Nijmegen School of Management
Department of Economics and Business Economics
Master's Thesis Economics (MAN-MTHEC)

The Finnish Experiment: Assessing the Dual Impact of the Carbon Tax on CO_2 Emissions and Air Quality

By Noam van Dooremolen (s1043470)

Nijmegen, 10 June 2024

Program: Master's Program in Economics
Specialisation: Economics, Behaviour and Policy
Supervisor: Dr. Olexiy Kyrychenko

Radboud Universiteit

Abstract

This quasi-experimental study is among the first to assess the effectiveness of a carbon tax in simultaneously reducing carbon emissions and air pollutants. Using the synthetic control method, this study compares the carbon and air pollutant emissions of the actual Finnish transportation sector to those of a synthetic control unit constructed from a similar group of OECD countries from 1990 to 2005. Initial results indicate that the Finnish carbon tax led to a significant absolute decrease in emissions per capita by 38.8% for CO_2, 24.5% for $PM_{2.5}$, and 53.4% for NO_x by the end of the dataset in 2005. However, subsequent robustness checks reveal no causal effect on $PM_{2.5}$ emissions and indicate a more modest reduction of approximately 7% for CO_2 and 18% for NO_x. By demonstrating the effectiveness of the Finnish carbon tax, this study adds to the limited body of ex-post research analysing their impact.

Keywords: Carbon tax, CO_2, $PM_{2.5}$, NO_x, Co-benefits, Synthetic control method

Table of Contents

1. Introduction

The adverse effects of climate change are now widely acknowledged, and its impacts on humanity have emerged as one of the most serious threats globally. This escalating crisis is largely driven by the use of fossil fuels. One of the main greenhouse gases (GHG) that contributes most to global warming is released during their combustion: carbon dioxide (CO_2). But there is a local threat in addition to the worldwide one. Air quality is directly impacted by the air pollutants released alongside CO_2 during the combustion of fossil fuels, causing respiratory illnesses and other health problems (Manisalidis et al., 2020). Climate change and air pollution can therefore be seen as complementary global and local externalities of the use of fossil fuels. Decisive action is necessary if we are to prevent widespread human suffering. Increasing interest is being directed towards carbon taxes, both in academic circles and in economic and environmental policy debates. Yet, relatively few countries have adopted a carbon tax, and there is an even greater scarcity of ex-post empirical studies on the causal relationship between carbon taxes and CO_2 emissions (Green, 2021). There is a lack of empirical evidence regarding their causal effect on local air pollution co-benefits too, with a majority of empirical research relying on simulation models (Sileci, 2023). Therefore, more ex-post empirical evidence on the effectiveness of carbon taxes is vital for building crucial public support.

This study takes a closer look at Finland, a pioneer in carbon pricing. Finland was the first country to adopt a carbon tax in 1990. The tax covers a spectrum of carbon-emitting sources, including all transport fuels, coal, and natural gas (Elbaum, 2021). At first, the tax amounted to a modest \$1.41 per ton of CO_2, but it has gradually risen over the years, finally reaching \$85.10 per ton of CO_2 by April 2022 (Bray, 2022). Since Finland implemented a carbon tax as early as 1990, it provides an interesting case study to investigate the long-term consequences and effectiveness of such policies. Delving into this "Finnish experiment," this study answers two research questions: *1. Has the Finnish carbon tax reduced CO_2 emissions, specifically within the transportation sector? 2. Has it yielded the co-benefit of improved air quality through reduced $PM_{2.5}$ and NO_x emissions?*

To answer these research questions, this study follows the approach of Andersson (2019) and uses the synthetic control method to estimate the causal effect of the Finnish carbon tax on per capita CO_2, $PM_{2.5}$, and NO_x emissions from the transportation sector. Using the synthetic control method (Abadie et al., 2010), I construct a counterfactual "synthetic Finland"

– a composite unit comprising a weighted combination of control countries that did not introduce carbon taxes or comparable policies during the treatment period and that closely mirror Finland prior to the treatment in terms of key predictors of CO_2, $PM_{2.5}$, and NO_x emissions in the transportation sector, exhibiting comparable levels and trends of these emissions - and compare emission paths of the actual and synthetic Finland transportation sector. To assess whether the findings are the product of random chance or indicate a genuine causal effect (Abadie et al., 2010), I conduct various placebo and sensitivity tests, including "in-time", and "in-space" placebos, as well as the "full-sample" and "leave-one-out" robustness tests.

This study focuses on the transportation sector for several reasons. To begin with, according to Clarke (2023), effective reduction of emissions from the transportation sector is a key requirement to mitigate climate change and achieve Finland's climate targets. They point out that in this sector, the carbon tax plays a key role in addressing this challenge. Thus, the transportation sector is especially interesting to investigate. Secondly, since transportation services are not subject to international trade, the potential for a confounding influence from international trade on the control group is limited (Mideksa, 2021). Finally, there are similarities between countries in the configuration of energy production in transportation activities, which makes it easier to create a credible counterfactual unit from the pool of control countries (Mideksa, 2021).

Overall, I find that the Finnish carbon tax had the desired impact of reducing emissions from the transportation sector. Initial results show that the tax resulted in a significant absolute decrease in emissions per capita by 38.8% for CO_2, 24.5% for $PM_{2.5}$, and 53.4% for NO_x by the end of the dataset in 2005. However, subsequent placebo- and robustness tests reveal no causal effect on $PM_{2.5}$ emissions and suggest a more modest reduction of approximately 7% for CO_2 and 18% for NO_X. These estimated emissions reductions are in line with the decrease in Finland's post-1990 diesel and gasoline consumption.

This study contributes to the literature in several ways. First, this paper contributes to the empirical literature that assesses the impact of carbon taxes on CO_2 emissions. As noted in their meta-review, Green (2021) found that there is a scarcity of ex-post quantitative evaluations of carbon taxes. The limited evidence suggests that its impact on emissions has been limited (Arcila and Baker, 2022; Lin and Li, 2011; Pretis, 2022), although some recent studies find significant reductions (Andersson, 2019; Basaglia et al., 2023; Elbaum, 2021). By examining the Finnish case, this study enriches the external validity of this literature. Secondly, this study is among the first to provide an ex-post evaluation of the air quality co-benefits of carbon taxes by investigating reductions in $PM_{2.5}$ and NO_x emissions. Previous studies – all except Basaglia et al. (2023) - solely focus on carbon abatement, thereby ignoring other benefits from carbon taxation.

The remainder of this thesis is structured as follows. Chapter 2 discusses the economic theory behind the carbon tax, the main findings of the existing literature and provides a brief description of the Finnish carbon tax. Chapter 3 presents the methodology and data. In chapter 4, the results and robustness checks are presented. Chapter 5 compares the findings in a discussion. Finally, chapter 6 concludes.

2. Theoretical Background

2.1 Economic theory

Market-based instruments (MBIs) have become essential instruments in climate politics in the last couple of decades. These tools include a range of measures intended to encourage emission reductions and attempt to internalise the external costs of pollution. Two notable MBI's are carbon taxes and Emission Trading Systems (ETS) (also known as cap-and-trade systems).

An ETS operates on the principle of capping the total allowable emissions within a predefined limit. Under this system, participating entities are allocated a specific quantity of emission allowances, reflecting the total permissible emissions. Allowances that are tradable allow lower-emitting entities to sell their surplus allowances to those who are exceeding their allotted amount. At the end of each year, companies must surrender enough allowances to offset all of their emissions, otherwise substantial fines are imposed (UNFCC, 2008). There are numerous ETSs active at the national, regional, and international levels right now. First introduced in 2005 and ratified by 25 member states, the European Union's Emission Trading Scheme (EU ETS) accounts for nearly half of global CO_2 emissions (Bayer and Aklin, 2020). Furthermore, since then, a number of countries have adopted ETSs at both national and regional levels, including Canada, China, Kazakhstan, and New Zealand (Santikarn, 2021).

Conversely, a carbon tax involves placing a direct price on each ton of emitted carbon. Of relevance here is the concept of the Pigouvian tax, which is a type of tax levied on activities that generate negative externalities. The aim of a Pigouvian tax is to internalise the external costs linked to these activities, motivating businesses and individuals to account for the social costs of their actions. Figure 1, which analyses the scenario involving a consumption good x that causes pollution, provides an illustration of this. MB(x) represents the marginal benefit of consumption, MC_{priv} denotes the private marginal cost, and MC_{soc} indicates the social marginal cost. The competitive market causes the private marginal costs and benefits to be equal to each other in the absence of environmental regulations, reaching market equilibrium at x_0. The marginal social cost MC_{soc} in this equilibrium is greater than the marginal benefit of consumption MB for all units consumed beyond x_p, meaning that the welfare loss is equal to the area CDF at this point (Schöb, 2008). Incremental extension of consumption from zero to x_p however, enhances welfare. When the marginal private cost MC_{priv} plus the external costs (that is, the marginal environmental damage) equals MB, Pareto optimality occurs. The Pigouvian tax t_p can maintain the Pareto-efficient outcome, generating tax revenues equivalent to the area shaded in grey.

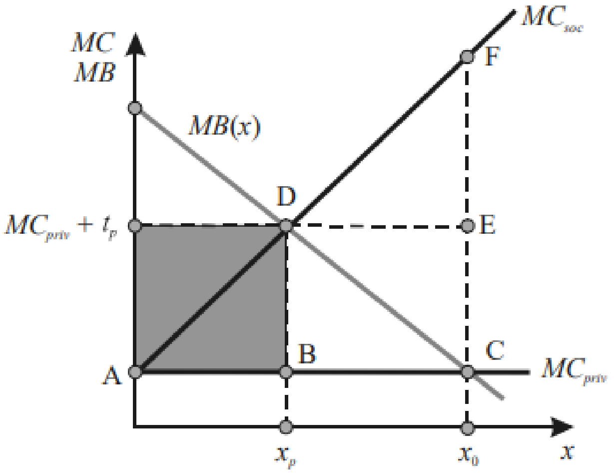


FIGURE 1. PIGOUVIAN TAX

Notes: Adapted from Schöb, R. (2005). The double-dividend hypothesis of environmental taxes: a survey. *The international yearbook of environmental and resource economics*, *2006*, 223-279.

A particular kind of Pigouvian tax is the carbon tax (Metcalf and Weisbach, 2006). By releasing CO_2 into the atmosphere, the burning of fossil fuels contributes to climate change. Moreover, air pollutants are released alongside CO_2 during fossil fuel combustion. Negative externalities consist of the environmental damage caused by CO_2 emissions and the adverse impact on air quality caused by $PM_{2.5}$ and NO_x emissions. A carbon tax aims to make the polluter internalise the costs of these externalities. The revenue generated from carbon taxes can be directed towards different objectives, for instance, financing renewable energy initiatives or alleviating the social repercussions of climate change and air pollution (Lin and Li, 2011).

An overview of the differences between carbon taxes and ETSs is presented in table 1.

TABLE 1. CARBON TAX VS. ETS

Aspect	**Carbon tax**	**ETS**
Mechanism	A tax imposed on each unit of GHG emissions	System where permits to emit GHG are bought/sold
Incentive for reduction	Direct incentive to mitigate pollution whenever the cost of doing so is lower than paying the tax	Market incentive to mitigate pollution by allowing trading of emission allowances
Quantity control	No control on the overall quantity of emissions	Certainty regarding the quantity of emissions by setting a cap
Industry impact	Greater initial impact on the balance sheet	Less expensive compliance for industry during the initial phases of the program

Source: Parry et al. (2022)

The effectiveness and choice between a carbon tax and ETS have been subjects of debate since the 1970s (Weitzman, 1974). There is no definitive answer; it depends on the situation. Both mechanisms can be successful if adequately designed and implemented in the appropriate sector (Haites, 2018).

2.2 Literature review

Increasing interest is being directed towards carbon taxes, both in academic circles and in economic and environmental policy debates. 36 jurisdictions had implemented carbon taxes by 2022, accounting for 5.66% of global GHG emissions (Köppl and Schratzenstaller, 2022). Carbon tax rates vary greatly; for example, the rate in Poland is US$0.08 per ton of CO_2 equivalent (CO_2e), while in Uruguay it is US$137.30. Comparably, the percentage of a country's GHG emissions that are subject to the carbon tax varies greatly as well, being as low as 4.1% in Poland, while in Norway, it is as high as 98% (Köppl and Schratzenstaller, 2022). However, public support for carbon taxes remains low (Carattini et al., 2018; Maestre-Andrés et al., 2019), with a common conviction that their costs outweigh their environmental benefits.

Nonetheless, studies suggest that when people are presented with proof that they actually decrease emissions, support for carbon taxes increases (Dechezleprêtre et al., 2022).

Studies exploring the impact of a carbon tax on CO_2, $PM_{2.5}$, and NO_x emissions can be categorised into two main categories: (i) ex-ante simulations, which normally use computable general equilibrium (CGE) models; and (ii) ex-post evaluations using empirical data, which normally use panel regression or quasi-experimental methods. The majority of existing studies are ex-ante analyses, which lead to estimates that differ greatly because of the initial assumptions made about baseline scenarios and unknown parameters. Since this study is interested in the evaluation of policies retroactively, the remainder of this section will focus on ex-post studies. Table 2 presents a summary of the reviewed studies. The remainder of the literature review consists of a more detailed discussion of three chosen studies to give a more sophisticated understanding of their methodologies and findings.

First, Lin and Li (2011) use the difference-in-differences approach to analyse the impact of carbon taxes on the growth rate of per capita CO_2 emissions for five early adopters: Denmark, Finland, the Netherlands, Norway, and Sweden. The control group consists of the European OECD member countries, with Italy, Germany and United Kingdom left out. The control variables selected are energy price, GDP per capita, industry structure, technological factor and urbanisation level.

Following Blundell and Bond (1998), the system GMM approach is used to estimate the model. The results show a 1.7% reduction in growth rate of CO_2 per capita in Finland only. In the case of Denmark, the Netherlands, and Sweden, the effects were negative but not statistically significant. In contrast, CO_2 emissions increased in Norway. The authors explain this by pointing out that Norway is a large oil and natural gas exporter, heavily reliant on energy-intensive industries. Moreover, a positive correlation between GDP per capita growth and per capita CO_2 emissions was found, while the urbanisation level showed no significant effect on CO_2 emissions. Furthermore, expenditure on R&D and energy prices were identified as having a significant and negative effect on per capita CO_2 emissions.

Nevertheless, it can be contended that the study by Lin and Li (2011) potentially produces biased estimates, primarily attributable to the limitations of the difference-in-differences methodology, as they violate fundamental assumptions in causal inference. Specifically, as noted by Andersson (2019), they incorporate outcome variables as covariates and merge treated and untreated sectors in their sample by using total CO_2 emissions, a practice that might introduce bias into the results.

Arcila and Baker (2022) analyse the impact of the 2008 carbon tax in British Columbia using the synthetic control method. They construct a synthetic British Colombia by taking a weighted combination of numerous regional jurisdictions in North America that do not have a carbon tax. Compared to the difference-in-differences approach employed by Lin and Li (2011), this has the advantage of relaxing the parallel trends assumption by allowing the effects of unobserved confounders to vary over time.

The study includes four outcome variables of interest: CO_2 emissions, gasoline prices, gasoline consumption, and the percentage of overall employment in energy. They select several covariates, including population, the number of vehicle registrations, real GDP growth, and the unemployment rate. Data is collected from 1998 to 2017.

