed as "intermediate". Dahl and Sterner (1991)[15] reports an average intermediate price elasticity of demand for gasoline among OECD countries of -0.53, so my estimate of -0.51 is in line with the previous literature.

[15] The Dahl and Sterner (1991) paper takes the average from 22 studies - that all use yearly time-series data - of the intermediate price elasticity of demand for gasoline across different OECD countries. 17 out of the 22 estimates are for European countries, most commonly France and Germany, but studies for Sweden are also included.

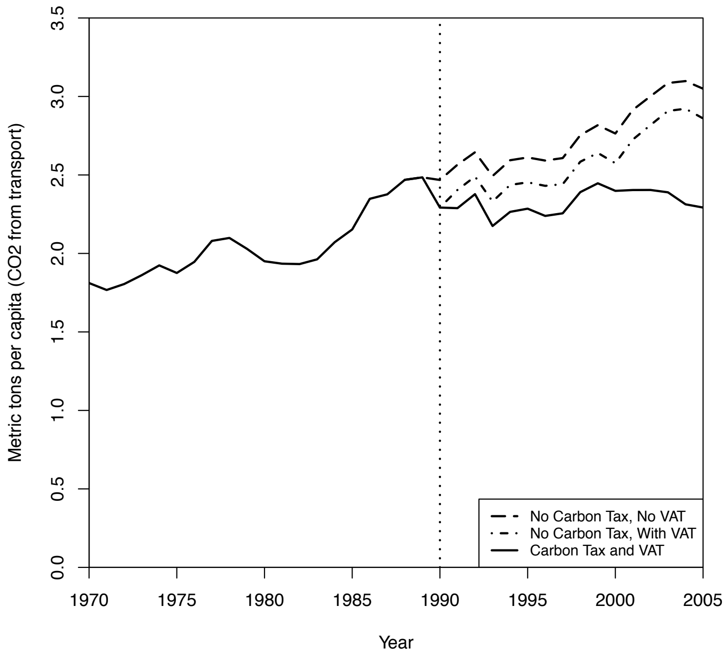


Figure 11: Disentangling the Carbon Tax and VAT

Note: The top (dashed) line shows predicted emissions when the carbon tax elasticity is set to zero, and the VAT is deducted from the gasoline price. For the middle line, the carbon tax elasticity is set to zero but VAT is still included. The bottom (solid) line gives predicted emissions using the full model with the differentiated tax and price elasticities. Note that the x-axis starts at 1970 instead of 1960 as earlier. This is due to a lack of price data for years prior to 1970.

5.1 Disentangling the Carbon Tax and VAT

Using the estimated tax and price semi-elasticities from specification (4) in Table 4, we can disentangle the effect of the carbon tax on emissions from the effect of the VAT, applying a simulation approach: the difference between a scenario where no VAT and no carbon tax is introduced and a scenario where either VAT or the carbon tax is added to the price of gasoline. Since the energy tax is included in both simulated scenarios the effect of movements in the rate cancels itself out, thereby keeping it constant.

The distance between the top (dashed) line and the middle (dot-dashed) line in Figure 11 measure the emission reductions attributable to the VAT. Similarly, the distance between the middle line and the bottom (solid) line measure the emission reductions attributable to the carbon tax. Up until the year 2000, the carbon tax and the VAT are separately responsible for around half of the reduction in each year. In 2000, the carbon tax contributes to a 5.5%, or -0.15 metric tons per capita, reduction in Swedish transport emissions. Between 2000 and 2005 the carbon tax is increased and consequently a larger and larger share of the emission reduction each year is attributed to it. In 2005, around three fourths of the total emission reduction is due to the carbon tax, a 9.4%, or -0.27 metric tons per capita reduction in transport emissions.

In an average year during 1990 to 2000, the carbon tax contributed to emission reductions of 4.8%, or -0.13 metric tons per capita. If we look at the entire post-treatment period of 1990 to 2005, the carbon tax resulted in emission reductions of 6.3%, or -0.17 metric tons per capita in an average year.

