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Quasi-Carbon Taxation - The German Eco Tax and Its Impact on CO_2 Emissions

Petrik Runst[a,*], David Höhle[a]

[a] *Volkswirtschaftliches Institut für Mittelstand und Handwerk an der Universität Göttingen, Heinrich-Düker-Weg 6, 37073 Göttingen*

Abstract:

Many countries have only recently introduced carbon taxation to reduce emissions and the time series data for evaluating these policies is not available yet. Consequently, we use the imposition quasi-carbon-taxes in the German transportation sector, i.e. taxes on fuel that are not calculated based on actual CO_2 content but which raise the implicit price of carbon emissions, to evaluate the effectiveness of environmental taxation. Our results indicate that the carbon price increase by about 66 €/t CO_2 led to a considerable decline of transport emissions by 0.2 to 0.35 t per person and year. Our quantitative results as well as a detailed qualitative analysis of a German car manufacturer's business reports suggests that the tax triggered an improvement in engine technology as well as an increased share of diesel engines.

JEL: H23, Q48, R48

Keywords: Carbon taxation, transport sector, carbon emissions

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[*] Corresponding author. Petrik Runst, Institute for Small Business Economics. Georg-August University of Goettingen; Heinrich-Düker-Weg 6, 37073 Göttingen, Germany; petrik.runst@wiwi.uni-goettingen.de

1. Introduction[1]

The effectiveness of carbon taxation is increasingly gaining research interest. Nevertheless, the data for such endeavors are limited by the fact that many countries have only recently introduced taxation based on carbon content. One of the prime movers is Sweden, where carbon taxation has existed since 1991 and subsequently been raised in various steps. Based on Swedish data, Andersson (2019), Thonipara et al. (2019) and Runst and Thonipara (2020) present evidence of a considerable emission reduction as a result of taxation in the transport and residential sectors, respectively. Whereas older studies compare before-and-after emission levels (Tietenberg, 2013), Andersson (2019) and Runst and Thonipara (2020) use synthetic control methods (SCM) and present evidence for a causal relationship. Some studies such as Shmelev and Speck (2018) and Lin and Li (2011) find little evidence on the effectiveness of carbon taxes in Sweden. However, as later studies highlight, using data on the overall impact within countries can mask important effects on sub-sectors if exemptions exist in many sub-sectors. Following Andersson (2019) and Runst and Thonipara (2020), we concentrate on the transport sub-sector in Germany and its increase in fossil fuel taxation between 1999 and 2003. The imposition of the so-called "eco tax" (*Ökosteuer*) was not based on carbon content, although it can be argued that it constitutes a quasi-carbon tax.

Given that many countries such as Switzerland and Germany have only recently introduced carbon taxes, there is a lack of time series data. In order to evaluate the effectiveness of carbon taxation, researchers must either wait until sufficient data can be gathered from the more recently-introduced carbon taxation schemes or focus on what can be called "quasi-carbon-taxation". We define quasi-carbon taxation as government-mandated taxes on goods that emit CO_2 but are not calculated based on actual CO_2 content, whereby they nevertheless raise the price of CO_2 emissions. Quasi-carbon taxes can be either explicitly motivated by environmental concerns or implemented for other reasons. For example, in 1999 Germany introduced the so-called "eco-tax", a hotly-debated policy whose impact was judged to be either successful in reducing emissions or a mere fiscal tool for generating public revenue without an environmental impact, depending on the commentator in question.[2] Nonetheless, as far as we know, the policy has never been subjected to an empirical evaluation.

The tax applies to fossil fuels used in transport and heating, as well as electricity generation. However, the transport sector has been singled out for the most severe price increases. There have been five annual tax increases by about 3 Euro Cents per liter of fuel (1999-2003). The cumulative taxation level of 15 cents/liter amounts to a quasi-carbon tax of about 66 Euro per ton of CO_2, which represents a more sizable tax than the recently-introduced German carbon taxation scheme, with an initial level of 25 €/tCO_2[3].

Quasi-taxes can be used to evaluate the effectiveness of carbon taxation in the absence of direct, CO_2-content based measures. By choosing this approach, we can contribute to the literature on carbon taxation and emissions in general, and the transport sector in particular, with its current lack of empirical evaluations (apart from Andersson, 2019). In addition, it is important to evaluate direct taxes as well as quasi-Pigovian taxation for a theoretical reason. As Nye (2008) highlights, "any tax calculation that is determined using the size of the measured externality but that does not consider all regulations and transfers affecting equilibrium will not tell us what the optimal tax should be". The author continues to state that "measuring the size of the observed Pigovian externality - even if done perfectly - is not a reliable guide to the proper level of the Pigovian tax" (ibid.), as the effects of all taxes and regulations should be jointly considered. While we do not believe this to be a significant practical problem at the time of writing – when the majority of states are most likely under-taxing emissions – it is a theoretical point well worth keeping in mind. At the very least, policy-makers need to be aware of the combined effects of all existing taxes (and regulations) when designing environmental legislation.

2. Methods & Data

We employ SCMs, which use several donor countries as comparison units and construct a synthetic control group from a weighted average of these donor-pool countries` observable characteristics (see: Abadie, Diamond, and Hainmueller, 2015; Abadie and Hainmueller, 2014; Abadie, Diamond, and Hainmueller, 2010). In order to estimate the effect of the quasi-tax in Germany, we require a synthetic German transport sector that closely tracks carbon emissions in the actual German transport sector prior to the tax. We then compare the transport emissions in Germany with those in the synthetic control group (our counterfactual scenario) after the imposition of the tax.

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[1] We are grateful for the excellent research support by Kübra Dilekoglu and Carsten Philipp Brockhaus.

[2] In favor: Uwe Nestle, CEO of Ökologisch-Soziale Marktwirtschaft (ecological and social market economy), in an interview with the public radio station Deutschlandfunk, March, 29, 2020; and opposed: Rainer Kambeck (DIHK, Association of German Chambers of Industry and Commerce), in an interview with the magazine "Wirtschaftswoche", April 2014; see also the press statement by DIW (economic research institute) of March 27, 2019.

[3] The carbon tax will subsequently increase to about 55 €/ tCO_2 in 2026.