Remarkably, the authors find that synthetic British Columbia experienced lower CO_2 emissions following the implementation of the carbon tax in British Columbia compared to the actual observed levels in British Columbia. It is noteworthy that both units, in the immediate aftermath of the carbon tax adoption, show an overall decrease in CO_2 emission levels, although this decline does not persist beyond 2012. The 2008 policy change coincides with the economic turmoil during the 2008-2009 global recession. The authors attribute the decrease in CO_2 emissions in this period to the economic recession. After remaining below 1998 levels for several years post carbon tax adoption, CO_2 emissions in British Columbia increase significantly, particularly starting in 2015 and rising by approximately 7.5% over the next two years. In contrast, the synthetic control consistently follows a declining trajectory from 2008 until the end of the sample period. According to the authors, this finding questions the theoretical mechanisms supporting the adoption of a carbon tax.

Finally, Basaglia et al. (2023) investigate the effectiveness of the German eco-tax in simultaneously delivering climate and health benefits. Applying the synthetic control method, the authors assess and compare carbon and air pollutant emissions between the actual German transportation sector and its synthetic counterpart.

The authors focus on three main outcome variables: emissions of CO_2, $PM_{2.5}$, and NO_x. In order to evaluate the impact of the eco-tax reform on CO2 emissions, a yearly panel dataset covering the years 1971 through 2009 is created. The OECD countries that have introduced a carbon tax in the transportation sector or made significant changes to their existing fuel taxes

(Finland, Italy, Sweden, Norway, the Netherlands, Spain, and the United Kingdom) and those with significant fuel tourism (Austria and Luxembourg) are removed from the control group. Moreover, the countries with limited data, such as the Baltic countries, Czech Republic, Slovakia, and Slovenia, are excluded. Multiple predictors of CO_2 emissions included, such as GDP per capita, the percentage of the population living in urban areas, the number of motor vehicles, the per capita consumption of gasoline and diesel, and lagged per capita emissions. Finally, the index on non-market stringency is also included in the panel dataset for $PM_{2.5}$ and NO_x emissions as a predictor to account for vehicle fume emissions thresholds.

According to the results of their synthetic control method, during the period from 1999 to 2009, the eco-tax led to average reductions of approximately 12% in CO_2 emissions, 10% in $PM_{2.5}$ emissions, and 6% in NO_X emissions within the transportation sector. This considerable reduction in emission can be opposed to the results of Arcila and Baker (2022) (who failed to find any significant CO_2 emissions reductions), which suggests potential heterogeneity in the impact of carbon taxes across different countries. Moreover, there was an average reduction in external damages amounting to 43 billion euros. More than 50% of the decrease in external damages is attributable to health benefits, so the authors stress the significance of considering co-pollution effects of carbon pricing.

To conclude, the examination of Table 2 together with the literature review underscores the prevalence of mixed findings regarding the impact of carbon taxes on emissions. Some studies suggest minimal or no effects of carbon taxes (Arcila and Baker, 2022; Lin and Li, 2011; Pretis 2022), while others show significant reductions (Abrell et al., 2019; Andersson, 2019; Basaglia et al., 2023). These conflicting results can be explained by, amongst others, methodological differences, differences in the time periods under investigation, the specific predictors selected, and the decision to focus either on sector-specific or economy-wide reductions.

2.3 The Finnish Carbon Tax

With a population of 5.5 million, Finland is a small, open economy with a GDP per capita that positions it as the eighteenth wealthiest nation globally in 2022 (O'Neill, 2023). Finland was the first country to adopt a carbon tax in January 1990. All transportation fuels, coal, and natural gas are among the various carbon-emitting sources that are subject to the tax (Elbaum, 2021). At first, the tax amounted to a modest $1.41 per ton of CO_2, but it has gradually risen over the years, finally reaching $85.10 per ton of CO_2 by April 2022 (Bray, 2022). Finland has the highest effective carbon rates for most fuels out of all EU member states (Clarke, 2023).

The carbon tax covers 76.0% of national GHG emissions (Köppl and Schratzenstaller, 2022). Among other things, the revenues from the carbon tax have been used to alleviate the financial burden that individuals with lower and middle incomes bear (Carl and Fedor, 2016).

TABLE 2. EX-POST ANALYSES OF CARBON TAXES

Author(s)	**Jurisdiction**	**Time period**	**Methodological approach**	**Result**
Abrell et al. (2019)	United Kingdom	2013-2016	Machine learning	Decrease of CO_2 emissions by 6.2% over 3 years at an average cost of €18 per ton.
Andersson (2019)	Sweden	1960-2005	Synthetic control method	Decrease of CO_2 emissions in transport sector by 6.3% per year.
Arcila and Baker (2022)	British Columbia	1998-2017	Synthetic control method	No reduction in CO_2 emissions.
Basaglia et al. (2023)	Germany	1971-2009	Synthetic control method	Decrease of CO_2, $PM_{2.5}$, and NO_x emissions by 12%, 10%, and 6%, respectively.
Dussaux (2020)	France	2001-2016	Regression analysis	Decrease of CO_2 emissions in manufacturing sector by 1%-5%.
Fernando (2019)	Denmark, Finland, Norway, Sweden	1990-2004	Synthetic control method	Average decrease of CO_2 emissions by 17.2% in Sweden and 19.4% in Norway per year. No significant impact in Denmark and Finland.
Lin and Li (2011)	Denmark, Finland, Netherlands, Norway, Sweden	1981-2008	Difference-in-difference	Only a reduction of growth rate of CO_2 emissions in Finland (1.7%). Virtually no decrease in Norway and not statistically significant for Denmark, Netherlands and Sweden.
Pretis (2022)	British Columbia	1990-2016	Difference-in-difference, synthetic control method and break detection approach	No statistically significant impact on CO_2 emissions at aggregate level.

Figure 2 illustrates the per capita consumption of gasoline and diesel from 1970 to 2005. The figure indicates that per capita gasoline consumption decreased after the carbon tax was adopted (i.e., after 1990) compared to an increase in the period before its implementation (i.e., before 1990). Meanwhile, per capita diesel consumption increased after the introduction of the carbon tax in 1990, even though there was a temporary reduction in the early 1990s, ultimately overtaking gasoline consumption per capita after 1999. Figure 3 demonstrates that total road sector fuel consumption (gasoline plus diesel) increased until 1990, after which this growth largely levelled off. This provides descriptive evidence that the Finnish carbon tax affected the amount of transportation fuel consumed, and that, in response to the tax, consumers replaced gasoline with diesel.

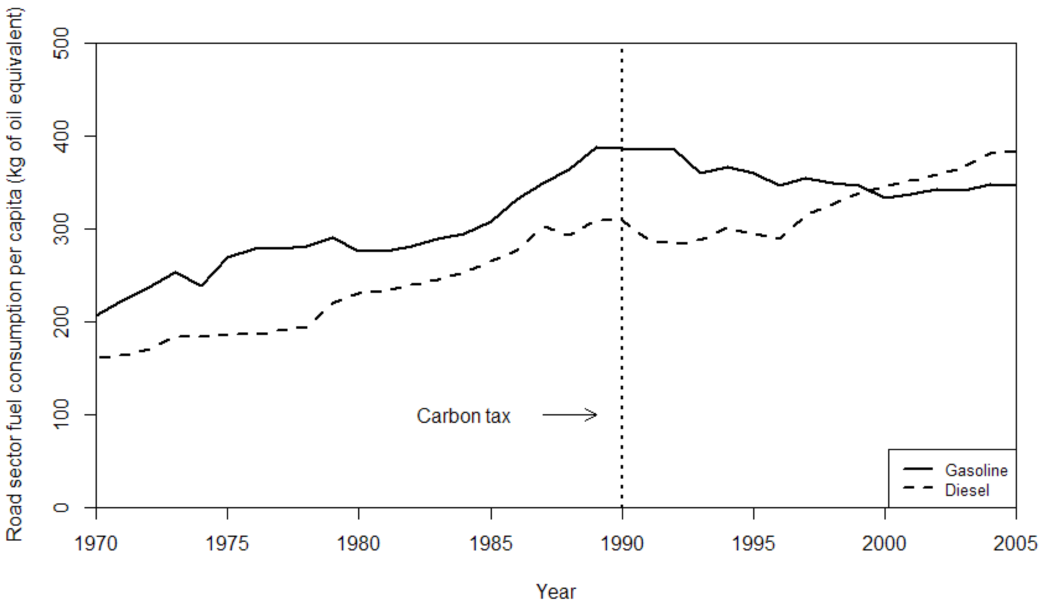


FIGURE 2. GASOLINE AND DIESEL CONSUMPTION PER CAPITA IN FINLAND (1970-2005)

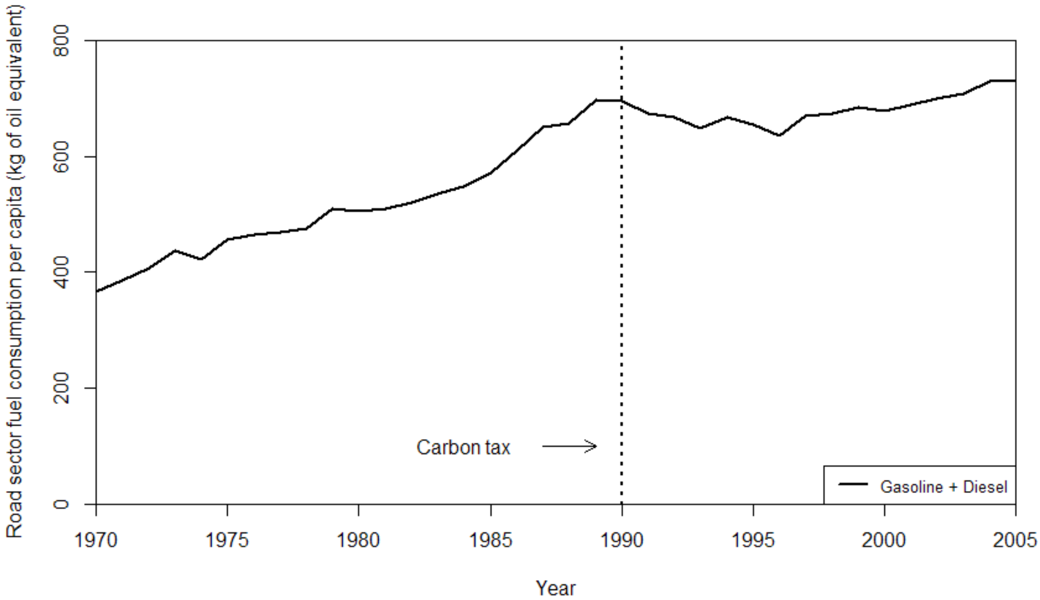


FIGURE 3. TOTAL ROAD SECTOR FUEL CONSUMPTION PER CAPITA (GASOLINE + DIESEL) IN FINLAND (1970-2005)

3. Methodology and Data

This section presents the fundamental framework of the synthetic control method and explains how it is applied in this study. Afterwards, I describe the data used and their sources.

3.1 Synthetic control method

3.1.1 Background

Quasi-experimental methods, including randomised control trials, the difference-in-differences (DiD) method, and the synthetic control method are commonly used in comparative case studies to assess the impact of policies. While a randomised control trial would involve selecting Finnish regions for carbon taxation at random, leaving the other regions as a control group, this proves to be problematic because countries tax carbon in all regions. Therefore, an alternative to randomised control trials is required. The DiD method creates the counterfactual by averaging the outcome variable from the control group without weighting. The DiD estimator provides an estimate of the emission reductions by comparing the change in the outcome variable for both the treated unit and the control group before and after the treatment. The appeal of the DiD estimator lies in its ability to account for time differences, hence removing the impact of unobserved covariates predicting the outcome variable, assuming that the impacts on the outcome variable do not change over time. Moreover, it assumes that the treated unit and the control group share any macroeconomic shocks or other time effects. Combining these two assumptions results in the "parallel trends assumption," which suggests that, in the absence of a carbon tax, CO_2, $PM_{2.5}$, and NO_x emissions from the transportation sector in Finland and the control group follow parallel trajectories. As Andersson (2019) notes, the challenge in confirming the parallel trends assumption poses a limitation for the DiD method. If the treated unit and control group deviate from a shared trend, the DiD estimator will be biased. Thus, for comparative case studies, it is desirable to employ a method that does not strictly rely on the parallel trends assumption. This concern is addressed by the synthetic control method, which weights the control group to allow for fluctuations over time in the effects of unobserved factors on the outcome variable (Andersson, 2019). This weighting ensures that, before the treatment, the synthetic control group's levels and trajectories of CO_2, $PM_{2.5}$, and NO_x emissions in the transportation sector closely mirrors that of Finland. Hence, the synthetic control method is used in this study because it enhances estimation compared to the DiD estimator by relaxing the parallel trends assumption.

First introduced by Abadie and Gardeazabal (2003) and later extended in Abadie et al. (2010), the synthetic control method (SCM) serves as a tool for assessing the impact of aggregate or large-scale interventions. This method uses a data-driven approach to create a control unit, referred to as the synthetic control, which is a weighted average of the untreated units within the donor pool. The underlying idea is that a composite of untreated units offers a more suitable comparison than relying on any individual untreated unit alone. What follows is a brief presentation of the fundamental framework of the SCM and how it is applied in this study.

3.1.2 Synthetic control estimator

Suppose there are J + 1 countries in the sample, indexed by j, with j = 1 denoting the treated country, which in this study is Finland. The donor pool, a collection of OECD countries unaffected by the intervention (Finnish carbon tax), is denoted by j = 2, 3, …, J + 1, and can be used to create a control group. The countries in the sample are observed for time periods t = 1, 2, …, T divided into pre-treatment and post-treatment, that is, after the introduction of the carbon tax in 1990. It is important to have a sufficient number of pre-treatment periods 1, 2, …, T_0 as well as post-treatment periods $T_0 + 1$, $T_0 + 2$, …, T to be able to both construct a synthetic Finland (using pre-intervention data) and to assess the impact of the treatment (using post-intervention data).

The synthetic control ("Synthetic Finland") is a weighted average of control countries j = 2, 3, …, J + 1 from the donor pool of OECD countries, which can be formally represented by a (J x 1) vector of weights

$$W = (w_2, \ldots, w_{J+1})' \text{ with } 0 \leq w_j \leq 1 \text{ and } w_2 + \ldots + w_{J+1} = 1 \qquad (1)$$

Each value of W corresponds to a set of weights that define a potential synthetic control. Additionally, X_1 represents a (k x 1) vector comprising pre-treatment predictors of Finland's (the treated unit) outcome variable (CO_2, $PM_{2.5}$, or NO_x emissions from the transportation sector). Similarly, X_0 is a (k x J) matrix that contains the same predictors for all units in the donor pool. Following Abadie et al. (2010), W is chosen such that it minimises the pre-treatment difference in crucial predictors between the treated country and the untreated donors. Put differently, the vector W* is chosen such that $||X_1 - X_0W||$ is minimised. Further details on the SCM can be found in Appendix A.

In order to determine whether the outcomes are obtained randomly or indicate genuine causal effect, the SCM also incorporates various placebo tests (Abadie et al., 2010). Chapter 4 discusses two placebo tests: the "in-time" placebo, and "in-space" placebo. It also discusses the "full sample" and "leave-one-out" robustness tests.

3.1.3 Choice of predictors

The diagonal matrix of predictor weights, denoted as V, can be obtained in various ways. As noted by Andersson (2019), this includes, amongst others, assigning weights derived from empirical findings in the literature concerning the key predictors of CO_2, $PM_{2.5}$, and NO_x emissions, cross-validation methods or simultaneously selecting V and the vector W to minimise the mean square predictor error (MSPE) of the outcome variable over the course of the pre-treatment period. This study employs the latter method[1].

