Transportation Research Part A 106 (2017) 22–50

Contents lists available at ScienceDirect

Transportation Research Part A

journal homepage: www.elsevier.com/locate/tra

Fuel consumption dynamics in Europe: Tax reform implications for air pollution and carbon emissions

Anne Zimmer[a,b,*], Nicolas Koch[c]

[a] Potsdam Institute for Climate Impact Research (PIK), PO Box 601203, 14412 Potsdam, Germany
[b] Technical University of Berlin, Department "Economics of Climate Change", Strasse des 17. Juni 145, 10623 Berlin, Germany
[c] Mercator Research Institute on Global Commons and Climate Change (MCC), Torgauer Str. 12-15, 10829 Berlin, Germany

ARTICLE INFO

Keywords:
Fuel price elasticity
Diesel
Gasoline
Climate policy
Air pollution
Dynamic panel

Jel codes:
H23
R48
Q41
Q48
Q53
Q54

ABSTRACT

This paper estimates the potential of fuel tax reforms to curb harmful air pollutants and carbon emissions from road transport in Europe. We provide robust estimates for the responsiveness of fuel consumption to changes in prices, which constitute a key determinant for emissions pathways in response to policy interventions. We show that accounting for the manifest shift to diesel in the European vehicle fleet, as well as slow consumption adjustments over time yield strong evidence that petrol and diesel demand are more price elastic already in the short run than previous studies suggest. In particular, we present evidence that diesel demand in Europe tends to be more price elastic than petrol demand, when instrumenting prices with excise taxes to account for endogeneity. Inspired by recent fuel tax reform proposals, we then show that both (i) a repeal of the preferential tax treatment for diesel and (ii) an introduction of a carbon content-based tax, could avoid considerable amounts of health damaging air pollutant exhaust while at the same time contributing substantially to achieving the EU climate policy goals for 2020. In many countries, abandoning the diesel tax advantage has nearly as strong an effect as a 50€/tCO_2 tax on fuel. Both reforms have significant revenue potential.

1. Introduction

Road transport was responsible for around 20% of total greenhouse gas (GHG) emissions in the EU-28 in 2013 (EEA, 2015). In fact, the transport sector is the only major sector which has exhibited an increase in GHG emissions since 1990 making it the second largest GHG emitter in the EU (EEA, 2015). Moreover, the World Health Organization (WHO) estimates that approximately 600,000 premature deaths in the European region in 2010 were due to health damaging air pollution (WHO Regional Office for Europe and OECD, 2015). In 2013, around 61% of the urban population in the EU-28 was exposed to fine particulate matter ($PM_{2.5}$) concentration levels exceeding the WHO Air Quality Guidelines (EEA, 2015). While most existing road transport policies, such as fuel efficiency standards, have failed to set consistent incentives across all fuels, technologies and other abatement options, price-based policies such as carbon content-based fuel taxes, could minimize perverse incentives (Creutzig et al., 2011). Indeed, several studies have demonstrated that emissions pricing can lead to notable emissions reductions (Fowlie et al., 2012) and that the policy-induced

Abbreviations: AB, Arellano-Bond; ADL, autoregressive distributed lag; CO_2, carbon dioxide; EC, European Commission; ECM, error correction model; ESD, effort sharing decision; FE, fixed effects; GHG, greenhouse gases; GMM, generalized method of moments; IV, instrument variable; LRM, long run multiplier; LSDV, least squares dummy variable; LSDVc, bias corrected least squares dummy variable; NO_x, nitrogen oxides; OLS, ordinary least squares; PAM, partial adjustment model; PM, particulate matter; $PM_{2.5}$, particulate matter with an aerodynamic diameter of up to 2.5 µm; SCC, social cost of carbon; WP, white paper

* Corresponding author at: Potsdam Institute for Climate Impact Research (PIK), PO Box 601203, 14412 Potsdam, Germany.
E-mail addresses: azimmer@pik-potsdam.de (A. Zimmer), Koch@mcc-berlin.net (N. Koch).

http://dx.doi.org/10.1016/j.tra.2017.08.006
Received 28 August 2016; Received in revised form 1 August 2017; Accepted 4 August 2017
Available online 17 September 2017
0965-8564/

improvements in ambient air quality and health benefits can be substantial (Malina and Scheffler, 2015; Chay and Greenstone, 2003; Currie and Neidell, 2005). Moreover, studies have revealed strong potential synergies between climate policies and air pollution policies (Bollen and Brink, 2014; Nam et al., 2014).