In order to select predictor weights, we use a fully-nested optimization method, which yields more precise estimates (Mcclelland and Gault, 2017). The model takes the following form:

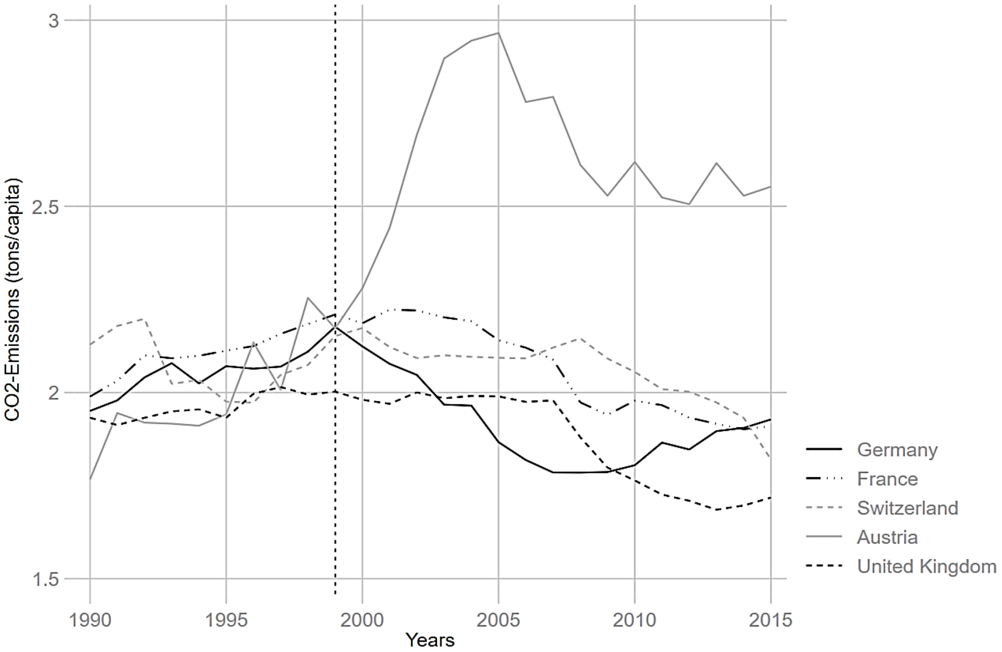
$$\sum_{m=1}^{k} v_m \, (X_{1m} - X_{0m}W)^2$$

Vector X_1 represents the characteristics of the treated unit – i.e. Germany – in the period prior to treatment, while m represents the comparison country. Vector X_0 captures the characteristics of the comparison units, which are multiplied by the vector of weights (W) of the control countries. Thus, $(X_{1m} - X_{0m}W)$ captures the difference between the treated unit and the comparison units. v_m is the weight for each comparison country. In the case of the synthetic control W*, the weights are chosen such that the difference $(X_{1m} - X_{0m}W)$ is minimized, meaning that it best resembles the German transport sector prior to 1999.

We follow Abadie et al. (2015), Abadie and Hainmueller (2014), and Abadie et al. (2010) in using several combinations of outcome lags. We ensure a good pre-treatment fit by using the specification with the lowest RMSPE value, the root mean squared prediction error. However, Kaul et al. (2015) and Klößner et al. (2018) demonstrate that including multiple lagged outcome variables alongside control variables can pose a problem, as the SCM algorithm tends to assign very high predictor weights (V-weights) to lagged outcomes and very low predictor weights to other covariates. We will therefore report predictor weights of all covariates to test whether the matching algorithm exploits the information contained in the covariates.

In order to control for a wider range of covariates and cross-validate our findings, we employ two separate data sets (see Table 1 for a description of all variables and appendix A1 for descriptive statistics). The first data set was largely obtained from Eurostat and the European Commission, supplemented by data from the OECD, the International Energy Agency (IAE) and the Ameco database. It contains country-level data for 31 European entities, from which we remove Sweden because it has implemented and raised a carbon tax during the period under consideration. We are left with 23 countries with non-missing information.[4] The panel data set covers the period from 1993 to 2005. The limited (pre-treatment) timeframe represents the main disadvantage of data set one, while the wider availability of relevant covariates such as fuel prices and road length represents its main appeal.

Figure 1. Development of transport carbon emissions over time (selected countries)



Source: Eurostat

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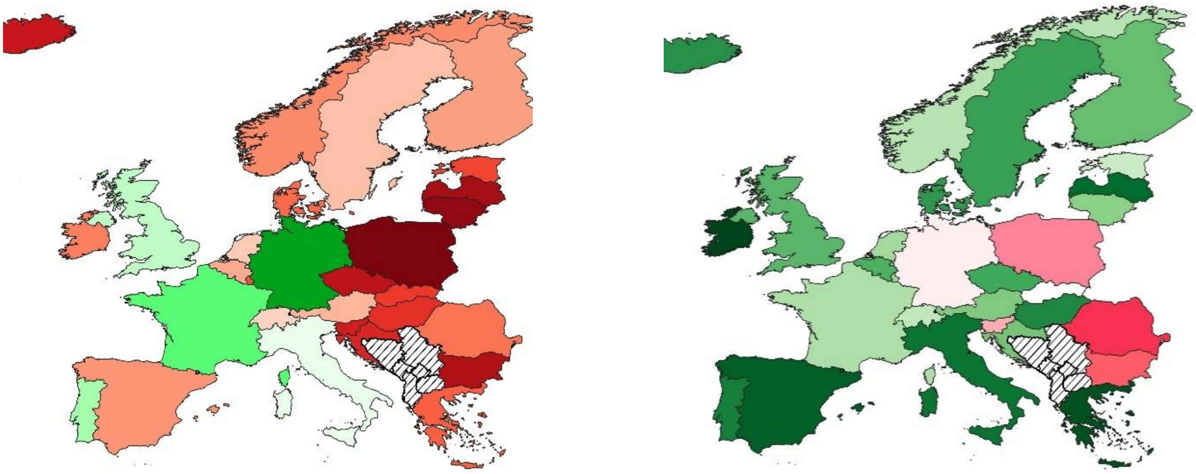
[4] Germany, Belgium, Bulgaria, Croatia, Czechia, Denmark, Estonia, Finland, France, Greece, Hungary, Italy, Latvia, the Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Switzerland, the United Kingdom.

Figure 1 depicts the development of transport carbon emissions for selected countries over time. In Germany – our treatment country – emissions slowly increase during the 1990s and peak in 1999, after which they decline until 2007 to 2009 and then increase again. Germany is the only country that displays a considerable emissions decline after 1999. There is also some decline in emissions in France, but it is of lower magnitude and sets in around 2004. It is noteworthy that Austria exhibits an emission decline after 2005. The joint decline in emissions in many countries emissions around 2007/08 is most likely a result of the economic crisis during this period.

Figure 2. Change in transport carbon emissions by country



2002 to 2007

2007 to 2012

Source: Eurostat, own depiction in QGIS.

Notes: Green areas depict emission reductions; red areas depict increases in emissions. Darker colors denote larger values. Countries with missing data are depicted as shaded areas. Iceland was moved south-east for illustration purposes.
In the 2002-07 period, the values range from -12.8% (Germany) to 61.9% (Poland). In the 2007-12 period, the values range from -29.1% (Ireland) to 21.9% (Romania). In the latter period, German emissions increase by 3.4%.