While the SCM is primarily data-driven, studies have highlighted that the specification of the SCM involves individual choice to an extent. Ferman et al. (2020) note that this introduces the possibility of "cherry-picking," where specific combinations of predictors are selectively chosen to affect the outcome. Lagged CO_2, $PM_{2.5}$ and NO_x emissions in 1989, 1985, 1980, and 1970 is taken as the baseline specification[2]. Additionally, this study adopts two

[1] This is done using the *Synth* package in R (Abadie et al., 2011).

[2] I experimented with various other combinations of years of lagged CO_2, $PM_{2.5}$, and NO_x, but none of them led to an improved pre-treatment fit or affected the estimated reductions in emissions significantly.

specifications from Ferman et al. (2020): using (1) the first, the middle, and the last outcome value, and (2) no covariates[3].

3.2 Data

To empirically analyse the effect of the introduction of the Finnish carbon tax in 1990, I create an annual panel dataset on per capita CO_2 emissions from the transportation sector for the period 1970-2005 for OECD countries. Even though data on CO_2 emissions from the transportations sector, which is taken from the World Bank WDI database, starts in 1960, the sample period begins in 1970 to align with the availability of data on NO_x and $PM_{2.5}$ emissions, which is only accessible from 1970 onwards[4]. Following Andersson (2019), the sample period ends in 2005 to avoid contamination from the EU ETS, which began in that year. Additionally, numerous countries within the sample began introducing carbon taxes or made substantial modifications to fuel taxation starting from 2005 onwards. Thus, the sample includes 20 pre-treatment years and 16 post-treatment years. I take population data from the World Bank to calculate per capita CO_2 emissions.

The initial sample consists of the 24 OECD members in 1990 plus Poland: Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Japan, Luxembourg, the Netherlands, New Zealand, Norway, Poland, Portugal, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. However, as emphasised by Abadie et al. (2010), it is essential to only include untreated countries in the donor pool. Therefore, from this initial sample, countries that introduced carbon taxes or made significant changes to existing fuel taxes during the sample period have been excluded: Italy, the Netherlands, Norway, Sweden (enacted carbon taxes in 2001, 1990, 1991, and 1991, respectively) as well as Germany (implemented an eco-tax in 1999), and the United Kingdom (adopted a climate change levy in 2001). Even though Denmark introduced a carbon tax around this time, Andersson (2019) notes that the transportation sector is exempted from the carbon tax. Thus, Denmark remains in the sample. Likewise, Poland introduced a carbon tax in 1990,

---

[3] Since there is no established best practice for including pre-treatment outcome lags, as Basaglia et al. (2023) note, I re-run the analysis using the first, middle, and last outcome value. This enables me to assess the sensitivity of the results to the specific outcome values chosen in the main analysis. In order to determine whether the SCM can still isolate the effect of the carbon tax even in the absence of extra controls, I also re-run the analysis without any covariates. This can strengthen the argument that any observed change in CO_2 emissions is indeed attributable to the introduction of the carbon tax.

[4] Andersson (2019) obtained data on CO_2 emissions from the World Bank WDI Database (2015). However, this data is no longer available in the database. Therefore, for the analysis, I use the data publicly packaged with Andersson (2019).

but the cost per ton of carbon dioxide is less than one dollar, rendering it negligible (Basaglia et al., 2023). For this reason, Poland also remains in the sample. As pointed out by Andersson (2019), there is a real possibility of substantial fuel tourism at the border of Austria, leading to distortions in its emissions data. Thus, Austria is also excluded from the sample. Lastly, Ireland is excluded due to extraordinary economic growth it experienced from the 1990s to the early 2000s (Andersson, 2019). All in all, this leaves 16 countries in the donor pool: Australia, Belgium, Canada, Denmark, France, Greece, Iceland, Japan, Luxembourg, New Zealand, Poland, Portugal, Spain, Switzerland, Turkey and the United States.

Following Andersson (2019), the following predictor variables of CO_2 emissions are included: GDP per capita, the number of motor vehicles, gasoline consumption per capita, the percentage of urban population, and lagged CO_2 per capita. Previous studies find a strong correlation between the level of GDP per capita and GHG emissions (Sharma, 2011). On top of that, less urbanised OECD countries exhibit greater reliance on motor vehicles, leading to higher emissions from the transportation sector (Neumayer, 2004). Incorporating lagged data of the dependent variable (per capita CO_2 emissions) as a predictor is also important as it enhances the accuracy of the synthetic control, as it reproduces the pre-treatment trajectory of the dependent variable more precisely. This inclusion is necessary to prevent the omission of significant predictors, as it encompasses the effects of all explanatory variables, regardless of whether they are explicitly incorporated into the analysis. Data comes from various sources. Data on GDP per capita comes from the Penn World Table. Moreover, data on gasoline consumption per capita and the percentage of urban population are obtained from the World Bank. Data on the number of motor vehicles is provided by Dargay et al. (2007).

To empirically analyse the effect of the introduction of the Finnish carbon tax on NO_x and $PM_{2.5}$ emissions for the period 1970-2005, I largely rely on the data sources mentioned in the previous paragraph. Data on NO_x and $PM_{2.5}$ emissions is taken from the EDGAR dataset[5]. Given that data on NO_x and $PM_{2.5}$ are only available from 1970 onwards, the sample for NO_x and $PM_{2.5}$ starts in 1970 and includes 20 pre-treatment years and 16 post-treatment years.

[5] Data on air pollution and GHG emissions are collected by the EDGAR database from every single country across the world, encompassing all human-induced activities, with the exception of Land Use, Change and Forestry (LULUCF). The database employs a coherent methodology and bottom-up approach for quantifying emissions. Additional information about the EDGAR database is provided in Appendix B.

4. Results

This section presents the findings of the econometric analysis. First, I present the results of the synthetic control method for CO_2 (section 4.1). Synthetic Finland is introduced and demonstrated to be a more credible counterfactual in section 4.1.1. Subsequently, section 4.1.2 delves into the findings concerning the impact of the carbon tax on CO_2 emissions. Lastly, sections 4.1.3 and 4.1.4 present the results of a number of placebo tests and robustness checks. Following the examination of CO_2 emissions, I extend the analysis to other pollutants. Section 4.2 presents the results of the synthetic control method for $PM_{2.5}$ and NO_x.

4.1 Results for CO_2

4.1.1 Finland vs. Synthetic Finland

The path of Finland's per capita CO_2 emissions from transportation from 1970 to 2005 is displayed in Figure 4, along with the unweighted average of the 16 donor countries. Its fit is poor; it constantly exceeds Finland's outcome. Furthermore, between 1985 and 1989, Finland's emissions rose noticeably more quickly. This finding implies a deviation from the common trends assumption that is necessary for the DiD estimator, implying bias in the outcomes if the DiD framework were applied. Hence, it is necessary to explore the synthetic control method to see if it leads to more encouraging outcomes.

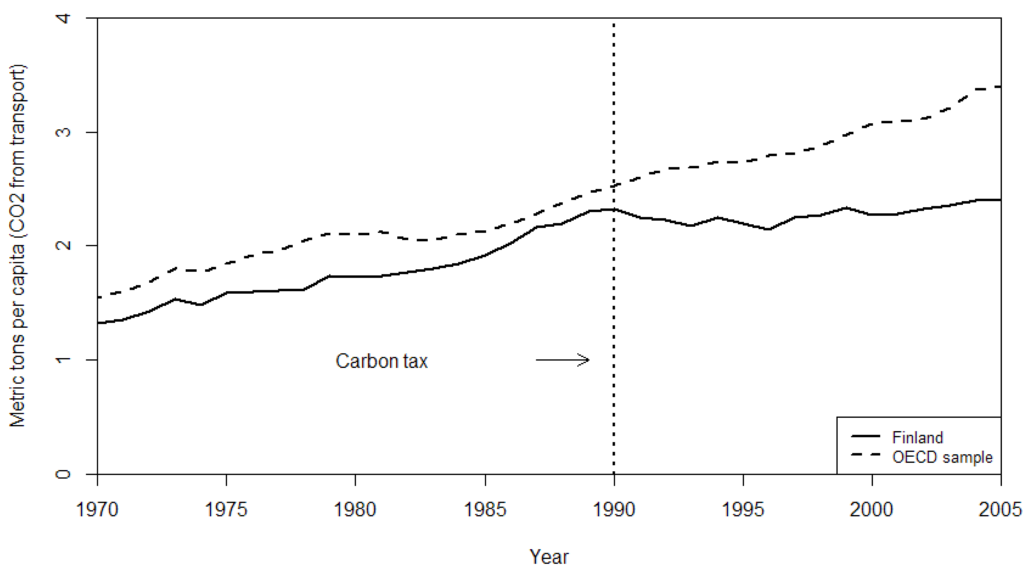


FIGURE 4. PATH PLOT OF PER CAPITA CO_2 EMISSIONS FROM TRANSPORTATION: FINLAND VS. THE UNWEIGHTED AVERAGE OF THE 16 DONOR COUNTRIES

To create a credible counterfactual, synthetic Finland must accurately mirror the CO_2 emissions trend from the transportation sector in Finland during the pre-treatment period (i.e., before 1990) and replicate the values of the main predictors. Figure 5 illustrates that before the implementation of the carbon tax, there is a close alignment between emissions from transportation in Finland and synthetic Finland. Although there are minor discrepancies in the paths in the late 1970s and 80s, overall, their alignment is highly satisfactory, which means that synthetic Finland offers a credible counterfactual. Moreover, Table 3 shows the means of the predictors for Finland, synthetic Finland, and the average of the 16 donor countries in the pre-treatment period. With the exception of the number of motor vehicles (per 1,000 people), there is less than 1% difference between the predictors of Finland and synthetic Finland. This close alignment in predictor means is encouraging.

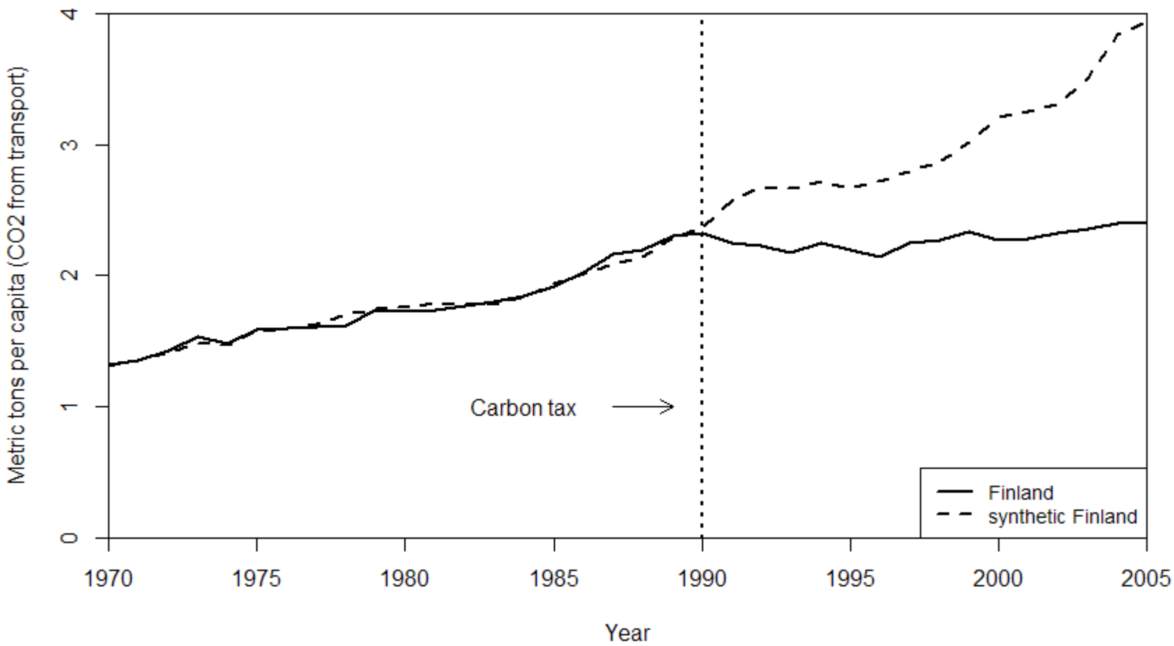


Figure 5. PATH PLOT OF PER CAPITA CO_2 EMISSIONS FROM TRANSPORTATION: FINLAND VS. SYNTHETIC FINLAND

The predictor weights of the V matrix are distributed as follows: GDP per capita (0.011), gasoline consumption per capita (0.003), motor vehicles (per 1,000 people) (0.088), urban population (0.139), and CO_2 emissions from transport per capita in 1989 (0.333), 1985 (0.072), 1980 (0.148), and 1970 (0.206). Moreover, table 4 presents the weights (W weights) assigned to each country in the donor pool. Synthetic Finland is a composite of Denmark, Poland, Luxembourg, Switzerland, New Zealand, Portugal, and the United States, with their respective weights decreasing accordingly. Other countries in the control group receive weights of zero or weights very close to zero. In line with Andersson (2019) and Elbaum (2021), Denmark receives the largest weight (0.270). This is likely due to its socio-economic resemblance to Finland.

TABLE 3. CO_2 EMISSIONS FROM TRANSPORTATION PREDICTOR MEANS BEFORE TREATMENT

Variables	Finland	Synthetic Finland	OECD sample
GDP per capita	16,722.6	16,698.4	17,212.9
Gasoline consumption per capita	285.8	331.3	408.0
Motor vehicles (per 1,000 people)	291.7	291.5	333.2
Urban population	71.4	71.4	73.3
CO_2 from transport per capita (1989)	2.3	2.3	2.5
CO_2 from transport per capita (1985)	1.9	1.9	2.1
CO_2 from transport per capita (1980)	1.7	1.8	2.1
CO_2 from transport per capita (1970)	1.3	1.3	1.5

Notes: The values are rounded to 1 decimal. All variables are averaged over the period 1970-1989, except lagged CO_2.

TABLE 4. COUNTRY WEIGHTS IN SYNTHETIC FINLAND

Country	Weight	Country	Weight
Australia	0.001	Luxembourg	0.141
Belgium	0	New Zealand	0.099
Canada	0.001	Poland	0.261
Denmark	0.270	Portugal	0.076
France	0.003	Spain	0.004
Greece	0	Switzerland	0.119
Iceland	0.002	Turkey	0
Japan	0.003	United States	0.020

Notes: The w_j weights are between $0 \leq w_j \leq 1$ and $\sum w_j = 1$.

4.1.2 Impact of the carbon tax

The distance between the lines representing Finland and synthetic Finland in the post-treatment period (i.e., after 1990) in figure 5 quantifies the decrease in CO_2 emissions. It shows that the adoption of the carbon tax had a significant effect on metric tons of CO_2 emissions per capita from transportation in Finland. This gap is depicted in more detail in the gap plot presented in figure 6. The introduction of the carbon tax and its gradual increase over time led to increasingly greater reductions in the post-treatment period. One year following the implementation of the intervention, there's a decrease of approximately 12.4% in CO_2 emissions, equivalent to 0.320 metric tons per capita. By the end of the sample period in 2005, the reduction in absolute terms amounts to 1.528 metric tons per capita (38.8%), which is a very large estimated decrease. While this finding is similar to that of Elbaum (2021), it is necessary to further investigate this to confirm the magnitude of this effect.