The European Commission (EC) and the European Environment Agency (EEA) have in this light both called for a reform of fuel pricing policies to correct the undesired externalities[1] from road transport (EEA, 2015; European Commission, 2011b). Although the EC had withdrawn its proposal for a carbon and energy content-based fuel tax reform in 2015 due to insufficient political support, two recent events have revived the debate on the current fuel pricing policy design. First, in the autumn of 2015, the fraud scandal of a major car producer using illegal software to pass approval tests, revealed that emissions limits were being substantially exceeded in diesel cars under real driving conditions (ICCT, 2014, 2015b; New York Times, 2016). This has provoked criticism into the political support for the dieselization of the car fleet in Europe and has refueled the debate on the effectiveness of emissions standards (Frondel et al., 2011) and the prevailing preferential tax treatment for diesel fuel (Harding, 2014; ICCT, 2015a; Schipper and Fulton, 2013; Burguillo-Cuesta et al., 2011). Second, the Paris Agreement on Climate Change of December 2015 – largely celebrated as a historic breakthrough in international climate negotiations – will need to be followed by ambitious mitigation policies in order to be successful. Compliance with the pledges made by European countries will require the transport sector to make a large contribution towards mitigation efforts, given its share in total GHG emissions. In order to achieve the 2 °C target, the EC estimates that GHG emissions from EU-transport will need to be reduced by 70% below 2008 levels by 2050 (European Commission, 2011b).

For the design of appropriate fuel pricing policies, policy makers need evidence about the consumer's response to fuel price changes and the distribution of the consumption changes over time. Despite the fact that fuel consumption price elasticity is a widely researched topic, reliable empirical estimates on recent European data, particularly for diesel, remain limited. While the proportion of diesel passenger cars is negligible in Northern America and many other countries, a substantial increase in the share of diesel vehicles since the 1990s is a distinguishing feature of European road transport. Yet, only very few empirical studies estimating petrol price elasticities account for the increasing proportion of diesel vehicles (see Pock, 2010). Previous studies on Europe also do not consider that an increase in fuel demand can cause the price of fuel to increase, which can result in the endogeneity of the price as highlighted by Burke and Nishitateno (2013), Davis and Kilian (2011) and Kim et al. (2011). Moreover, important questions on dynamics have remained unanswered; when designing pricing policies, policy makers might also be interested in "when" and especially "how fast" the consumption responds to shifts in fuel prices.

In this study, we focus on the potential of fuel pricing policies in the European road transport sector in addressing climate change and air pollution. Our contribution to the literature is twofold. First, using a panel of 16 European countries from 1990 to 2012, we present estimates on the diesel and petrol price elasticity that are free of potential biases from diesel stock shift effects or price endogeneity. In particular, we provide a comprehensive analysis of the dynamics of fuel demand, which reveals important insights into the hitherto hidden adjustment behavior and the distribution of the demand response over time. In a comparison of a range of fuel demand equations, including a flexible error correction specification, we show that ignoring dynamics – for instance by imposing the widely-used partial adjustment model specification – masks consumers' responses to fuel price changes.

Second, equipped with robust estimates of the price induced fuel consumption reduction, we assess the potential of two fuel pricing policy scenarios to reduce emissions of CO_2, $PM_{2.5}$ and NO_x. These scenarios are inspired by specific policy proposals in the recent political debate. In a first scenario we explore the expected effects of adjusting diesel excise tax levels to petrol taxation levels as proposed in the wake of the 2015 diesel car scandal (Reuters, 2015; Umweltbundesamt, 2015). Our second policy scenario relates to the implementation of more ambitious climate policies in order to achieve the Intended Nationally Determined Contributions (INDCs) under the Paris agreement. More specifically, we explore the potential effects of introducing – in addition to the pre-existing taxes – a carbon content-based tax of 50€/tCO_2 on both diesel and petrol. We conclude with an assessment of how much these two policies would contribute to achieving the existing EU climate policy targets for the transport sector in 2020.

The remainder of the paper is structured as follows. Section 2 reviews the related empirical literature. Section 3 introduces the empirical model framework, followed by the data and variable definition in Section 4. Section 5 presents the elasticity estimation results. Section 6 assesses the impact of the two policy scenarios on CO_2 emissions, as well as NO_x and $PM_{2.5}$ exhaust. Section 7 concludes with policy implications.