Figure 2 displays the percentage change in transport emissions for all countries in data set one for two five-year periods (2002-07 and 2007-12). While emissions fell in France (-5.9%), the UK (-1.1%), and Portugal (-5%) in the 2002-07 period, the decline in Germany is more than twice as large (-12.8%). Eastern European countries display a strong emissions increase, which can most likely be explained by rapid economic growth. During the 2007-12 period, the development of carbon emissions is clearly affected by the economic crisis of 2007/08, in which the hard-hit Mediterranean countries as well as Ireland exhibit a distinct decline in emissions, most likely caused by the business cycle shock. Figure A (see appendix) displays the positive relationship between the change in income and the change in emissions in the 2007-12 period.

Table 1. Variables and data sources

Variable	Source	Description
Data Set One – European countries (N=23)		
Carbon emissions	Eurostat	Tons of CO_2 from road transportation
Fuel prices (net of taxes)	European Commission, Supplemented with OECD/IEA data	In Euros per 1000 l, fuel type RON95 (average prices per year, without taxes)
National disposable income	Ameco database	Billion Euros/ ECU
Population	Eurostat	-
Passenger kilometers	Eurostat	in km per year
Road length	Eurostat	State roads in km
Rail freight	Eurostat	In tons
Motor Fuel	Eurostat	In TOE, tons of oil equivalent
Data Set Two – Worldwide data (N=25)		
Carbon emissions	Carbon Dioxide Information Analysis Center (CDIAC), also UN energy statistics, US Department of Interior's Bureau of Mines, and World Bank	Tons of CO_2 from road transportation
GDP per capita	World Bank	US$ per capita
Road density	Global Roads Inventory Project (GRIP)	meters per km^2

In order to compensate for the main shortcoming of data set one (limited pre-treatment data), the data provided by the CDIAC enables us to expand the analysis back to 1970. This allows for an improved fit in the pre-treatment period. The dataset is available from Boden et al. (2017) and their methods are outlined in Boden et al. (1995). As sources of CO_2 emissions, they consider the consumption of several fuels and cement production. Data on fuel consumptions can be can be obtained from the UN energy statistics. Fuel consumption is then translated into CO_2 emissions using a simple equation considering the properties of different fuel types. Bunker fuels for international transport are excluded. Data on cement production are obtained from the US Department of Interior's Bureau of Mines. The resulting emissions can be calculated using the tons of cement production and the average calcium oxide content of the cement produced.

This dataset has some noteworthy features: until 1990, the data for Germany was disaggregated into the western Federal Republic of Germany and the eastern German Democratic Republic. Afterwards, the data is only available for reunited Germany. The unification process was associated with a de-industrialization process in the east. Consequently, there is a CO_2 emissions decline around the year of reunification, especially from 1990 to 1991. As the overall trend around this year is consistent, the data can be used for the SCM analysis, although we expect a somewhat lower pre-treatment fit for 1990 to 1992.

The amount of CO_2 emissions from traffic is not directly available from the CDIAC dataset, although it can be easily calculated in combination with the World Bank data on the share of traffic emissions from fuel combustion.[5]

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[5] The CDIAC data differentiates between different sources of emissions and their total. The sources included are different forms of fuel and

As additional predictors, GDP per capita from the World Bank and the density of the road network are included. The control variable of road density was obtained from the Global Roads Inventory Project (GRIP, see Meijer et al., 2018). The raster file map contains worldwide data on road density. Each raster cell has a size of 5 arcminutes (Or roughly 9 km). Within each cell, road density is measured in meters per square km. We use the QGIS software to generate an average road density by country. Data set two contains 25 developed countries.

3. Results

3.1. Results for data set one – European data

3.1.1. Transport emissions decline

The baseline SCM results are presented in Figure 3.A. We plot the difference in transport emissions between Germany and its synthetic counterpart. The first specification uses two lags of the outcome variable (1993 and 1997). The second specification adds two additional covariates – i.e. road length and disposable income – and specification three ads passenger km and rail freight. Despite the low number of pre-treatment years, the matching algorithm works well and all pre-treatment values remain close to zero. Between 1999 and 2005, all three lines fall as emissions in Germany decline relative to its synthetic counterpart. We do not display values after 2005 (which keep falling until 2007 and then slowly and steadily increase) due to the low number of pre-treatment years in data set one. The emissions reduction in Germany in 2005 amounts to 250 kg, or about 11.5% of transport emissions in 1999. Country weights for all specifications are reported in appendix Table A2. France, the Netherlands, and Switzerland are mostly used to construct a synthetic Germany for the three specifications in Figure 3.A.

As stated in the methods section, when using multiple lags, the algorithm may assign high predictor weights to lagged outcome variables and consequently low predictor weights on other covariates (Kaul et al., 2015; Klößner et al., 2018). For two of the three specifications in Figure 3.A, the predictor weight mostly lies on the lagged outcome variables, although income plays a somewhat important role (see appendix Table A4). Another set of specifications (Figure 3.B) is designed to more extensively exploit the information contained in the covariates. We use alternative lags, as well as single lag, and a no-lag model to generate specifications with higher covariate predictor weights and test the robustness of our baseline results. As can be seen in Figure 3.B, this new set of specifications confirms our baseline results. Pre-treatment differences between Germany and its synthetic counterpart are small and post-treatment effects are slightly larger than before. The emission reduction amounts to about 350 kg in 2005, i.e. a 16% decrease compared with 1999 emission levels. The country weights also remain similar to those used in the baseline specifications (France, the Netherlands, Switzerland) although Belgium, Denmark and Finland start playing a more important role in generating the synthetic control group (see appendix Table A2). The predictor weights of our variables for road length, income, passenger km, and rail freight are larger in some of these specifications (see appendix Table A3). The variable ‘fuel price’ – which is also included in some of these specifications – does not contribute to the predictive power of the models.

3.1.2. Mediation Channels

The SCM results presented in Figure 3 (A and B) provides first empirical evidence of moderate to sizable emissions reduction as a result of the quasi-carbon tax of about 66 €/t $C0_2$ on motor fuel. The next two panels of Figure 3 (C and D) present a different set of specifications in which we seek to explore the channels through which the emissions reduction is achieved. First, we investigate whether and how the implementation of the tax in Germany affects the amount of fuel used per year. Therefore, we perform additional SCMs for the dependent variable of motor fuel per capita (see Figure 3.D). The matching algorithm works well and the differences between real and synthetic Germany in the pre-treatment period are small. There is a temporary increase in fuel consumption in 1999. Starting in 2002 or 2003, fuel consumption noticeably declines. Thus, there seems to be a lag of three to four years until the tax affects motor fuel consumption. In 2005, we observe a decline by 38 to 58 TOEs (total oil equivalents) compared with 1999 levels, which amounts to a relative decline of 9.6% to 14.7%. In constructing the synthetic counterfactual, Denmark and the United Kingdom are the most heavily-weighted countries (see appendix, Table A2) and apart from lagged outcome variables, state roads and fuel prices display the highest predictor weights (see appendix, Table A3).