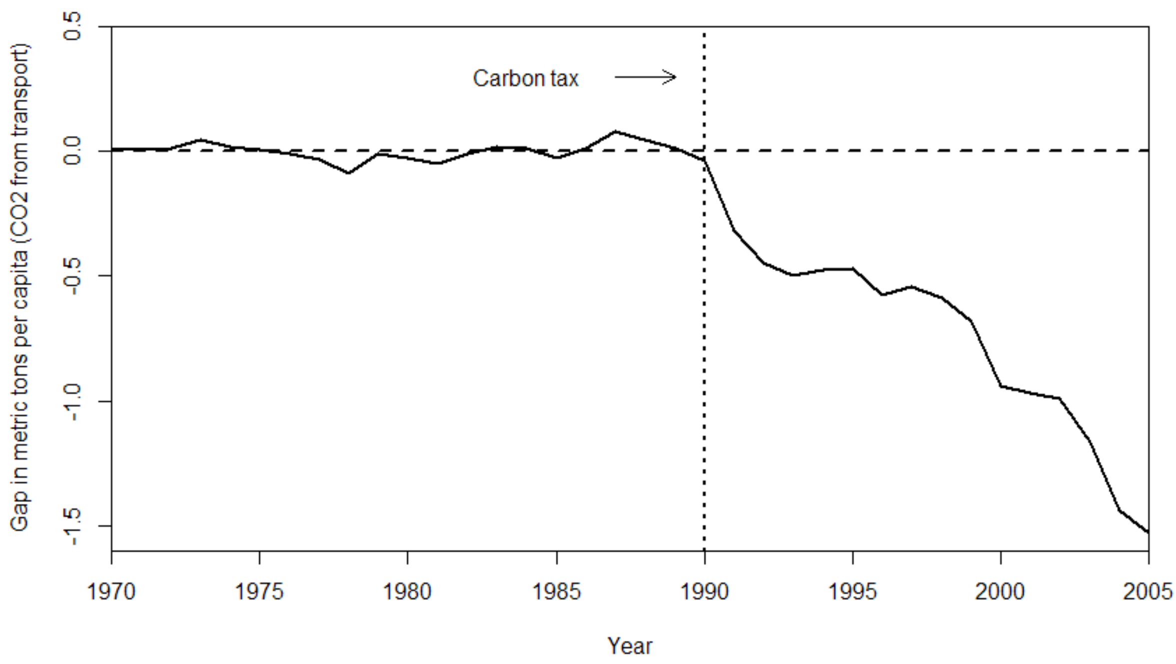


Figure 6. GAP BETWEEN PER CAPITA CO_2 EMISSIONS FROM TRANSPORTATION OF FINLAND AND SYNTHETIC FINLAND

4.1.3 Placebo tests

To assess whether the findings are the product of random chance or indicate a genuine causal effect (Abadie et al., 2010), and thus to assess the validity of the results, I conduct various placebo tests: namely, “in-time”, and “in-space” placebos. The “in-time” placebo test involves reassigning the treatment to a year preceding the actual year in which the carbon tax was introduced. The goal is to show that this placebo treatment does not cause a significant difference in emission trend in the post-treatment period. The results of figures 4 and 5 regarding the causal impact of the carbon tax would be called into question if the placebo treatment caused a significant divergence in emissions. The same predictors as in the main analysis are used for the "in-time" test, which adjusts the treatment year to 1980, ten years prior the actual treatment. Figure 7 displays the outcome of the “in-time” placebo test. While there is a small deviation in the paths after 1985 (similarly to Elbaum (2021)), it appears that there is no substantial difference.

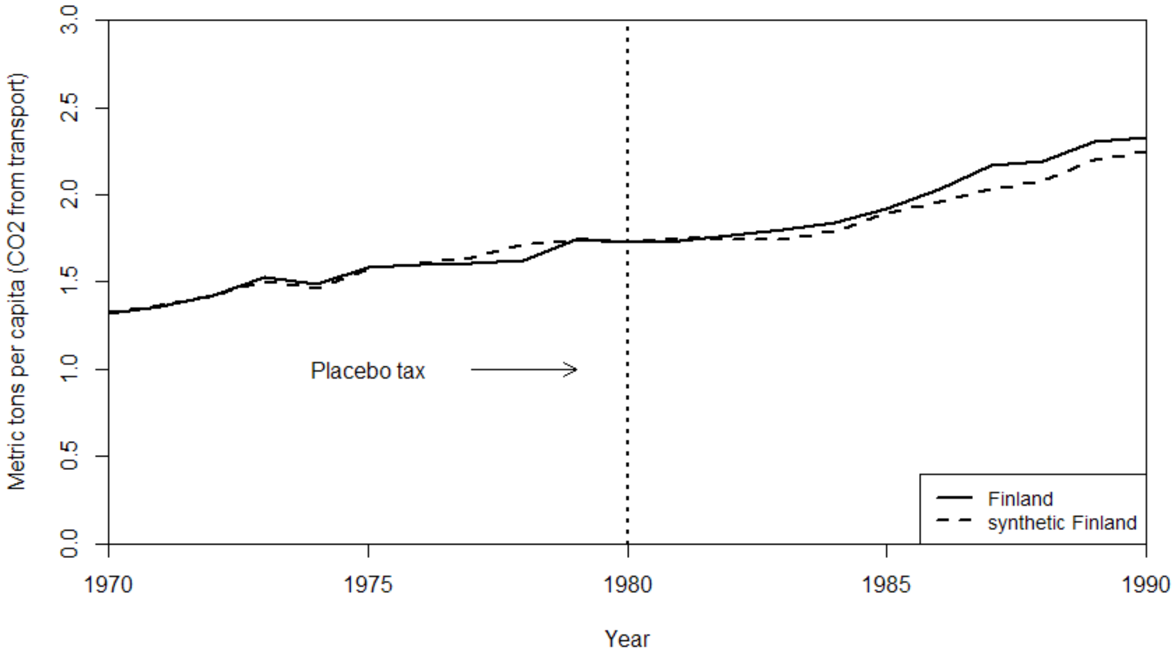


Figure 7. IN-TIME PLACEBO TEST (1980)

By allocating the treatment to the countries that did not enact a carbon tax, the "in-space" placebo test is conducted. To do this, the treatment must be iteratively reassigned to each country in the donor pool, with synthetic controls being created using the synthetic control method. Consequently, a distribution of estimated effects is produced, enabling comparison of the treated unit's (Finland) effect with a set of placebo effects. This approach provides a way to determine whether the observed outcome for Finland is extraordinarily large (Andersson, 2019). The results of the "in-space" placebo test are shown in Figure 8, displaying Finland's trajectory alongside the donor countries that were given the placebo intervention (represented by the grey lines). After excluding countries with a pre-treatment MSPE at least 20 times greater than Finland's (as does Andersson, 2019)), 12 countries remain in the donor pool. It is reassuring to note that none of the donor countries exhibit an impact as substantial as that of Finland. The p-value for estimating this large of a gap is 1/13 = 0.077.

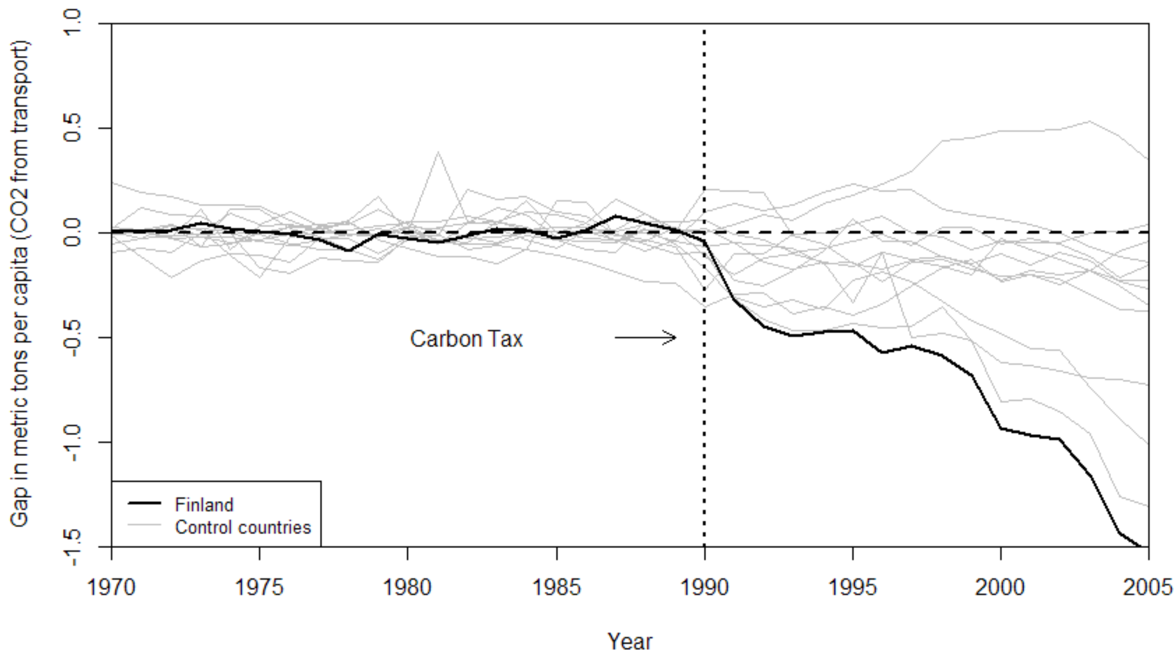


Figure 8. IN-SPACE PLACEBO TEST

However, solely relying on the post-treatment gap depicted in figure 8 is not enough to evaluate the effect's magnitude. A big gap only implies a substantial effect if the synthetic control strictly replicates the pre-treatment outcome. A more robust inferential approach involves examining the ratio of post-treatment MSPE to pre-treatment MSPE (Andersson, 2019), based on the assumption that a large ratio for Finland and small ratios for the other countries demonstrates a genuine causal effect from the carbon tax. By using this ratio test, it's not necessary to exclude countries based on an arbitrarily set cutoff rule, making the test particularly advantageous when dealing with a small number of control countries. As can be seen in figure 9, Finland has by far the largest ratio among all included countries. If the carbon tax was assigned randomly, the likelihood of obtaining a ratio of this magnitude would be 1/17 = 0.059.

4.1.4 Robustness tests

To further evaluate the robustness of the results, I conduct three additional robustness checks: first, given the possibility of cherry-picking, I adopt two alternative specifications from Ferman et al. (2020), namely (1) the first, the middle, and the last outcome values, and (2) no covariates. Afterwards, I perform the "full sample" and "leave-one-out" tests.

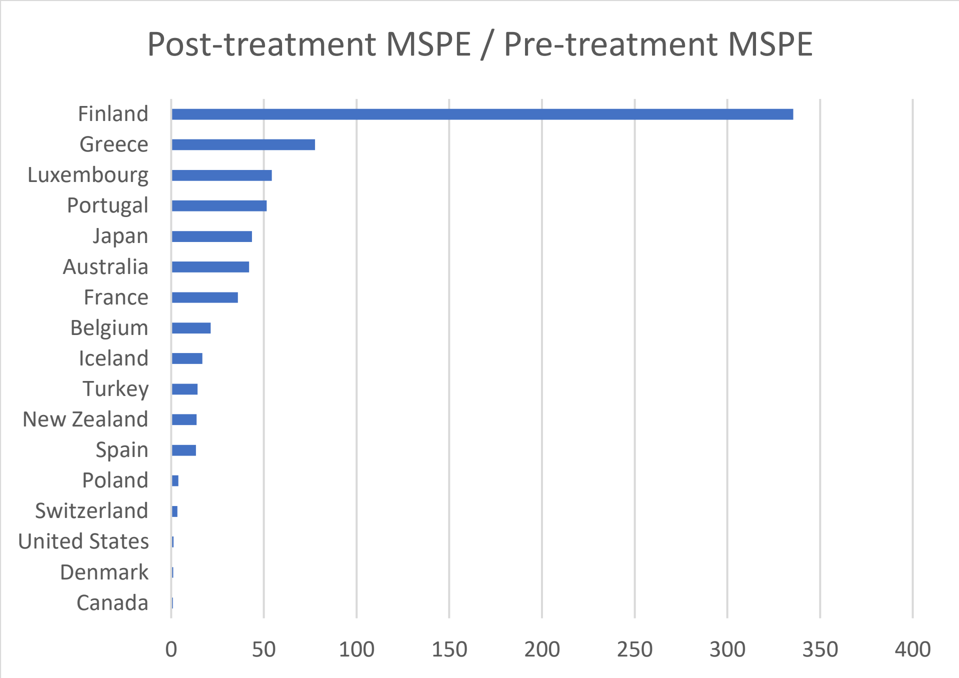


Figure 9. RATIO TEST: RATIO OF POST-TREATMENT MSPE TO PRE-TREATMENT MSPE FOR FINLAND AND 16 DONOR COUNTRIES

As can be seen in figure 10, both alternative specifications indicate a substantial impact of the Finnish carbon tax on CO_2 emissions within the transportation sector subsequent to its introduction in 1990. In the "full sample" test (see figure 11), the entire set of the 24 OECD donor countries plus Poland is used to create the counterfactual. Only two initially excluded countries now get a weight above 0.002, namely Norway and the United Kingdom. Canada, which previously had a weight of 0.001, is now dropped from the synthetic control. Problematically, the path plot is quite different from the main result, with the line representing the full sample (grey line) being significantly lower than line representing the original synthetic Finland. While in the main result, by the end of the sample period in 2005, the reduction in absolute terms amounts to 1.528 metric tons per capita, with the full sample, the reduction is 'only' 0.993 metric tons per capita. This indicates that the exclusion of countries from the donor pool affects the estimated decrease in CO_2 emissions.

Lastly, the "leave-one-out" test involves dropping one of the eleven donor nations at a time with a W weight greater than 0.001. This is done to determine if the finding is driven by one or a small number of powerful donor countries. In figure 12, the outcome of this robustness test is displayed. With the exception of three countries—Switzerland, Luxembourg, and Poland—the leave-one-out synthetic Finland is almost identical to the donor pool's synthetic Finland. The line that represents synthetic Finland is still significantly higher than Finland even if it is lower than the other synthetic controls when Poland and Switzerland are excluded. One possible explanation for this can be found in the large weights (26.1% and 11.9%, respectively) assigned to these countries in synthetic Finland. However, it is especially Luxembourg which is problematic (which was assigned a weight of 14.1%). When leaving out Luxembourg, the line representing synthetic Finland is only slightly above that of Finland. This indicates that Luxembourg has a significant influence on the observed outcome. While the main finding doesn't change (the carbon tax reduced per capita CO_2 emissions), the magnitude of the effect is only a fraction of the initial finding. This robustness test offers a minimum estimate of the impact, yielding a much more conservative outcome. Dropping Luxembourg, the effect by the end of the post-treatment period is only about 7%, in contrast to the initial estimate of approximately 39% reduction. It should be noted that Elbaum (2021) also finds that his results are driven by Luxembourg to a large extent. Nevertheless, he still finds a 15% reduction in CO_2 emissions at the end of the post-treatment period when excluding Luxembourg.