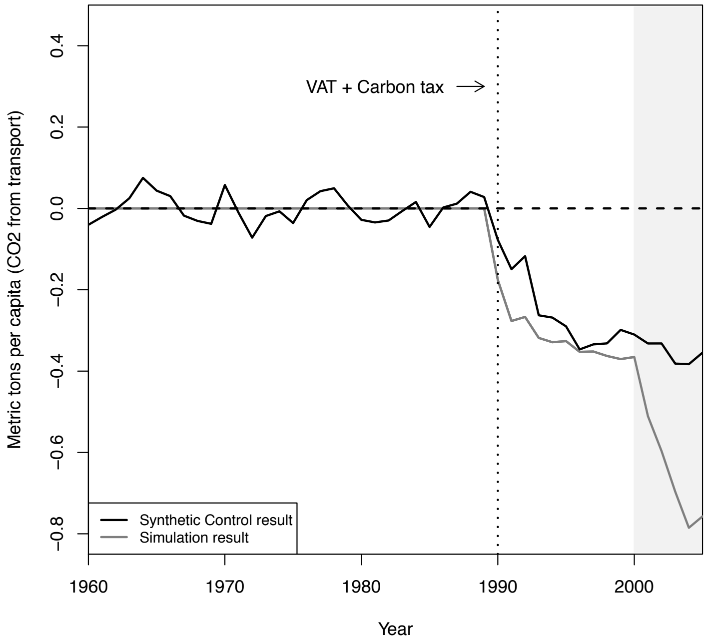


Figure 12: Emission Reduction: Synthetic Control vs. Simulation

Note: The shaded area highlights the period between 2000 and 2005 when the carbon tax rate was more than doubled (first tax increase in 2001).

Now, comparing the emission reductions we find using the simulation approach (Figure 11) with the earlier results from our empirical analysis (Figure 5), we can get an estimate of the likely impact on emissions from the increase in the carbon tax rate in the years 2001 to 2005, had not the energy tax rate simultaneously decreased. The two estimates in Figure 12 track each other quite closely from 1990 to 2000, before diverging in the subsequent years. In 2005, the estimated emission reduction is more than twice as large in the simulation case compared to the results using the synthetic control method: -0.757 to -0.355. This big difference in 2005 is due to the real carbon tax rate increasing by almost 130% from 2000 to 2005. The synthetic control method thus give us an estimate of the actual emission reductions due to the introduction of VAT and the carbon tax in 1990-1991 and the subsequent changes in the carbon and energy tax rate between 1991 and 2005. The simulation exercise further tells us what the possible emission reductions from the carbon tax would have been if policy makers in Sweden had kept the (real) energy tax level constant between 2000 and 2005.

5.2 Estimates from Previous Literature

My estimated emission reductions can be compared to previous estimates from analyses of the Swedish carbon tax.

In Bohlin (1998) the author concludes that during 1990-1995 the carbon tax had no impact on emissions from the transport sector. I instead find an average emission reduction of 3.6% during 1990-1995 attributed to the carbon tax with a reduction in 1995 alone of 5.8%. Bohlin (1998, p. 283) states that he doesn't use a modelling approach and instead relies on ex-post data, but other than "using criteria developed by OECD in 1997" we are not given any detail on the methodology used to, for instance, derive the counterfactual emission levels. It is thus hard to determine why our estimates differ.

Lin and Li (2011) adopts a DiD framework to estimate reductions in emission growth rates due to carbon taxation in Sweden, Denmark, Norway and the Netherlands. They find a significant effect for Finland only, a 1.7% reduction in the growth rate of CO_2 per capita. However, there are countries in their control group that are less than ideal when creating the counterfactual emissions, such as Austria, Luxembourg, and Ireland.[16] Furthermore, by having total CO_2 emissions per capita as their dependent variable, they include many sectors that are exempted from taxation. Lastly, some of their added control variables, e.g. urbanisation level, industry structure, and energy price, are likely themselves effected by the carbon tax and thus also outcome variables. Including them on the right hand side of their regression will thus bias the results.

Lastly, Sweden's fifth national report on climate change (Ministry of the Environment

[16] See section 3.1 to why this is.

and Energy, 2009) estimates that the reduction of CO_2 emissions from the transport sector in 2005 is 1.7 million metric tons compared to if Sweden had kept taxes at the 1990 level – an important assumption since the tax level then already includes VAT. The emission reduction is simulated by estimating changes in fuel consumption, using price elasticities of demand. Their estimate is markedly lower compared to my empirical estimate using the synthetic control method, which shows a reduction in 2005 of 2.4 million metric tons of CO_2 from the carbon tax. Besides assuming that the real gasoline tax stays constant at the 1990 level when calculating their counterfactual, they apply a (long-run) price elasticity of demand for gasoline of -0.8 (Edwards, 2003), based on an average from a number of European studies. That I find, using empirical ex-post data, an estimate of the emission reduction in 2005 that is 40% larger, and a carbon-tax elasticity of -1.57, around twice the size of the price elasticity they use, show how modelling analyses may underestimate the effectiveness of carbon taxes.