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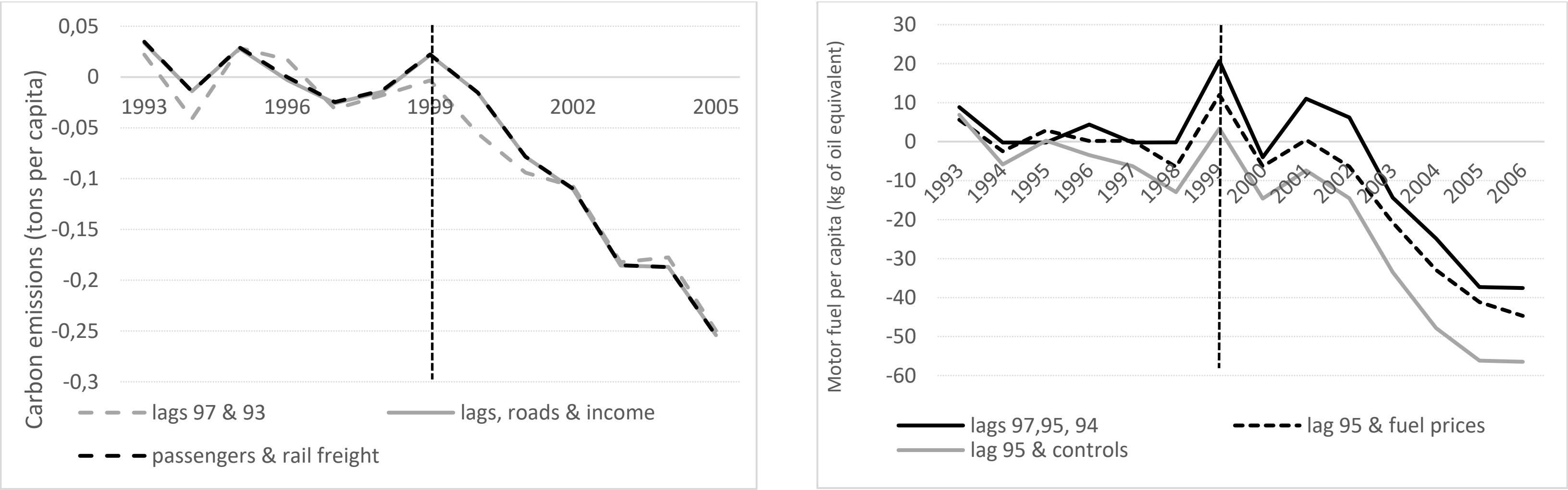
cement production, where CO_2 emissions are a chemical byproduct. Hence, the CO_2 emissions associated with cement production are subtracted from the total of the CO_2 emissions. Next, they are multiplied by the share of traffic emissions from total fuel combustion and then divided by the population and multiplied by 1,000, so that the result is the number of tons per capita of CO_2 emissions associated with traffic.

As the passenger driving distances in Germany steadily rise across the whole time period, the reduction in motor fuel consumption is most likely not the result of transport mode substitution (e.g. due to an increased use of trains) nor is it caused by less overall road transportation. In fact, an unreported SCM specification – in which we use passenger km as the dependent variable – does not yield any evidence for a reduction in road transportation in Germany. The decline in motor fuel consumption is most likely the result of increased fuel efficiency, which in turn can be achieved by a changing vehicle fleet composition (e.g. smaller cars, different fuels) or technological improvements. However, the small-car hypothesis seems to be a priori unlikely. Data on the vehicle composition (see appendix, Table A6) shows some increase in the sales share of small cars, albeit which is compensated by a similar decline in the sales share of mini cars. In addition, the sales share of large vans rapidly expands during the period, which speaks against the hypothesis of a changing fleet composition. The two most likely mediation channels are therefore a switch from gas to diesel – because diesel engines emitted less CO_2 in this time period – and some form of technological improvement. The three to four year lag of the decline in motor fuel consumptions further hints at the possibility of technological improvements, as producers need time to respond to changing market conditions caused by the tax.

Figure 3.D displays a number of SCM specifications for the dependent variable of the share of diesel vehicles. The pre-treatment matching seems to be acceptable but worse than in previous SCM models and the results must be interpreted with caution. In contrast to motor fuel consumption, the diesel share only responds with a small lag of one year after the imposition of the tax. In 2005, the share of diesel cars has risen by 2% compared with the synthetic control group, which is largely composed of Croatia, Denmark, the Netherlands and Poland (see appendix, Table A2).

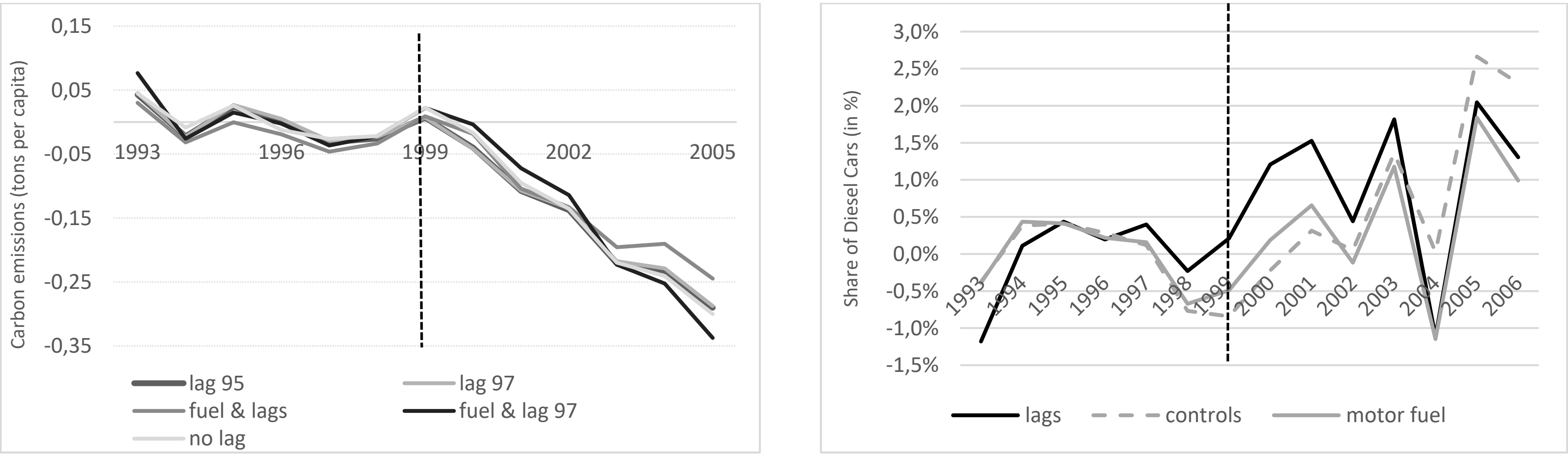
In summary, the causal effect of quasi-carbon taxation on transport emissions seems to be mediated by a decline in motor fuel consumption, which is most likely the result of technological improvements. In addition, there is some evidence of an increase in the share of diesel cars, which emitted less CO_2 in the time period under consideration.