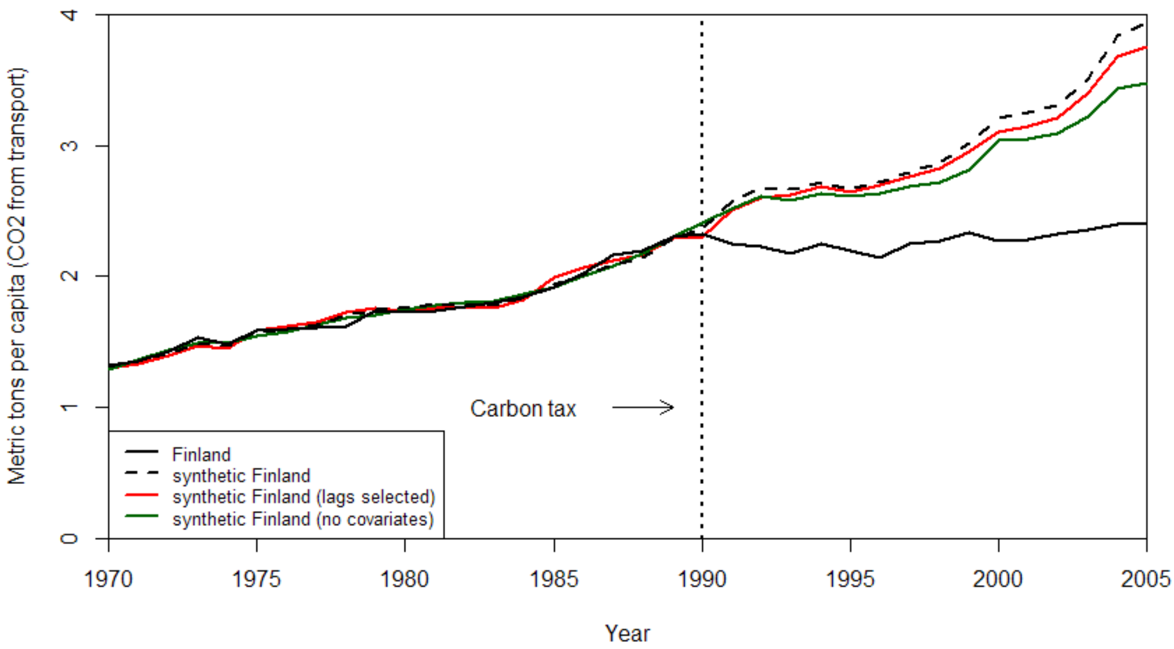


Figure 10. ALTERNATIVE SPECIFICATIONS

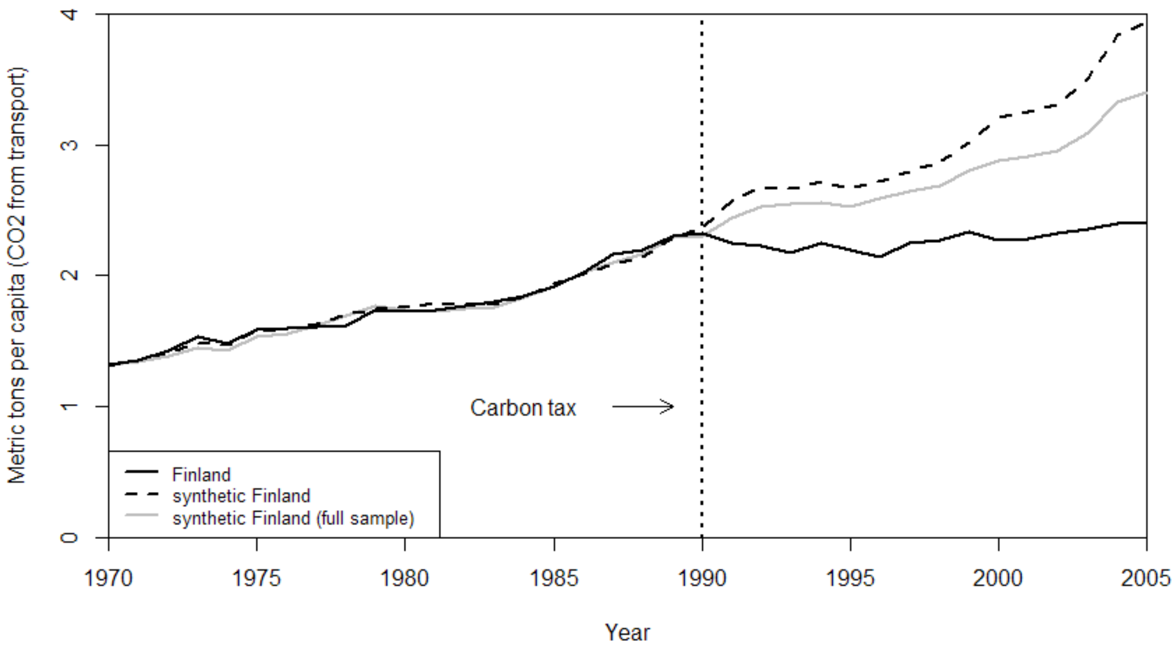


Figure 11. PATH PLOT OF PER CAPITA CO_2 EMISSIONS FROM TRANSPORTATION: MAIN RESULTS VS. FULL SAMPLE

Notes: The main result (dotted line) is based on a limited sample of 16 OECD countries for constructing synthetic Finland. The full sample result (grey line) includes all 24 OECD donor countries plus Poland for constructing synthetic Finland.

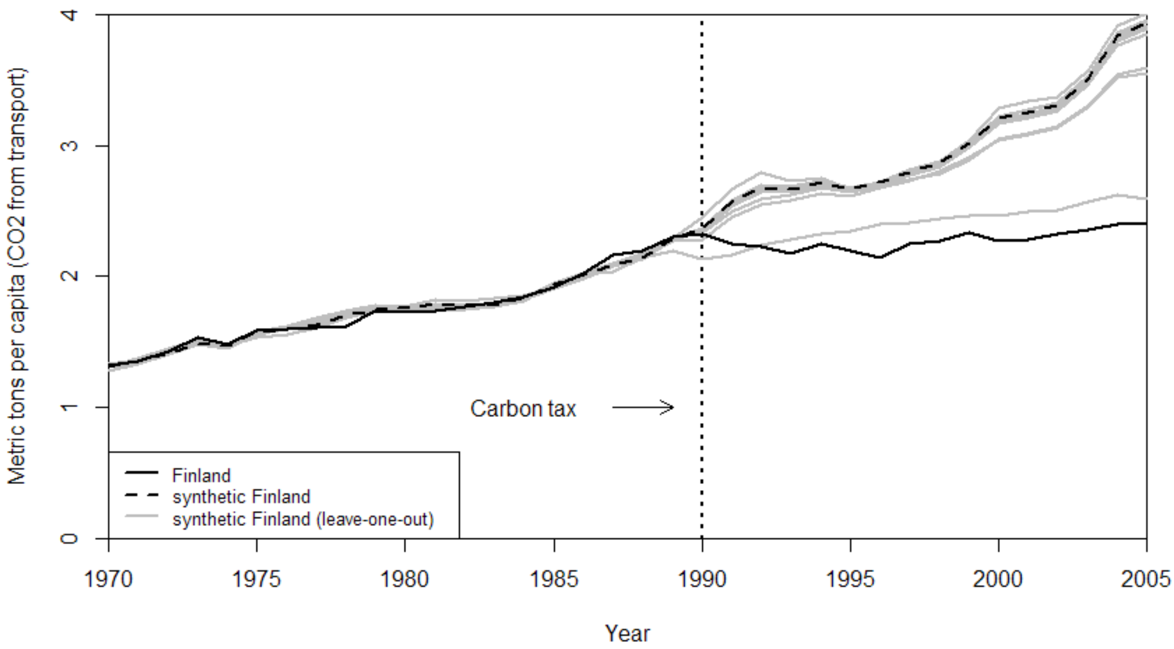


Figure 12. LEAVE-ONE-OUT TEST

4.2 Results for $PM_{2.5}$ and NO_x

4.2.1 Finland vs. Synthetic Finland

In order to construct a reliable counterfactual, synthetic Finland must closely replicate the values of the key predictors and closely match the $PM_{2.5}$ and NO_x trend observed in Finland's transportation sector during the pre-treatment period. Figure 13 panels (a) and (b) demonstrate that, before the carbon tax was introduced, $PM_{2.5}$ and NO_x emissions from transportation in Finland and synthetic Finland were aligned relatively closely. Overall, the alignment is satisfactory despite some differences in the paths, especially in the late 1980s. This suggests that synthetic Finland provides a credible counterfactual. Moreover, tables 5 and 7 in Appendix C show the means of the predictors for Finland, synthetic Finland, and the average of the 16 donor countries in the pre-treatment period for $PM_{2.5}$ and NO_x, respectively. Most of the weight assigned to the predictors is given to lagged values of $PM_{2.5}$ and NO_x emissions. Tables 6 and 8 in Appendix C display the weights (W weights) assigned to each country in the donor pool for $PM_{2.5}$ and NO_x, respectively. For $PM_{2.5}$, synthetic Finland is primarily made up of Portugal, Iceland, New Zealand, Japan, Greece, Canada, and the United States, listed in descending order of their weights. In the case of NO_x, synthetic Finland consists of Denmark, New Zealand, Portugal, Luxembourg, and Belgium, again with decreasing weights. For both pollutants, other countries in the control group are given zero or near-zero weights.

(a) Finland vs. Synthetic Finland: $PM_{2.5}$ (b) Finland vs. Synthetic Finland: NO_x

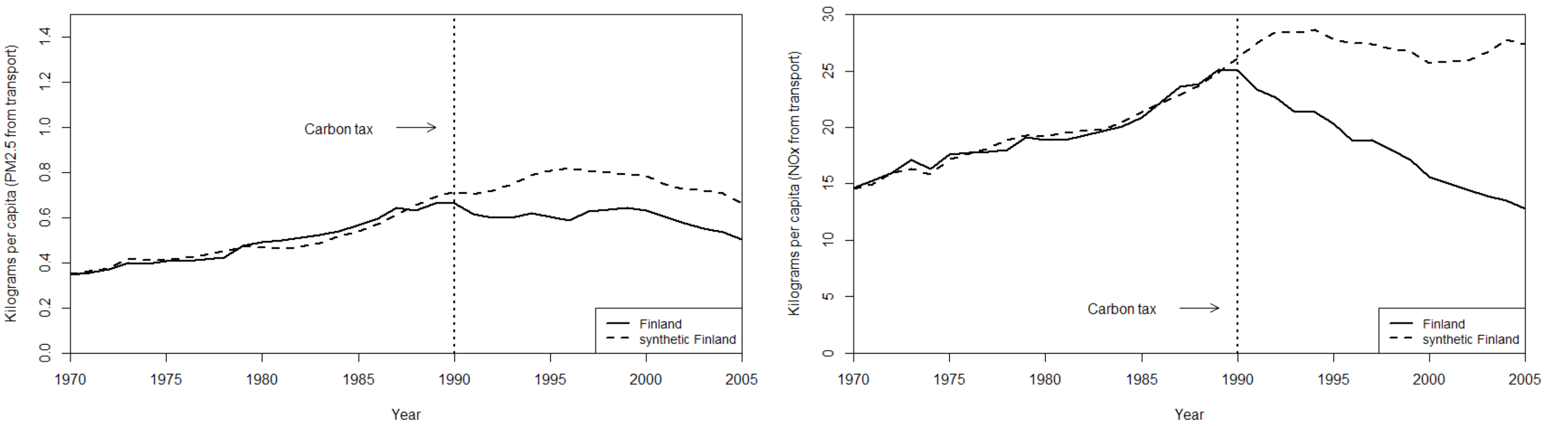
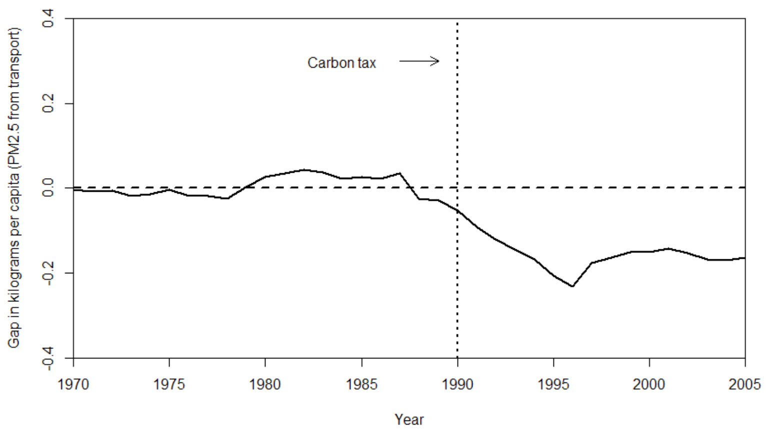


Figure 13. PATH PLOT OF PER CAPITA $PM_{2.5}$ and NO_x EMISSIONS FROM TRANSPORTATION: FINLAND VS. SYNTHETIC FINLAND

4.2.2 Impact of the carbon tax

The distance between the lines representing Finland and synthetic Finland in the post-treatment period (i.e., after 1990), as depicted in panels (a) and (b) of figure 13, quantifies the decrease in $PM_{2.5}$ and NO_x emissions, respectively. It demonstrates that the introduction of the carbon tax had a significant effect on kilograms of $PM_{2.5}$ and NO_x emissions per capita from transportation in Finland. This gap is further illustrated in the gap plots presented in panels (a) and (b) of Figure 14. As for $PM_{2.5}$, there was a decrease of 0.091 kilograms per capita, or approximately 12.9%, within a year of the carbon tax going into effect. The greatest difference in $PM_{2.5}$ emissions between Finland and synthetic Finland occurred in 1996, amounting to 0.232 per capita kilograms. By 2005, the final year of the sample period, $PM_{2.5}$ emissions from transportation in Finland were reduced by 24.5%, or 0.16 kilograms per capita, compared to what they would have been without the carbon tax. For NO_x, the effect is particularly huge. Within a year of introducing the carbon tax, NO_x emissions decreased by about 14.8%, which amounts to 4.067 kilograms per capita. The progressive increase of the carbon tax only caused greater and greater reductions throughout the post-treatment period. In 2005, NO_x emissions decreased by 53.4%, or 14.65 kilograms per capita, relative to synthetic Finland. To verify the magnitudes of these effects, further examination is needed; this will be done in sections 4.2.3 and 4.2.4.

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



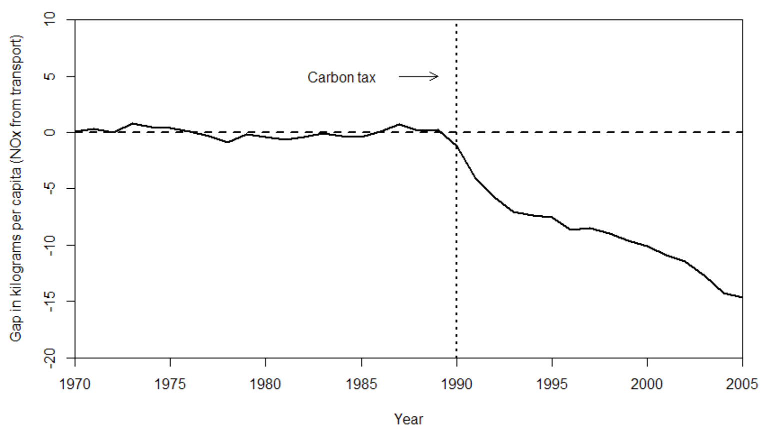


Figure 14. GAP BETWEEN PER CAPITA $PM_{2.5}$ and NO_x EMISSIONS FROM TRANSPORTATION OF FINLAND AND SYNTHETIC FINLAND

4.2.3 Placebo tests

The "in-time" placebo test reassigns the intervention to the year 1980, a decade before the actual introduction of the carbon tax. If the placebo has a significant and persistent effect, the validity of the results shown in figures 13 and 14 would be called into question. I use the same predictors as in the main analysis for the "in-time" test. Panels (a) and (b) in figure 15 show the outcome of the "in-time" placebo test for $PM_{2.5}$ and NO_x, respectively. There is a divergence in the paths in both panels. The paths diverge persistently for $PM_{2.5}$ after 1987, while for NO_x, the divergence begins just one year after the carbon tax is introduced and only keeps getting wider over time. These placebo effects raise questions about whether the outcomes depicted in figures 13 and 14 truly reflect the causal impact of the carbon tax.