In addition to the the empirical finding that the Swedish carbon tax has been envrionmentally efficient, this paper show that Swedish consumers exhibit larger behavioural responses to changes to the carbon tax rate compared to equivalent changes to the carbon tax-exclusive gasoline price. This finding of the salience/persistence of the Swedish carbon tax is similar to Rivers and Schaufele's (2015) result from analysing the carbon tax in British Columbia, Canada, and other studies that have analysed gasoline taxes (Davis and Kilian, 2011; Li, Linn, and Muehlegger, 2014; Antweiler and Gulati, 2016). My study is the first, however, that analyses a European market whereas earlier studies have focused on North America – the US and Canada – where gasoline taxes are markedly lower. In 2008, excise gasoline taxes in US cents per litre was 120 in Sweden but only 32 in Canada and 13 in the US (IEA, 2009). As a percentage of the overall gasoline price, excise taxes constitutes 61.6% in Sweden, but only 27.5% in Canada, and 14.6% in the US. Consequently, the tax-inclusive gasoline price is much less volatile in Sweden compared to the US and Canada, since the stable and certain part, the excise taxes, comprises a larger part of the whole. Due to large differences in consumer prices for gasoline a, say, 10 cent increase in gasoline taxes will create larger price increases (in percentage terms) in the US and Canada compared to Sweden, and thus larger relative reductions in consumption – assuming tax elasticities are similar across the three countries. Therefore, one should be careful with regards to the external validity of the estimated emission reductions found in this paper. A Swedish sized carbon tax rate applied to low-tax level countries will most likely lead to larger emission reductions than what is found in this paper.

6 Conclusion

This paper has shown empirically that a carbon tax can be successful in significantly reducing emissions of CO_2. This result is in contrast to earlier empirical studies that find little to no effect on emissions from carbon taxes. The identification strategy adopted is to carefully construct a control unit that did not implement a carbon tax, or similar policies, but had similar level and trajectory of CO_2 emissions before treatment. The control unit, synthetic Sweden, is able to very accurately reproduce the values for Sweden on a number of key predictors of CO_2 emissions from the transport sector, and to closely track emissions during the thirty years prior to treatment. The results obtained are furthermore robust to a series of placebo tests, both in-time and in-space. Reassigning the treatment at random in the sample shows that the probability of obtaining a post-treatment result as large as that for Sweden is just 0.067.

Furthermore, this paper find, similar to other recent studies, that consumers respond more strongly to changes to the carbon tax rate than equivalent market-driven gasoline price changes. If carbon tax elasticities are indeed larger than price elasticities of demand for some goods, this has implications for climate change policies as well as economic theory. In the policy arena, carbon taxes would be more effective in reducing GHG emissions and air pollution than previous simulation studies using available price elasticities suggests. When conducting policy analysis of the impact of price changes on the demand for a certain good or service, it would thus be important to consider the source of the price variation (Li, Linn, and Muehlegger, 2014). The salience finding also has implications for calibrations of optimal tax rates (combining Pigouvian and Ramsey taxation).

When numerically calculating the optimal gasoline tax for the UK and the US, Parry and Small (2005) use estimates of the price elasticity of demand for gasoline in each country. If, however, the absolute value of the tax elasticity is three to four times larger than the corresponding price elasticity, using the correct tax elasticity will result in a lower optimal tax rate. Finally, a central assumption in public economics is that agents fully optimize when it comes to tax policies and thus react in a similar way to tax changes as to equivalent price changes. Chetty, Looney, and Kroft (2009) points out that canonical results in the analyses of tax incidence, efficiency costs and optimal income taxation all rely on this assumption. Analyses of the economics of climate change thus ought to take into consideration the finding that consumers' response to carbon taxes may be larger than existing estimates of price elasticities of demand indicate.

Appendix: Data Sources

- CO_2 emissions from transport. Measured in metric tons per capita. Source: The World Bank (2015) WDI Database. Available at: data.worldbank.org/indicator.

- GDP per capita (PPP, 2005 USD). Expenditure-side real GDP at chained PPPs, divided by population. Source: Feenstra, Inklaar, and Timmer (2013), "The Next Generation of the Penn World Table". Available at: www.ggdc.net/pwt.

- Motor Vehicles (per 1000 people). Source: Dargay, Gately, and Sommer (2007), "Vehicle Ownership and Income Growth, Worldwide: 1960-2030".

- Gasoline consumption per capita. Measured in kg of oil equivalent. Source: The World Bank (2015) WDI Database. Available at: data.worldbank.org/indicator.

- Urban Population. Measured in percentage of total. Source: The World Bank (2015) WDI Database. Available at: data.worldbank.org/indicator.

- Unemployment rate in Sweden. Source: Statistics Sweden (2015), statistical databases. Available at: statistikdatabasen.scb.se.

- Gasoline prices and taxes in Sweden. Measured in 2005 Swedish Kronor. Source: SPBI (2016). Available at: spbi.se/statistik/priser.

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