Figure 3. Synthetic control specifications, data set one (European data)



3.A. Baseline results (Dep. var. carbon emissions)

3.C. Mediation channels (Dep. var. motor fuel consumption per capita)



3.B. Additional specifications (Dep. var. carbon emissions)

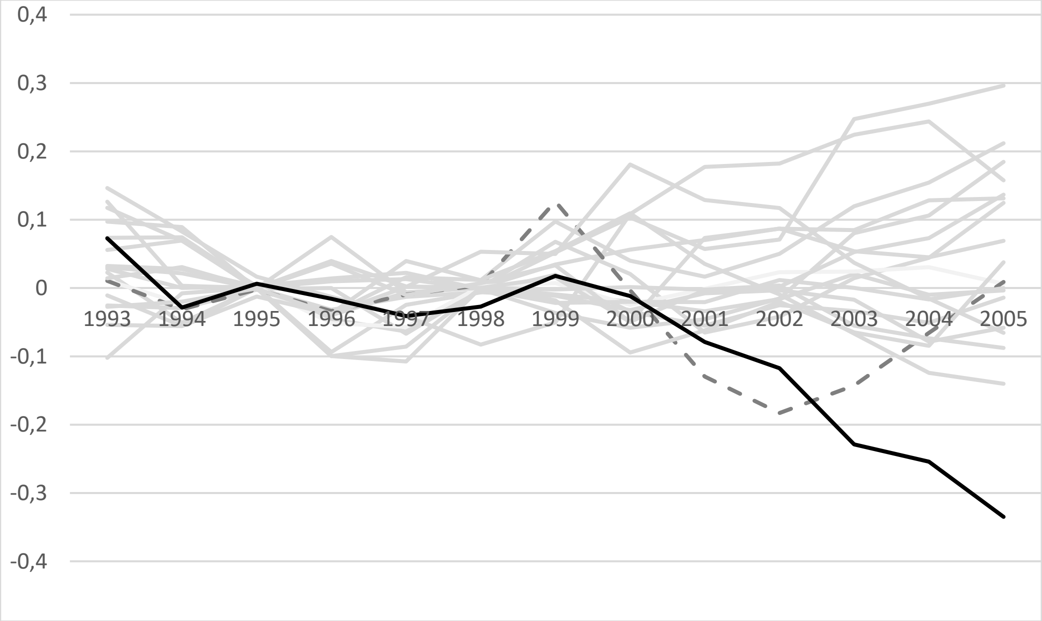
3.D. Mediation channels (Dep. var. share of diesel cars)

Source: Authors' calculations

3.1.3. Placebo Tests

We run a country placebo test to ensure the robustness of our results, using data set one. Figure 4 plots the results of this placebo test based on our baseline specifications (see Figure 3.A), using 1998 and 1995 as lagged outcomes. Each line represents a separate synthetic control model. Germany is depicted in black. We cycle through all sample countries, iteratively assigning treatment status to each of them. The graph displays the resulting differences in the outcome variable between each treatment country and its synthetic counterpart. We omitted countries for which the minimization of pre-treatment differences did not work (i.e. if the pre-treatment deviation from the real carbon development exceeded 10% in more than one year); for example, Slovenia, Romania, and Estonia. There is only one country besides Germany that displays a visible emissions decline after 1999, i.e. Poland (dashed line). However, the emissions reduction in Poland appears to be only temporary (2001 to 2003), whereas the German emissions continue to fall over time. Overall, the placebo test constitutes additional evidence for the causal impact of the eco tax on transport emissions reduction.

Figure 4. Placebo test, data set one



Source: Authors' calculations

3.2. Results for data set two (global data)

We test several different models in search of the best fit in the pre-treatment period. We include three equidistant lags for the entire pre-treatment period, and one additional lag for the final pre-treatment year. Out of ten models, the best-performing ones contain dummies for 1972, 1982, 1992 and 1998. The synthetic emissions closely follow the true emissions and display no structural departures (see Figure 5.B). As expected, there is a small deviation between real and synthetic Germany in the immediate post-reunification period. However, the deviation does not exceed 6% in any specification and it quickly vanishes after two years. In the post-treatment period, the emissions for real Germany are considerably lower than those in synthetic Germany. We include the explanatory variables, road density and GDP per capita. The predictor weights of these covariates are small due to the inclusion of multiple lagged outcome variables. Hence, we search for an alternative model with fewer lags, in which the explanatory variables are more substantially weighted. When including two lagged outcomes 1975 and 1995, GDP per capita plays a stronger role (see Figure 5.C), whereas road density seems to be less important. The RMSPE value is still quite satisfactory when compared with our baseline models. In the pre-treatment period, deviations between emissions in real and synthetic Germany remain within a 5% band, except for 1990. In the treatment period, there is a strong decline in emissions, starting in 2000.

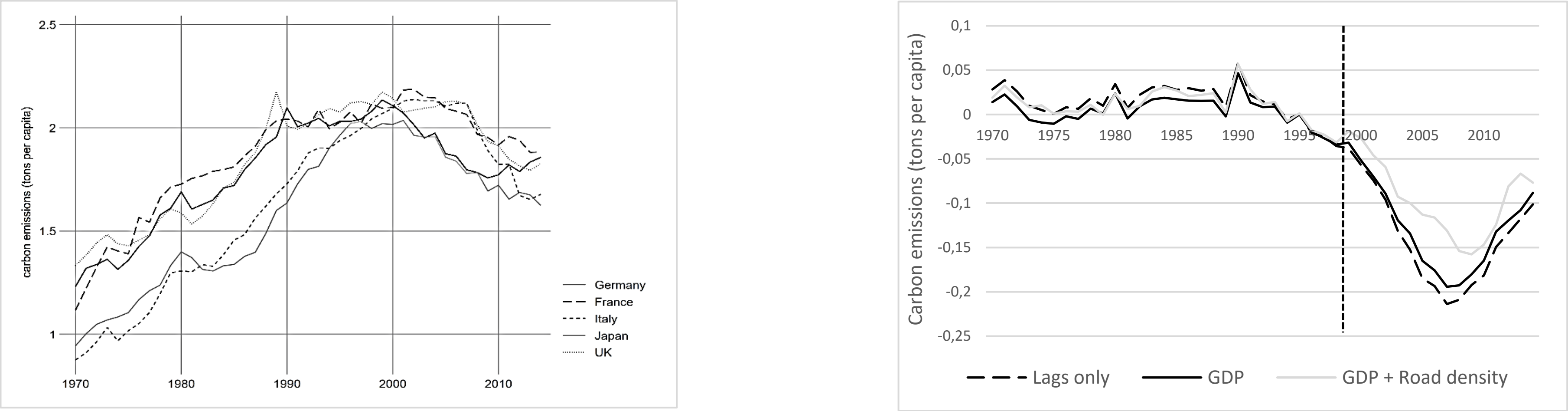
Country weights are reported in appendix Table A4. In the baseline specification, synthetic Germany is constructed by weighting the emissions in Belgium, Switzerland, and Iceland. All other countries enter the calculation to a much lower extent. In the two-lag model, we again find Belgium as the most heavily-weighted country. Overall, the two-lag specification utilizes a broader combination of all countries, while emphasizing Belgium in the full specification that includes covariates. As expected, the predictor weights display larger weights on lagged outcomes and no weight on covariates in the baseline specification (see appendix, Table A.5). By contrast, the two-lag specification utilizes the information of the covariates, most importantly GDP per capita.