(a) $PM_{2.5}$ (b) NO_x

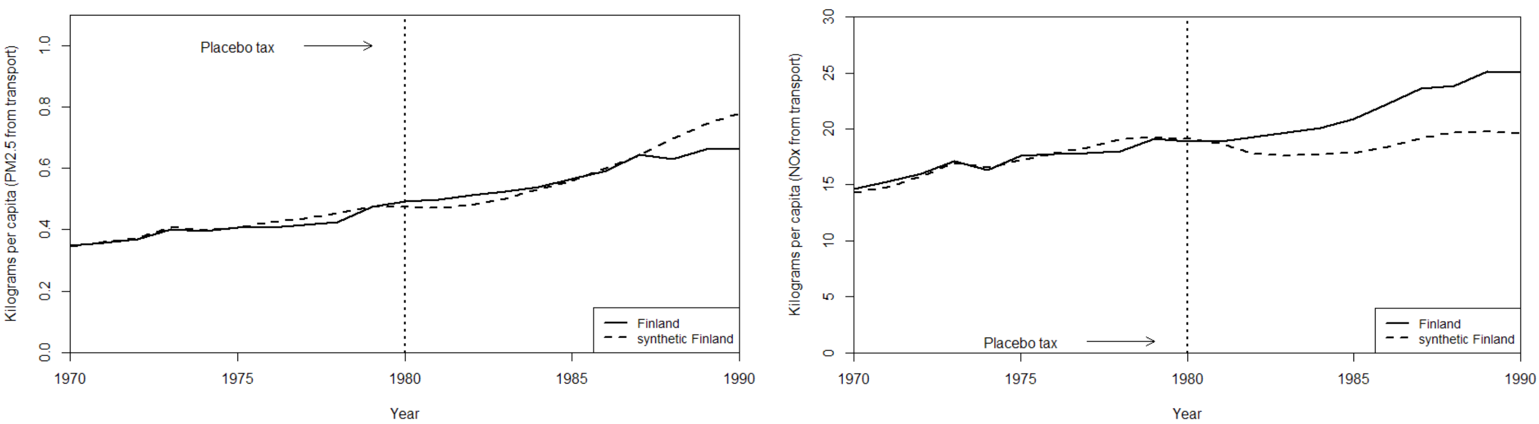


Figure 15. IN-TIME PLACEBO TEST (1980)

In the "in-space" placebo test, the intervention is iteratively reassigned to each country in the donor pool, with synthetic controls again being created using the synthetic control method. As explained in section 4.1.3, this approach allows us to assess whether the outcomes observed for Finland are exceptionally large. Panels (a) and (b) in figure 16 show the outcomes of the "in-space" placebo test for $PM_{2.5}$ and NO_x, respectively. After excluding countries whose pre-treatment MSPE exceeds Finland's by at least 20 times, 14 countries remain in the donor pool for $PM_{2.5}$, and 13 countries remain for NO_x. In the case of NO_x, none of the remaining donor countries show effects as substantial as those observed for Finland. However, for $PM_{2.5}$, several countries display larger impacts on emissions than Finland. Again, this suggests that the observed reduction in $PM_{2.5}$ emissions in the original analysis might not be solely attributable to the carbon tax.

(a) $PM_{2.5}$ (b) NO_x

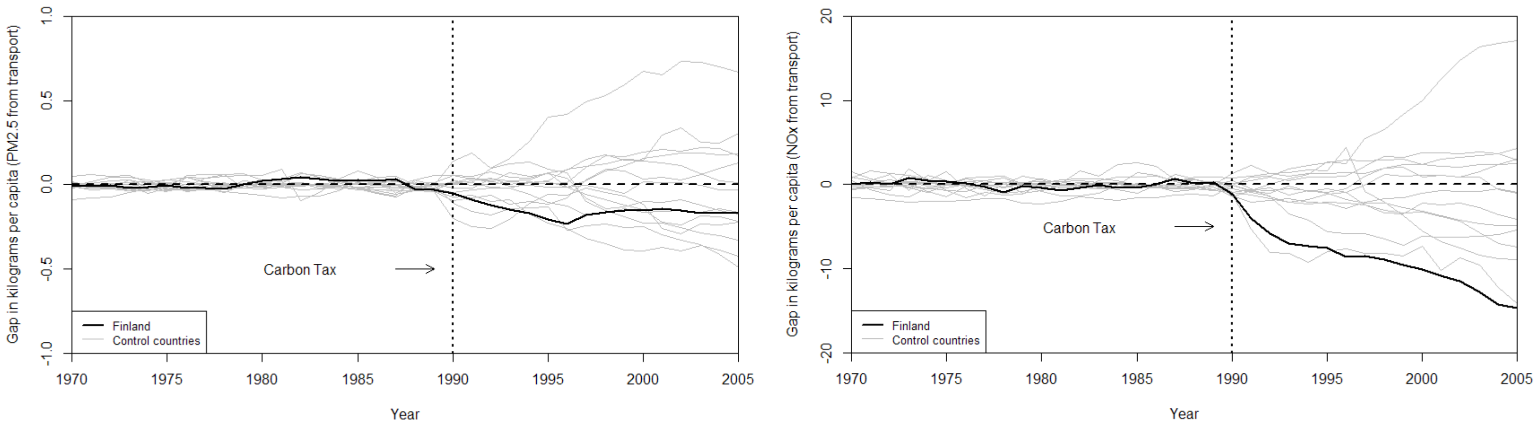


Figure 16. IN-SPACE PLACEBO TEST

However, solely relying on the post-treatment gaps depicted in figure 16 is not enough to evaluate the effect's magnitude. A more robust approach for inference involves analysing the ratio of post-treatment MSPE to pre-treatment MSPE, based on the assumption that a higher ratio for Finland compared to smaller ratios for the donor countries indicates a real causal effect from the carbon tax. In Appendix C, figure 17 presents these ratios for Finland and the donor countries for $PM_{2.5}$ emissions, while figure 18 does the same for NO_x emissions. In the case of NO_x, Finland exhibits the highest ratio; although Japan and New Zealand also have relatively large ratios, what really matters is that these ratios do not come close to that of Finland. For $PM_{2.5}$, five countries have a larger ratio than Finland, with New Zealand's ratio being particularly huge compared to Finland's. Again, this casts doubt on the validity of the findings presented in figures 13 and 14 for $PM_{2.5}$.

4.2.4 Robustness tests

Two additional robustness tests—the "leave-one-out" and "full sample" tests— are performed to further assess the results' robustness. Panels (a) and (b) of figure 19 illustrate the "full sample" test, in which the counterfactual is constructed using all 24 OECD donor countries plus Poland. With regards to $PM_{2.5}$, all of the countries that were previously excluded—namely, Austria, Ireland, Italy, the Netherlands, Norway, Sweden, and the United Kingdom—now receive weights greater than 0.002. On the contrary, Belgium, which previously had a weight of 0.001, is now dropped from the synthetic control. Problematically, the path plot diverges significantly from the main results; beginning in 2005, the line representing the full sample (depicted in grey) is notably lower than that representing the original synthetic Finland. In fact, after 2000, the two lines mostly converge. While the original analysis showed a reduction of 0.163 kilograms per capita by 2005, the full sample shows a reduction of just 0.009 kilograms per capita, suggesting that the previously observed decrease in $PM_{2.5}$ emissions is almost completely driven by the exclusion of specific countries from the donor pool. Similarly, for NO_x, the path plot also shows a significant deviation from the main analysis, though not as badly as with $PM_{2.5}$. While in the main result, by the end of the sample period in 2005, the reduction in NO_x emissions was 14.65 kilograms per capita, with the full sample, the reduction is 'merely' 10.60 kilograms per capita. Again, this shows that the exclusion of countries from the donor pool significantly affects the estimated decrease in NO_x emissions.

(a) $PM_{2.5}$ (b) NO_x

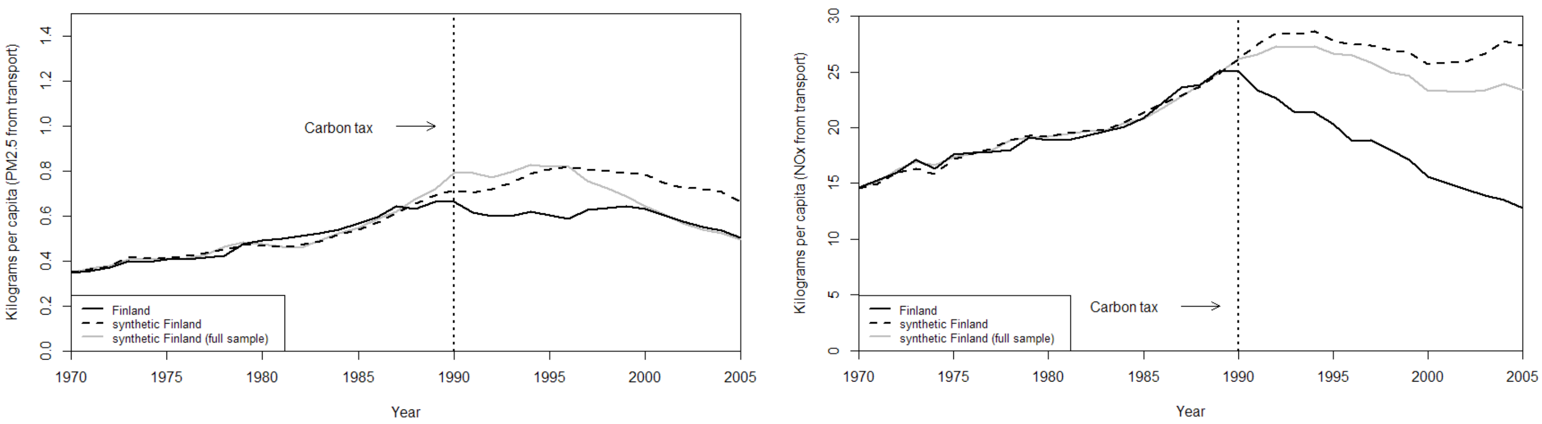


Figure 19. PATH PLOT OF PER CAPITA CO_2 EMISSIONS FROM TRANSPORTATION: MAIN RESULTS VS. FULL SAMPLE

Secondly, the "leave-one-out" test involves sequentially excluding every donor country that has a W weight greater than 0.001. This is done to determine if the findings are driven by one or a few powerful donor countries. Panels (a) and (b) in figure 20 display the results of this robustness test. If Portugal and New Zealand are excluded from the $PM_{2.5}$ analysis, synthetic Finland line is substantially lower than the original synthetic Finland. These countries' significant influence on the outcome is probably explained by the large weights (20.0% and 26.3%, respectively) that were given to them in synthetic Finland. This indicates that New Zealand and Portugal are key drivers of the observed effect. When these countries are excluded, the reduction effect at the end of the post-treatment period drops to around 13%, significantly less than the initially estimated 25% decrease. For NO_x emissions, the leave-one-out synthetic Finland is mostly identical to the donor pool's synthetic Finland, with the notable exceptions of Luxembourg and New Zealand. Excluding New Zealand, the line representing synthetic Finland is lower than that of the other synthetic controls, yet it still remains significantly above actual Finland's emissions. However, similarly to the situation for CO_2, it is especially Luxembourg which is problematic; excluding this country leads to a drastically lower trajectory for synthetic Finland compared to the original synthetic Finland. This suggests that Luxembourg has a significant influence on the observed result. Without Luxembourg, the observed reduction in NO_x emissions by the end of the post-treatment period is only about 18%, in contrast to the initially estimated reduction of 53.4%.

(a) $PM_{2.5}$ (b) NO_x

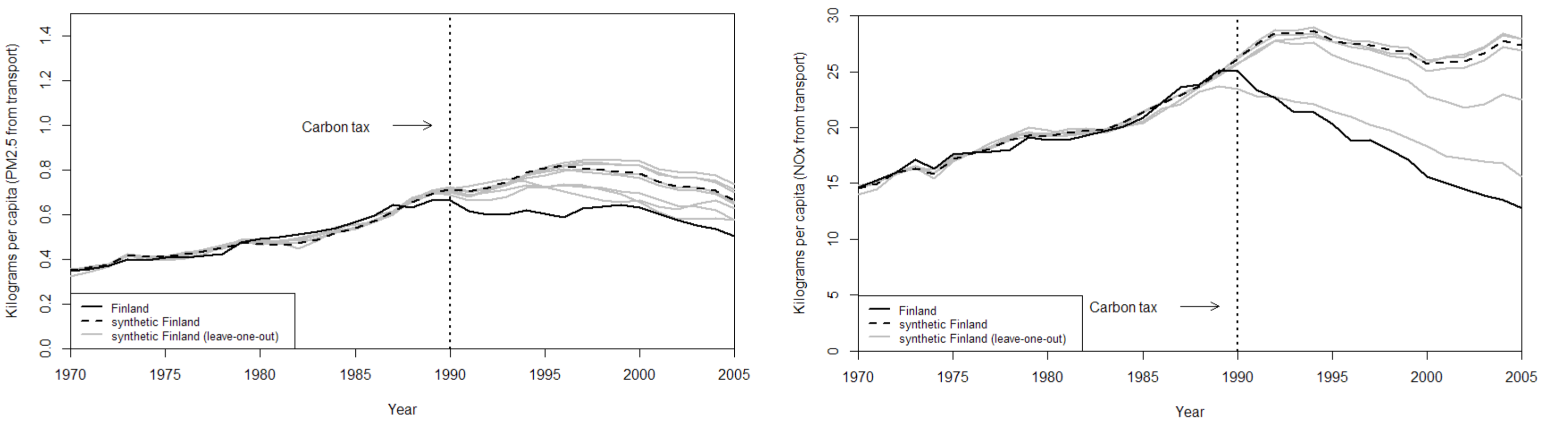


Figure 20. LEAVE-ONE-OUT TEST

5. Discussion

5.1 Effect of the Finnish carbon tax on CO_2, $PM_{2.5}$, and NO_x emissions from transportation

The results for CO_2 show that, when compared to synthetic Finland in 2005, there is an absolute decrease in CO_2 emissions per capita by 1.528 metric tons, or 38.8%, indicating that the carbon tax had the desired impact. Moreover, the "in-time" and "in-space" placebos demonstrate that this finding is indicative of a genuine causal effect, thereby underscoring the validity of the result. But in the "full sample" robustness test, the path plot differs notably from the initial result; the line representing the full sample is substantially lower than that of the original synthetic Finland. This implies that the estimated reduction in CO_2 emissions is influenced by leaving certain countries out of the donor pool. Similarly, the "leave-one-out" test demonstrates that Luxembourg is a significant driver of the result because, when Luxembourg is excluded, the effect at the end of the post-treatment period is only approximately 7%, as opposed to the initially estimated 38.8% reduction. This establishes a lower bound of the carbon tax's impact.

Moreover, although the initial analysis suggests a 24.5% reduction in $PM_{2.5}$ emissions from transportation in Finland, amounting to 0.16 kilograms per capita, the placebo tests reveal that this reduction cannot be attributed solely to the carbon tax. Furthermore, the robustness tests demonstrate that the observed decrease in $PM_{2.5}$ emissions is largely driven by the exclusion of specific countries from the donor pool. Consequently, it appears that the Finnish carbon tax did not have a causal effect on $PM_{2.5}$ emissions. In the case of NO_x, the findings indicate a substantial reduction of 53.4%, or 14.65 kilograms per capita in 2005, compared to synthetic Finland. Although the "in-time" placebo test reveals a divergence between Finland and synthetic Finland in the post-treatment period, casting doubt on the causal impact of the carbon tax, the “in-space” placebo demonstrates that no donor country exhibits effects as large as those seen for Finland. As was the case for CO_2, the “leave-one-out” test shows that excluding Luxembourg leads to a significant decrease in the observed reduction in NOx emissions; by the end of the post-treatment period, it is ‘only’ about 18%. Again, this provides a lower bound of the carbon tax's effect.

The results for CO_2 align with prior research that finds a reduction effect due to the carbon tax, especially Andersson (2019). He shows that by 2005 (the last year of his sample period), transportation emissions in Sweden had fallen by 12.5% compared to the scenario without the carbon tax. After disentangling the effect of the carbon tax and the VAT[6], he attributes three-quarters of the observed decrease in emissions, or 9.4%, to the carbon tax alone. This is comparable to the approximately 7% reduction observed in my analysis by the end of the post-treatment period. As for NO_x, I find, in line with Basaglia et al. (2023), that the carbon tax resulted in a significant decrease in NO_x emissions from transportation, although my findings indicate a reduction (18%) that is three times as large as the 6% observed by Basaglia et al. (2023).

The results are, nonetheless, in contrast with a number of previous investigations of the Finnish carbon tax. For instance, Lin and Li (2011) used the DiD method to analyse the impact of carbon taxes on the growth rate of per capita CO_2 emissions among early adopters such as Denmark, Finland, the Netherlands, Norway, and Sweden. Their results show a 1.7% reduction in growth rate of CO_2 emissions per capita in Finland only. This is significantly less than the reduction observed in my analysis. Nevertheless, it can be contended that the study by Lin and Li (2011) potentially produces biased estimates, primarily due to the limitations inherent to the DiD methodology, as they violate fundamental assumptions in causal inference. Specifically, they include outcome variables as covariates (such as energy prices and industry structure) and merge treated and untreated sectors in their sample by using total CO_2 emissions, which might have introduced bias into the findings. Moreover, the control group in their study included countries like Austria and Ireland, which may not have been the best choices for constructing an accurate counterfactual for emissions[7]. The findings also diverge from Elbaum (2021), who similarly uses the SCM to assess the impact of the Finnish carbon tax. While Elbaum also finds that his results are significantly driven by Luxembourg, he still observes a 15% decline in CO_2 emissions at the end of the post-treatment period after excluding Luxembourg. In contrast, my analysis shows only a 7% reduction when excluding Luxembourg. While the reason for this difference is not directly clear, differences in the setup of the analysis might play a role. For example, Elbaum's study begins in 1965, whereas mine starts in 1970; he uses fossil fuel consumption per capita as a predictor, whereas I use gasoline consumption per capita; and unlike in my study, his control group includes Austria and Ireland rather than Poland.

[6] This is necessary because, the year before implementing the Swedish carbon tax, Sweden expanded the scope of its existing VAT to also cover gasoline and diesel.
[7] See section 3.2.1 for an explanation of this.

5.2 External validity in time

Introduced more than thirty years ago, the carbon tax examined in the Finnish case study was likely a factor in significant changes that happened during that time, such as the shift from gasoline to diesel. But after thirty years, the transport landscape has undergone substantial transformations, most notably with rise in the popularity of electric vehicles. For instance, the global stock of electric passenger vehicles has increased from a mere 0.02 million in 2013 to 40 million in 2023 (IEA, 2024). In Finland, electric vehicles sales have risen sharply since 2019, and in 2023, the share of electric vehicles sold exceeded those of non-electric vehicles for the first time (Ritchie, 2024). This denotes a decrease in the percentage of fuel combustion vehicles, which means a policy targeting the price of gasoline and diesel would become less relevant. Consequently, while the insights from 1990-2005 remain valid for that period, the generalisability of these results to the present and future can be questioned. Also, over time, public perceptions of environmental policies have changed. Support for national carbon taxes in Finland is strongly correlated with perceptions of climate risk, according to recent studies like Sivonen (2023). Moreover, Pohjolainen et al. (2018) noted that, in contrast to other European countries, the public in Finland is relatively supportive of imposing a tax on fossil fuels. Because of the previously mentioned changes in consumer preferences and technological development, the price elasticity of demand for fuel is also likely to shift over time. The growing popularity of electric vehicles is a prime illustration of how substitutes for conventional combustion engine vehicles can lessen dependency on gasoline and diesel, thus increasing consumer sensitivity to fuel price fluctuations.

5.3 Limitations

This study is not without limitations. First, the SCM for $PM_{2.5}$ and NO_x employs the same predictors as the SCM for CO_2, notably leaving out important environmental variables like precipitation and temperature. Including these predictors requires the use and analysis of remote sensing data, which is a skill set that I do not currently possess[8]. Problematically, the validity of the results may be impacted if temperature and precipitation are excluded from the analysis. While temperature can have an impact on chemical reaction rates in the atmosphere that affect the formation and dissipation of $PM_{2.5}$ and NO_x, precipitation can affect the rates of dispersal and deposition of these pollutants (Megaritis et al., 2014). The study might not fully

[8] While data on precipitation is available from the World Bank WDI database, it is problematic because it is the same for every country for every year.

account for natural variations that, independent of any policy interventions (such as a carbon tax), have a significant impact on $PM_{2.5}$ and NO_x levels if these factors are not taken into account. This could therefore result in an overestimation or an underestimation of the actual impact of the carbon tax on the reduction of $PM_{2.5}$ and NO_x emissions. This could be improved in future research by including these environmental factors in the synthetic control analysis.

Secondly, existing research demonstrates a correlation between GDP growth and increases in CO_2 emissions (Andersson, 2019). Therefore, it raises the question of whether the Finnish economic downturn from 1990 to 1993 (Mideksa, 2021) might actually be the real cause of the reductions in emissions observed during the post-treatment period. This potential explanation has not been explored in the current study. Future research could investigate this to increase the robustness of the results. One possible way of deriving the impact of the recession would be to analyse emissions in the sector most likely affected, that is, the industrial sector. If the economic downturn similarly influences emissions across both the industrial and transportation sector, a comparable reduction pattern would be observed in both activities.

6. Conclusion

Climate change and air pollution represent complementary global and local externalities resulting from fossil fuel use. Economists often advocate for the use of pricing mechanisms to internalise these negative externalities (Elbaum, 2021), with carbon taxes increasingly becoming a focal point in economic and environmental policy debates. This thesis empirically analyses the impact of such a tax in Finland, focusing specifically on the following research question: *Has the Finnish carbon tax reduced CO_2 emissions, specifically within the transportation sector, and has it yielded the co-benefit of improved air quality through reduced $PM_{2.5}$ and NO_x emissions?*

This study advances upon previous research, which primarily consists of ex-ante simulations. Such studies often produce estimates that vary significantly due to the initial assumptions made about baseline scenarios and parameters that remain unknown. This study is only the second to employ a quasi-experimental approach to evaluate the effectiveness of a carbon tax in simultaneously reducing carbon emissions and air pollutants. Using the synthetic control method, this study compares the carbon and air pollutant emissions of the actual Finnish transportation sector to those of synthetic Finland from 1990 to 2005. The control unit, synthetic Finland, effectively replicates Finland on several key predictors of CO_2, $PM_{2.5}$, and

NO_x emissions from the transportation sector, and accurately mirrors emissions throughout the two decades preceding the implementation of the tax.

The initial results show that the Finnish carbon tax considerably reduced CO_2, $PM_{2.5}$, and NO_x emissions within the transportation sector. By 2005, there was an absolute decrease in emissions per capita by 38.8% for CO_2, 24.5% for $PM_{2.5}$, and 53.4% for NO_x. But further investigation reveals that the observed drop in $PM_{2.5}$ emissions cannot be fully attributed to the carbon tax and is mostly driven by the exclusion of specific countries from the donor pool. It would seem, therefore, that the Finnish carbon tax had no causal effect on $PM_{2.5}$ emissions. In the case of CO_2 and NO_x, the influence of one particular country, Luxembourg, significantly drives the findings. Synthetic Finland's emissions path is substantially lower when Luxembourg is excluded from the donor pool, resulting in a much smaller observed reduction by the end of the post-treatment period—approximately 7% for CO_2 and 18% for NO_x. Nevertheless, the effectiveness of the carbon tax is confirmed given the methodology and data used in this study.

Public support for carbon taxes remains low (Carattini et al., 2018), yet studies have shown that presenting evidence that these taxes actually decrease emissions can increase public support (Dechezleprêtre et al., 2022). Therefore, the findings of this study can help in building crucial public support for carbon taxes, especially since it demonstrates that the tax also yields the co-benefit of improved air quality through reduced NO_x emissions.

The importance of ex-post analyses in assessing the causal impact of carbon taxes is emphasised by this thesis. To expand the empirical literature on this topic, further research is needed to evaluate the effectiveness of carbon taxes implemented in different countries. While the Finnish carbon tax was found to have effectively reduced emissions in this study using the synthetic control method, further econometric approaches should be investigated too. Using machine learning in fixed effects panel estimation, Pretis (2022) novel break-detection method is one interesting alternative. Although the synthetic control method is useful for evaluating whether the carbon tax succeeded in reducing emissions, it does not reveal whether other, previously unidentified interventions had significant impacts. Providing a more nuanced understanding of policies such as carbon taxes, a break-detection method enables the identification of treated units and the dates of interventions without needing prior information about when they occurred.

7. References

Abadie, A., Diamond, A., & Hainmueller, J. (2010). Synthetic control methods for comparative case studies: Estimating the effect of California's tobacco control program. *Journal of the American statistical Association*, 105(490), 493-505. https://doi.org/10.1198/jasa.2009.ap08746

Abadie, A., Diamond, A., & Hainmueller, J. (2011). Synth: An R package for synthetic control methods in comparative case studies. *Journal of Statistical Software*, *42*(13). https://doi.org/10.18637/jss.v042.i13

Abadie, A., & Gardeazabal, J. (2003). The economic costs of conflict: A case study of the Basque Country. *American economic review*, 93(1), 113-132. https://doi.org/10.1257/000282803321455188

Andersson, J. J. (2019). Carbon taxes and CO2 emissions: Sweden as a case study. *American Economic Journal: Economic Policy*, *11*(4), 1-30. https://doi.org/10.1257/pol.20170144

Arcila, A., & Baker, J. D. (2022). Evaluating carbon tax policy: A methodological reassessment of a natural experiment. *Energy Economics*, *111*, 106053. https://doi.org/10.1016/j.eneco.2022.106053

Basaglia, P., Behr, S. M., & Drupp, M. A. (2023). De-Fueling Externalities: How Tax Salience and Fuel Substitution Mediate Climate and Health Benefits. DIW Discussion Papers, No. 2041.

Bayer, P., & Aklin, M. (2020). The European Union emissions trading system reduced CO2 emissions despite low prices. *Proceedings of the National Academy of Sciences*, *117*(16), 8804-8812. https://doi.org/10.1073/pnas.1918128117

Blundell, R., & Bond, S. (1998). Initial conditions and moment restrictions in dynamic panel data models. *Journal of econometrics*, *87*(1), 115-143. https://doi.org/10.1016/s0304-4076(98)00009-8

Bray, S. (2022). 2022 Carbon Tax Rates in Europe | European Countries with a Carbon Tax. Tax Foundation. https://taxfoundation.org/data/all/eu/carbon-taxes-in-europe-2022/

Carattini, S., Carvalho, M., & Fankhauser, S. (2018). Overcoming public resistance to carbon taxes. *Wiley Interdisciplinary Reviews: Climate Change*, 9(5), e531. https://doi.org/10.1002/wcc.531

Carl, J., & Fedor, D. (2016). Tracking global carbon revenues: A survey of carbon taxes versus cap-and-trade in the real world. *Energy Policy*, *96*, 50-77. https://doi.org/10.1016/j.enpol.2016.05.023

Clarke, S. (2023). *Background Report for the Economic Policy Council on Carbon Pricing in Finland*. VATT.

Dargay, J., Gately, D., & Sommer, M. (2007). Vehicle ownership and income growth, worldwide: 1960-2030. *The energy journal*, *28*(4), 143-170. https://doi.org/10.5547/issn0195-6574-ej-vol28-no4-7

Dechezleprêtre, A., Fabre, A., Kruse, T., Planterose, B., Chico, A. S., & Stantcheva, S. (2022*)*. Fighting climate change: International attitudes toward climate policies (No. w30265). National Bureau of Economic Research. https://doi.org/10.3386/w30265

Dussaux, D. (2020). The joint effects of energy prices and carbon taxes on environmental and economic performance: Evidence from the French manufacturing sector. Working Paper, OECD Environment.

Elbaum, J. D. (2021). *The effect of a carbon tax on per capita carbon dioxide emissions: evidence from Finland* (No. 21-05). IRENE Working Paper.

Ferman, B., Pinto, C., & Possebom, V. (2020). Cherry picking with synthetic controls. *Journal of Policy Analysis and Management*, *39*(2), 510-532. https://doi.org/10.1002/pam.22206

Fernando S 2019 The environmental effectiveness of carbon taxes: a case study of the nordic experience *The 1st Int. Research Conf. on Carbon Pricing* (New Delhi, India: World Bank) 349–68.

Green, J. (2021). Does carbon pricing reduce emissions? A review of ex-post analyses. *Environmental Research Letters*, 16(4), 043004. https://doi.org/10.1088/1748-9326/abdae9

Haites, E. (2018). Carbon taxes and greenhouse gas emissions trading systems: what have we learned?. *Climate policy*, *18*(8), 955-966. https://doi.org/10.1080/14693062.2018.1492897

IEA (2024). Global EV Outlook 2024, IEA, Paris. https://www.iea.org/reports/global-ev-outlook-2024/trends-in-electric-cars

JRC. (2021). EDGAR - The Emissions Database for Global Atmospheric Research. https://edgar.jrc.ec.europa.eu/methodology

Köppl, A., & Schratzenstaller, M. (2022). Carbon taxation: A review of the empirical literature. *Journal of Economic Surveys*, 1–36. https://doi.org/10.1111/joes.12531

Lin, B., & Li, X. (2011). The effect of carbon tax on per capita CO2 emissions. *Energy policy*, *39*(9), 5137-5146. https://doi.org/10.1016/j.enpol.2011.05.050

Maestre-Andrés, S., Drews, S., & van den Bergh, J. (2019). Perceived fairness and public acceptability of carbon pricing: a review of the literature. *Climate policy*, 19(9), 1186-1204. https://doi.org/10.1080/14693062.2019.1639490

Manisalidis, I., Stavropoulou, E., Stavropoulos, A., & Bezirtzoglou, E. (2020). Environmental and health impacts of air pollution: a review. *Frontiers in public health*, 8, 14. https://doi.org/10.3389/fpubh.2020.00014

Megaritis, A. G., Fountoukis, C., Charalampidis, P. E., Denier Van Der Gon, H. A. C., Pilinis, C., & Pandis, S. N. (2014). Linking climate and air quality over Europe: effects of meteorology on PM 2.5 concentrations. *Atmospheric Chemistry and Physics*, *14*(18), 10283-10298. https://doi.org/10.5194/acp-14-10283-2014

Metcalf, G. E., & Weisbach, D. A. (2009). Design of a carbon tax. *Social Science Research Network*. https://doi.org/10.2139/ssrn.1324854

Mideksa, T. K. (2021). Pricing for a cooler planet: An empirical analysis of the effect of taxing carbon. CESifo Working Paper No. 9172. https://doi.org/10.2139/ssrn.3885415

Neumayer, E. (2004). National carbon dioxide emissions: geography matters. *Area*, *36*(1), 33-40. https://doi.org/10.1111/j.0004-0894.2004.00317.x

O'Neill, A. (2023). GDP per capita, by country 2022 | Statista. Statista. https://www.statista.com/statistics/270180/countries-with-the-largest-gross-domestic-product-gdp-per-capita/

Parry, I. W., Black, S., & Zhunussova, K. (2022). Carbon Taxes or Emissions Trading Systems?: Instrument Choice and Design. *IMF eLibrary*. https://doi.org/10.5089/9798400212307.066.A001

Pohjolainen, P., Kukkonen, I., Jokinen, P., et al. (2018). Public Perceptions on Climate Change and Energy in Europe and Russia : Evidence from Round 8 of the European Social Survey. Public Attitudes to Welfare Climate Change and Energy in the EU and Russia (PAWCER). London, European Social Survey.