Finally, we also perform a placebo analysis in the global sample, iteratively assigning treatment status to each country (see Figure 5.D). We remove any countries for which the pre-treatment fit is not acceptable, i.e. if it is larger than 10% for more than two years. We use the best fitting model with outcome lags for 1998, 1992, 1982, and 1972, as well as the two covariates. However, the results are nearly identical when using the two-lag model. Germany clearly displays a considerable treatment effect and the decline in carbon emissions is stronger than in most other countries. However, a number of countries also display a large decline in transport carbon emissions during the treatment period, most notably Japan, France, Italy, and the UK. It is instructive to compare these SCM results with the descriptive graph in Figure 5.A. We can see that the decline in carbon emissions in France, Italy, and the UK sets in much later, around 2008 or 2009. It is therefore most likely the result of technology spill-overs – where German cars are purchased or manufacturers adopt fuel saving technologies – and an emissions decline due to the business cycle shock. By contrast, we will analyze the emissions decline in Japan in further detail in the discussion section. Overall, Germany displays a considerable emissions reduction compared with the countries in the global sample, such that its line lies at the bottom of the placebo graph. Thus, the evidence supports our main hypothesis in that the eco tax reduced transportation carbon emissions in Germany after 1999.

Figure 5. Synthetic control specifications, data set one (world data)

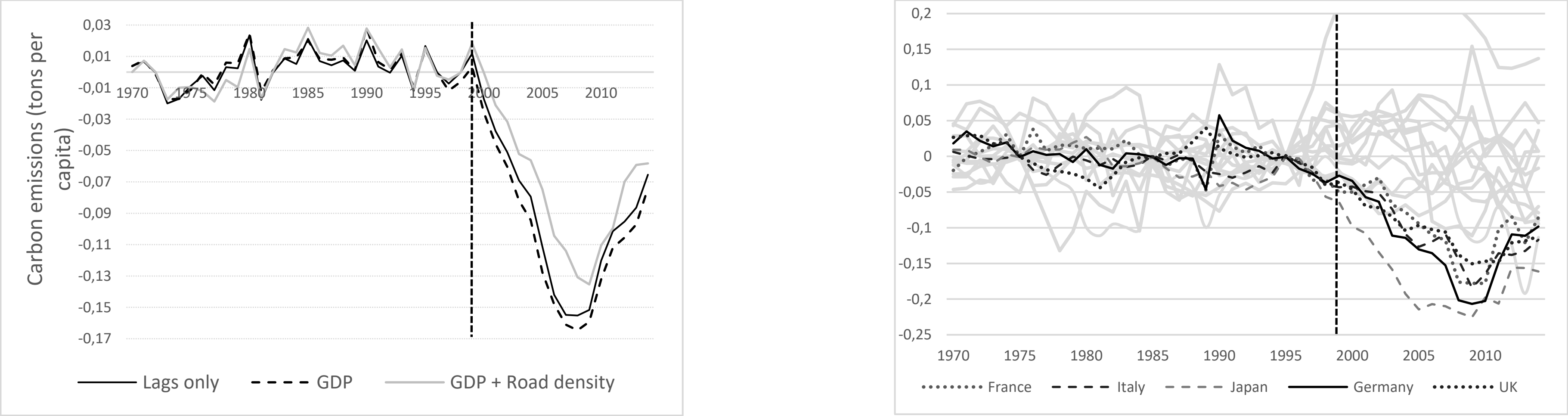
5.A. Descriptive statistics

5.C. Additional specifications with two outcome lags



5.B. SCM Baseline results

5.D. Placebo test



Source: Authors' calculations

4. Discussion

4.1. Confounding factors

The SCM placebo tests show that few countries besides Germany display a significant decline in transport emissions in the treatment period, potentially pointing to the existence of confounding factors. While the UK, Italy and France display some decline in emissions according to the placebo model in data set 2, the descriptive data shows that the decline in emissions only occurred only after 2008, and thus it is most likely the result of the financial crisis and technology spillover.

However, Japan exhibits a visible decline in transport emissions during the treatment period. We performed a literature review to explore the most likely causes for this development. Between 1999 and 2008, nominal CO_2 emissions from the Japanese transport sector decreased from 261 to 234 Mt CO_2 and the carbon intensity of road consumption declined by 0.3 g CO_2/MJ (IEA 2021a). The reduction is most likely caused by the 1998 revision of the Act on the Rational Use of Energy (Energy Efficiency Act), which extended the so-called Top Runner Program to passenger and freight vehicles (IEA 2021b; Foundation for Promoting Personal Mobility and Ecological Transportation 2020; Energy Conservation Center Japan 2021). The program adopts a largely market-based approach. It sets the energy efficiency target equal to the most energy efficient vehicle currently available in the market but also incorporates expected future technological change (Kimura 2010). The first vehicle emissions standard was set in 1998 and it therefore represents a likely explanation for the Japanese emissions decline that we find in our empirical results.

Another set of confounding factors may arise at the European level. In fact, there were voluntary agreements between the European Commission and European, Japanese and Korean car manufacturers to reduce emissions from new passenger vehicles for 1998 and 2000 (Fontaras and Samaras 2007; Banister 2007). The agreements stipulated target emissions of 140g CO_2/km for the average passenger vehicle in 2008 (Fontaras und Samaras 2007). However, the emission reduction target was not met by 2008 (EEA, 2011). Most importantly, if the policy had been effective, we should have seen evidence of a simultaneous emission decline in many European countries. Consequently, we can rule out this explanation with some degree of certainty. We conclude that the German eco tax is the most likely explanation for the decline in transport emissions that we observe in Germany after its implementation in 1999.

4.2. Secondary evidence: Volkswagen's response to the eco tax

The development and subsequent sale of a new engine technology – i.e. gasoline direct injection (FSI, Fuel stratified injection) – coincides with the timing of the reduction in motor fuel consumption beginning in 2002. The first vehicle to utilize this technology was the small sized VW Lupo 1.4 FSI (VW environmental report, 1999:44), which was named the as most fuel-efficient car by a large automobile association in 2003/04 (VCD, 2003). Volkswagen's annual report asserted in 1999 that FSI would be the most important future engine technology (VW report 1999:40). Similarly, VW's environmental report of 2001/02 describes it as a future technology with a considerable potential to save fuel. It also states that FSI engines would be installed in most VW models by the 2005 (VW environmental report 2001/ 2002: 42). VW began implementing the FSI technology in mid-sized and larger cars (Audi Nuvolari Quattro, Audi Gran Tourismo) around 2003 (VW report 2003:100). By 2004, it appears to have permeated the majority of its models (VW Golf, Seat Altea, Audi A4, see VW annual report 2004).

The diesel direct injection (TDI) already existed in 1999 and started to be widely employed across diesel vehicles in the following years. It was further refined in creating the CSS or Combined Combustion System (see VW environmental report 1999/2000:52). The development of next-generation direct diesel injection (TSI) was implemented in 2005 with the goal to save fuel and lower emissions (VW annual report 2005:18).

Overall, Volkswagen developed fuel saving technologies in advance of other manufacturers as several ecology ratings list their FSI and TDI/TSI cars as the most fuel-efficient ones in the 2002-06 period (Öko-Trend; 1997-2008; VCD, 2003). The decline in fuel consumption suggested by our empirical results – which began around 2002/03 – is therefore a plausible consequence of the introduction of the FSI engine, whose more rapid development was likely spurred by the imposition of the eco tax. In fact, the VW 2000 annual report explicitly states that the eco tax poses a risk for VW's business model, which needed to be mitigated by introducing more fuel-efficient technologies (VW report 2000:40).

Similarly, the immediate increase in the diesel share after 1999 also appears to be a plausible response to the imposition of the eco tax because the technology was already available in many car models. Diesel fuel was not subject to the eco tax and diesel cars emitted less CO_2 at the time. The fuel substitution from gasoline to diesel is therefore another likely – if minor – contributor to the fall in transport carbon emissions after 1999.

5. Summary

We have analyzed the effectiveness of the German eco tax, which was implemented in 1999 and raised the price of automotive fuel by about 15 cents per liter, which amounts to a sizable quasi-carbon tax of about 66 € / t CO_2. We have used SCM on European and global data, and our findings suggest that annual transport emissions have declined by 0.2 to 0.35 t CO_2, which represents a considerable decrease in emissions.

Of course, causality can never be establish with certainty. It is conceivable that the development of new engine types such as FSI gasoline direct injection or the broader implementation of the already-existing diesel direct injection (TDI) was already under way and it incidentally coincides with the tax implementation. Nevertheless, the timing of the innovation as well as statements in Volkswagen's business reports speak in favor of a causal connection. After the eco tax was implemented, the share of cars using non-taxed diesel increased immediately. By contrast, motor fuel consumption decreased with a time lag of three to four years as the new FSI technology required some years to be developed and applied in all models. In addition, the Volkswagen annual reports identified the eco tax as a business risk, which was to be explicitly mitigated by introducing these new technologies. Overall, the evidence suggests that (quasi) carbon taxation can spur companies' environmental innovation, and thereby cause significant emissions reductions.

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Appendix

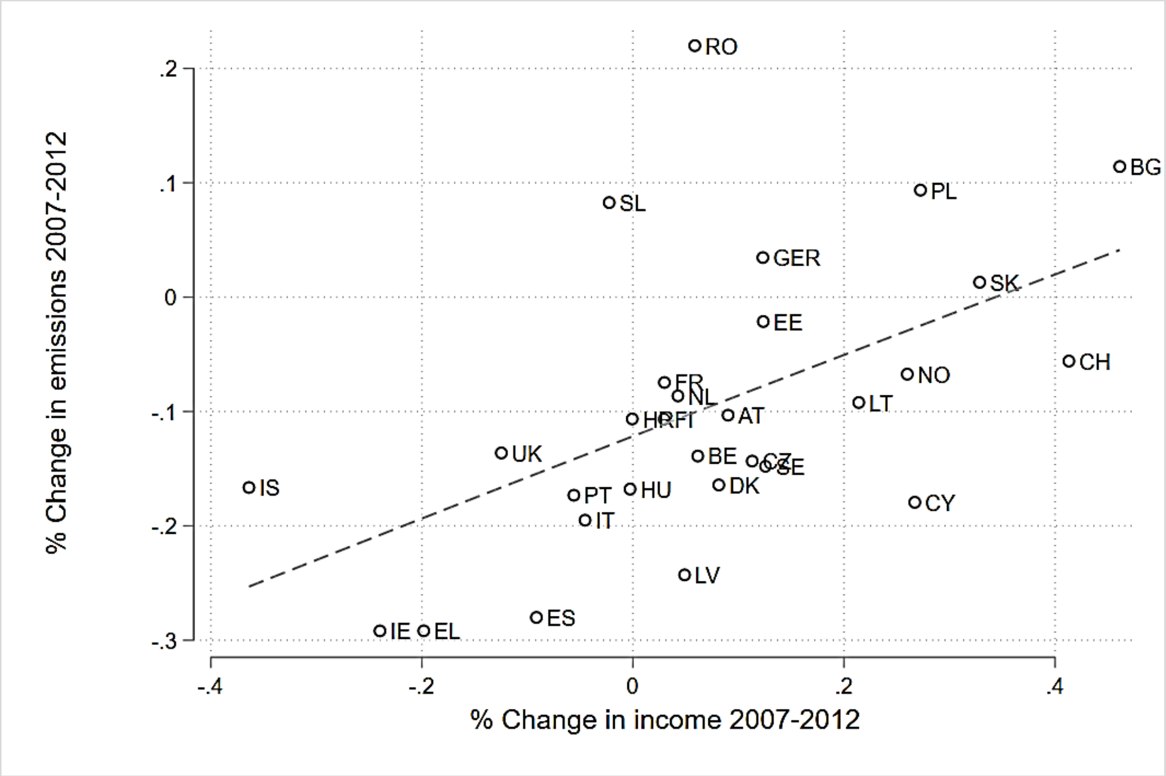
Table A1. Descriptive statistics

	Data set 1, European data			
	1991-1998		**1999-2005**	
Variable	**Mean**	**St.dev.**	**Mean**	**St.dev.**
Emissions per capita (from transport)	1.47	0.65	1.71	0.68
Road length (in km per 1000 people)	3.57	5.69	3.20	4.28
Income per capita	11,256.73	8,067.64	16,257.45	10,828.69
Passenger km per capita	6,999.74	4,583.25	8,171.33	4,441.87
Rail freight per capita (in tons)	1,117.83	1,075.98	1,333.36	1,746.42
Motor fuel per capita (in 1000 TOE)	268.51	132.39	259.50	129.55
Share of diesel cars	39.31	36.78	75.55	59.64
price of Super95 ***(1000 liter, w/out taxes)***	216.40	51.56	372.26	89.41