Pretis, F. (2022). Does a carbon tax reduce CO2 emissions? Evidence from British Columbia. Environmental and Resource Economics, 83(1), 115-144. https://doi.org/10.1007/s10640-022-00679-w

Ritchie, H. (2024, April). Tracking global data on electric vehicles. Our World in Data. https://ourworldindata.org/electric-car-sales

Santikarn, M., Nanue, A., Kallhauge, C., Bozcaga, M. (2021) *State and Trends of Carbon Pricing 2021 (English).* Washington, D.C. : World Bank Group. http://documents.worldbank.org/curated/en/771941622009013802/State-and-Trends-of-Carbon-Pricing-2021

Schöb, R. (2005). The double-dividend hypothesis of environmental taxes: a survey. *The international yearbook of environmental and resource economics*, *2006*, 223-279. https://doi.org/10.4337/9781845425593.00013

Sharma, S. S. (2011). Determinants of carbon dioxide emissions: empirical evidence from 69 countries. *Applied energy*, *88*(1), 376-382. https://doi.org/10.1016/j.apenergy.2010.07.022

Sileci, L (2023). Carbon pricing with regressive co-benefits: evidence from British Columbia's carbon tax. *Centre for Climate Change Economics and Policy*. Working Paper 430/Grantham Research Institute on Climate Change and the Environment Working Paper 405. London: London School of Economics and Political Science

Sivonen, J. (2023). Attitudes toward global and national climate policies in Finland–The significance of climate change risk perception and urban/rural-domicile. GeoJournal, 88(2), 2247-2262. https://doi.org/10.1007/s10708-022-10750-0

UNFCC (2008). *Kyoto protocol reference manual on accounting of emissions and assigned amount*. Bonn: United Nations Framework Convention on Climate Change.

Weitzman, M.L. (1974). Prices vs. Quantities. Review of Economic Studies, 41(4), 477-91.

8. Appendix

Appendix A Description of the Synthetic Control Method

Suppose there are J + 1 countries in the sample, indexed by j, with j = 1 denoting the treated country, which in this study is Finland. The donor pool, a collection of OECD countries unaffected by the intervention (Finnish carbon tax), is denoted by j = 2, 3, …, J + 1, and can be used to create a control group. The countries in the sample are observed for time periods t = 1, 2, …, T divided into pre-treatment and post-treatment, that is, after the introduction of the carbon tax in 1990. It is important to have a sufficient number of pre-treatment periods 1, 2, …, T_0 as well as post-treatment periods $T_0 + 1$, $T_0 + 2$, …, T to be able to both construct a synthetic Finland (using pre-intervention data) and to assess the impact of the treatment (using post-intervention data).

The outcome of interest (CO_2, $PM_{2.5}$, or NO_x emissions from the transportation sector) is observed for each country (j) and time (i), and is denoted as Y_{jt}. I define Y_{jt}^{I} as the outcome of the unit in period t under treatment and Y_{jt}^{N} as the outcome in period t under non-treatment. Estimating the effect of the intervention on the treated country is the aim, which can be formalised as

$$\alpha_{1t} = Y_{1t}^{I} - Y_{1t}^{N} \quad (1)$$

However, it's only possible to observe one aspect, specifically the treated outcome of the treated unit. The potential untreated outcome of the treated unit is not observed post-intervention. Consequently, it is necessary to create a theoretical counterfactual that reliably estimates what would have occurred to the treated unit if the intervention had not taken place.

The synthetic control ("Synthetic Finland") is a weighted average of control countries j = 2, 3, …, J + 1 from the donor pool of OECD countries, which can be formally represented by a (J x 1) vector of weights

$$W = (w_2, \dots, w_{J+1})' \text{ with } 0 \leq w_j \leq 1 \text{ and } w_2 + \dots + w_{J+1} = 1 \quad (2)$$

Each value of W corresponds to a set of weights that define a potential synthetic control. Additionally, X_1 represents a (k x 1) vector comprising pre-treatment predictors of Finland's (the treated unit) outcome variable (CO_2, $PM_{2.5}$, or NO_x emissions from the transportation sector). Similarly, X_0 is a (k x J) matrix that contains the same predictors for all units in the donor pool. Following Abadie et al. (2010), W is chosen such that it minimises the pre-treatment difference in crucial predictors between the treated country and the untreated donors. Put differently, the vector W* is chosen such that $||X_1 - X_0W||$ is minimised, which means that vector W* is selected to minimise the mean square predictor error (MSPE) over k pre-treatment predictors.

$$MSPE = \sum_{m=1}^{k} v_m \, (X_{1m} - X_{0m}W)^2 \qquad (3)$$

where v_m represents the weight assigned to the *m*-th variable when assessing the difference between X_1 and X_0. More relevant predictors are assigned more weight.

Y_1 is a (T_1 x J) vector comprising the post-treatment values of the outcome of the treated country, and Y_0 is a (Y_1 x J) matrix that aggregates the outcome values for the donor pool. The impact of the intervention is determined by the difference between the post-treatment outcome of the treated country and the post-treatment outcome of the synthetic control, denoted as $Y_1 - Y_0W^*$. Accordingly, the difference between the (CO_2, $PM_{2.5}$ or NO_x) emissions in the treated country in the post-treatment period and emissions in the synthetic control during the same period is the treatment effect α_{1t}:

$$\alpha_{1t} = Y_{1t} - \sum_{j=1}^{J+1} w_j^* \, Y_{jt} \qquad (4)$$

Appendix B EDGAR database

Data on air pollution and GHG emissions are collected by the EDGAR database from every single country across the world, encompassing all human-induced activities, with the exception of Land Use, Change and Forestry (LULUCF). The database uses a coherent methodology and bottom-up approach for quantifying emissions. Comprehensive information on fuel consumption is provided by activity data sets (which include up to 68 vectors). These data sets come from various sources, such as the energy balances of the International Energy Agency (IEA). While data for other countries is presented at the regional level, this information pertains to 155 countries. Using data from the Energy Information Administration (EIA), which incorporates country-level shares in total regional fuel consumption for aggregated fuel categories, emissions are adjusted from regional to national levels.

When available, technology based emission factors tailored to specific countries are integrated. Emissions (EM) for a country C are computed annually and sector-wise (across i sectors). This involves multiplying the country-specific activity data (AD), which quantifies human activity in each of the i sectors, with the combination of j technologies (TECH) in each sector i, and their abatement percentage through one of the k end-of-pipe (EOP) measures for each technology j. Moreover, it incorporates the relative reduction (RED) of the uncontrolled emission by the installed abatement measure k, as well as the country-specific emission factor (EF) unique to each sector i and technology j (JRC, 2021).

Appendix C SCM: Additional results

TABLE 5. $PM_{2.5}$ EMISSIONS FROM TRANSPORTATION PREDICTOR MEANS BEFORE TREATMENT

Variables	Finland	Synthetic Finland	OECD sample
GDP per capita	16,722.6	15,489.6	17,212.9
Gasoline consumption per capita	285.8	311.2	408.0
Motor vehicles (per 1,000 people)	291.7	323.0	333.2
Urban population	71.4	70.6	73.3
$PM_{2.5}$ from transport per capita (1989)	0.7	0.7	0.7
$PM_{2.5}$ from transport per capita (1980)	0.5	0.5	0.4
$PM_{2.5}$ from transport per capita (1975)	0.4	0.4	0.3
$PM_{2.5}$ from transport per capita (1970)	0.3	0.4	0.3

Notes: The values are rounded to 1 decimal. All variables are averaged over the period 1970-1989, except lagged $PM_{2.5}$.

TABLE 6. COUNTRY WEIGHTS IN SYNTHETIC FINLAND ($PM_{2.5}$)

Country	Weight	Country	Weight
Australia	0.002	Luxembourg	0
Belgium	0.001	New Zealand	0.200
Canada	0.026	Poland	0
Denmark	0	Portugal	0.263
France	0.001	Spain	0
Greece	0.117	Switzerland	0
Iceland	0.238	Turkey	0
Japan	0.129	United States	0.021

Notes: The w_j weights are between $0 \leq w_j \leq 1$ and $\sum w_j = 1$.

TABLE 7. NO_X EMISSIONS FROM TRANSPORTATION PREDICTOR MEANS BEFORE TREATMENT

Variables	Finland	Synthetic Finland	OECD sample
GDP per capita	16,722.6	17,829.6	17,212.9
Gasoline consumption per capita	285.8	368.4	408.04
Motor vehicles (per 1,000 people)	291.7	362.2	333.2
Urban population	71.4	77.8	73.3
NOx from transport per capita (1989)	25.1	24.9	24.0
NOx from transport per capita (1980)	18.8	19.2	20.7
NOx from transport per capita (1975)	17.6	17.2	18.3
NOx from transport per capita (1970)	14.6	14.6	15.1

Notes: The values are rounded to 1 decimal. All variables are averaged over the period 1970-1989, except lagged NO_x.

TABLE 8. COUNTRY WEIGHTS IN SYNTHETIC FINLAND (NO_X)

Country	Weight	Country	Weight
Australia	0	Luxembourg	0.120
Belgium	0.062	New Zealand	0.289
Canada	0	Poland	0
Denmark	0.392	Portugal	0.136
France	0	Spain	0
Greece	0	Switzerland	0
Iceland	0	Turkey	0
Japan	0	United States	0

Notes: The w_j weights are between $0 \leq w_j \leq 1$ and $\sum w_j = 1$.

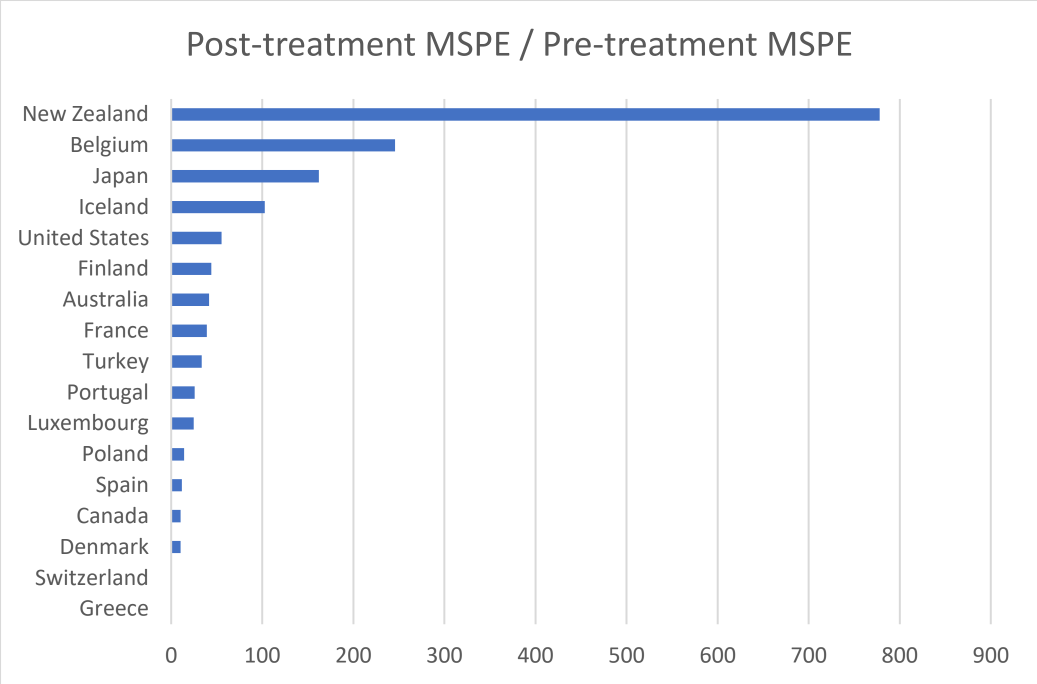


Figure 17. RATIO TEST FOR $PM_{2.5}$: RATIO OF POST-TREATMENT MSPE TO PRE-TREATMENT MSPE FOR FINLAND AND 16 DONOR COUNTRIES

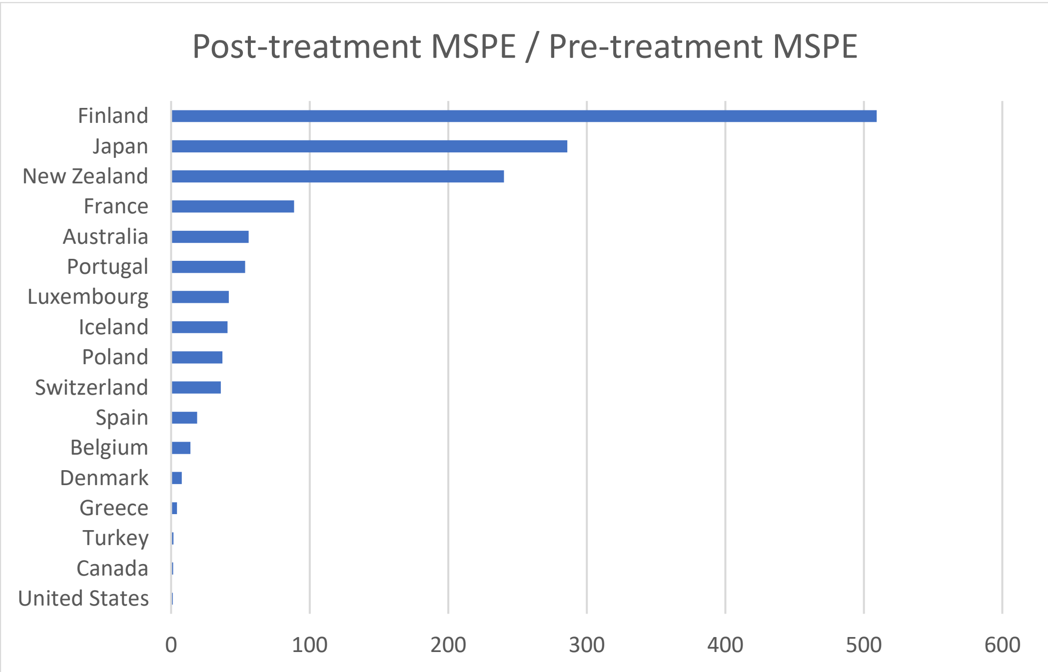


Figure 18. RATIO TEST FOR NO_x: RATIO OF POST-TREATMENT MSPE TO PRE-TREATMENT MSPE FOR FINLAND AND 16 DONOR COUNTRIES