	Data set 2, Global data			
	1982-1998		**1999-2014**	
Variable	**Mean**	**St.dev.**	**Mean**	**St.dev.**
Emissions per capita (from transport)	2.28	1.49	2.83	2.29
GDP per capita	32,562.89	15,015.58	43,138.23	20,843.56
road density	847.68	600.41	847.68	600.41

Source: Eurostat, CDIAC, World Bank (see Table 1)

Figure A1. Change in income and emissions, 2007 to 2012



Source: Authors' calculations

Table A2. Country weights, data set one (European data)

	Figure 3.A			**Figure 3.B**					**Figure 3.C**			**Figure 3.D**		
	lags 97 & 93	lags, roads & income	passengers & rail freight	lag 95	lag 97	fuel & lags	fuel & lag 97	no lag	lags 97,95, 94	lag 95 & controls	lag 95 & fuel prices	lags 98,95, 94	lags & controls	fuel
Belgium				0.154	0.16			0.183	0.003	0.001			0.152	0.212
Bulgaria									0.001					
Croatia									0.004			0.425		
Czechia									0.004					
Denmark							0.404		0.023	0.47	0.324		0.132	0.274
Estonia									0.048					
Finland			0.012			0.003	0.146		0.08		0.023			
France	0.487	0.621	0.615	0.565	0.551	0.962	0.426	0.535	0.008	0.001	0.077			
Greece				0.056	0.053				0.007	0.001				
Hungary									0.004					
Italy									0.008	0.002				
Latvia			0.002						0.005					
Netherlands		0.246	0.227	0.042		0.005		0.263	0.007	0.001			0.342	
Norway									0.045	0.016				
Poland									0.003			0.575	0.374	0.514
Portugal									0.005	0.001				
Romania									0.002					
Slovakia					0.006	0.03	0.024	0.019	0.003					
Slovenia									0.028					
Spain									0.008	0.001				
Switzerland	0.513	0.133	0.144	0.183	0.23									
United Kingdom									0.705	0.504	0.576			

Source: Authors' calculations

Table A3. Predictor weights, data set one (European data)

	Figure 3.A			Figure 3.B					Figure 3.C			Figure 3.D		
	lags 97 & 93	lags, roads & income	passengers & rail freight	lag 95	lag 97	fuel & lags	fuel & lag 97	no lag	lags 97,95, 94	lag 95 & controls	lag 95 & fuel prices	lags 98,95, 94	lags & controls	fuel
Lag 98												34.53%	32.99%	36.77%
Lag 97	30.56%	6.82%	41.07%		0.00%	0.03%	18.91%		30.51%					
Lag 95				0.08%		38.94%			59.47%	83.99%	0.85%	0.06%	59.59%	62.70%
Lag 94									10.02%			65.40%		
Lag 93	69.44%	6.59%	39.48%											
state roads		0.06%	1.78%	35.24%	2.17%	60.89%	0.94%	99.78%		12.07%	0.41%			
income		86.54%	14.99%	57.50%	0.00%	0.00%	29.51%	0.03%		3.95%	0.12%		0.00%	0.21%
passenger km			1.98%	7.16%	64.77%	0.00%	1.26%	0.12%		0.00%	0.00%		0.00%	0.00%
rail_freight			0.70%	0.01%	33.06%	0.13%	46.46%	0.01%			0.06%			
fuel price						0.00%	2.92%	0.06%			98.56%			

Source: Authors' calculations

Table A4. Country weights, data set two (global data)

	Figure 5.A			**Figure 5.B**		
	Lags only	GDP	GDP + Road density	Lags only	GDP	GDP + Road density
Australia	0.02	0.03		0.03	0.02	0.01
Austria	0.01	0.02		0.04	0.04	0.01
Belgium	0.02	0.02	0.43	0.04	0.04	0.60
Canada	0.01	0.02		0.02	0.02	0.01
Denmark	0.02	0.02		0.03	0.04	0.01
Finland	0.02	0.02		0.04	0.03	0.01
France	0.03	0.03		0.04	0.04	0.01
Greece	0.02	0.02		0.08	0.07	0.07
Hungary	0.01	0.03		0.05	0.03	0.02
Iceland	0.12	0.07	0.13	0.03	0.03	0.01
Ireland	0.01	0.01		0.04	0.04	0.02
Italy	0.03	0.03		0.04	0.05	0.02
Japan	0.02	0.02		0.04	0.05	0.01
Luxembourg	0.02	0.03	0.00	0.03	0.02	0.00
Netherlands	0.02	0.01	0.06	0.04	0.04	0.00
New Zealand	0.01	0.02		0.03	0.03	0.01
Norway	0.02	0.02		0.03	0.03	0.01
Poland		0.02		0.04	0.03	0.02
Portugal	0.02	0.02		0.06	0.06	0.02
Spain	0.02	0.02		0.04	0.04	0.02
Switzerland	0.38	0.35	0.31	0.04	0.12	0.07
Turkey	0.15	0.16	0.07	0.11	0.10	0.03
United Kingdom	0.02	0.02		0.04	0.03	0.01
United States	0.01	0.01		0.02	0.02	0.01

Source: Authors' calculations

Table A5. Predictor weights, data set two (Global data)

	Figure 5.A				Figure 5.B		
	Lags only	GDP	GDP + Road density		Lags only	GDP	GDP + Road density
Lag 1972	0.00	0.00	0.27	**Lag 1975**	0.54	0.33	0.00
Lag 1982	0.98	0.00	0.27	**Lag 1995**	0.46	0.00	0.01
Lag 1992	0.01	0.93	0.33	**-**	-	-	-
Lag 1998	0.01	0.07	0.12	**-**	-	-	-
GDP per cap		0.00	0.00	**GDP per cap**		0.67	0.99
Road density			0.00	**Road density**			0.00

Source: Authors' calculations

Table A6. Vehicle sales share by class size

	1999	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
Mini	7.1	6.8	6.8	5.9	4.5	3.7	4	4.4
Small	15.9	16.6	16.6	18.6	19.7	18	17.6	17.6
Compact	30.9	29.1	27.4	26	23.7	25.5	26.9	24.9
Medium	22.5	21.8	25	23.2	21.3	18.7	17	16.6
Medium +	8.3	8.9	7.2	7.6	7.7	7.7	6.4	5.8
Luxury	1.3	1.3	1.2	1.1	1.2	1.2	1.1	1.2
Off Road	2.8	2.9	3	3.9	4.8	5.5	5.8	6.5
Convertibles	2.7	3.4	3.5	3.7	4.4	4.9	4.4	4.2
Vans	5.9	6.8	6.8	7	9.7	11.8	12.8	13.6
Utility	2.3	2.3	2.1	2.3	2.3	2.8	3.8	4.3
Other	0.3	0.1	0.4	0.7	0.7	0.2	0.2	0.9

Source: Federal Department of Vehicle Registration (Kraftfahrzeugbundesamt)