2. Empirical literature

Motivated by concerns over future scarcities, triggered by oil crises rather than by environmental concerns, fuel consumption behavior was studied intensely in the 1980s and 1990s (see the reviews or meta-analyses of Espey, 1998; Basso and Oum, 2007; Brons et al., 2008; Dahl, 2012; Dahl and Sterner, 1991; Graham and Glaister, 2002; Havranek et al., 2012). Study design and methodologies, as well as estimation results, vary widely (see Basso and Oum, 2007, for a comprehensive assessment of different empirical methodologies). A meta-analysis of Brons et al. (2008) finds mean short-run and long-run petrol price elasticities of −0.34 and −0.84, while Havranek et al. (2012) presents more price inelastic results of −0.09 (short-run) and −0.31 (long-run). Using IV-estimation techniques, a recent study of Burke and Nishitateno (2013) documents a quasi-global long-run petrol price elasticity of between −0.2 and −0.5.

While there is a large body of literature dealing with fuel demand in Northern America, Europe has been studied less

[1] Parry (2009) suggests that aggregated social costs of noise, congestion, traffic accidents, oil dependence and infrastructure – which are not considered in this study – even surpass costs from climate change and air pollution.

intensely. However, the meta-analysis of Brons et al. (2008) provides evidence that petrol demand response in Europe might differ from Northern American estimates. Baltagi and Griffin (1997) use a panel of mainly European OECD countries and find a range of −0.07 to −0.29 for the short-run and −0.24 to −1.42 for the long-run petrol price elasticity. Based on a similar OECD panel, Johansson and Schipper (1997) estimate the long-run price elasticity to be between −0.4 to −1.0, stating −0.7 to be their "best guess". Liddle (2012) documents a petrol price elasticity of −0.16 (short-run) and −0.19 to −0.43 (long-run) for a panel of 14 OECD countries with low diesel car shares. Highlighting the importance of accounting for the rising proportion of diesel cars in Europe, Pock (2010) finds a petrol price elasticity range of −0.03 to −0.19 in the short-run and −0.32 to −0.84 in the long-run.

Only a few notable exceptions provide estimates for diesel price elasticities in Europe (Ramli and Graham, 2014; Bonilla, 2009; Burguillo-Cuesta et al., 2011). Burguillo-Cuesta et al. (2011) estimate for a panel of EU-15 countries an elasticity of −0.27 with respect to diesel excise taxes. In a meta-analysis, Dahl (2012) finds diesel price elasticity estimates to range between −0.13 and +0.38, strongly encouraging more research on diesel demand.

While environmental impacts from transportation have gained more attention, comparably few studies combine their empirical estimates of price elasticities with an investigation of fuel pricing effects on emissions. Davis and Kilian (2011) provide one of the first studies to investigate this effect for road transport in the United States. Based on estimates for the petrol price elasticity, they calculate that a tax of US$10 per ton of carbon dioxide, translated into a 10 US cents tax (per gallon) on petrol, would decrease US carbon emissions from the transport sector by about 1.5%. Kim et al. (2011) follow a similar approach to Davis & Kilian and provide comparable evidence for South Korean data. Melo and Ramli (2014) use fuel price elasticities for the Lisbon Metropolitan Area to predict road transportation CO_2 emissions. In contrast, the implications for air pollution remain widely unexplored.

3. Dynamic models of fuel demand

3.1. Empirical model specifications

In road transportation, overall fuel demand can be assumed to be largely driven by the aggregate of individual households' and firms' demand for fuel, maximizing their utility or profit. The key factors determining fuel consumption are the price of fuel and the spending capacity of households or firms reflected in the level of income. A higher fuel price is expected to lead to a decrease in consumption, while a higher income is expected to increase demand for fuel. Moreover, we expect a certain stock effect for a given population; e.g. if a household has a second car, it will generally not be used as much as the main car. Thus, the fuel demand per vehicle is expected to decrease with an increasing vehicle stock.

The general relationship between fuel consumption per vehicle and its determinants can be written in the form of a log linear demand equation (see also Baltagi et al., 2003; Pock, 2010),

$$c_{i,t} = \alpha + \beta\ price_{i,t} + \gamma\ income_{i,t} + \delta\ stock_{i,t} \tag{1}$$

where $c_{i,t}$, $price_{i,t}$, $income_{i,t}$ and $stock_{i,t}$ denote the log of fuel consumption, fuel price, income level and vehicle stock of country $i = 1,\ldots,N$ in period $t = 1,\ldots,T$, respectively.

This demand equation is based on the assumption that adjustments to changes in prices, income or stock have taken full effect. While this relationship serves well to describe the long-run, in the short run, immediate adjustment to changes in the fuel price or in the income level are hampered for a number of reasons. To begin with, there is convincing evidence that consumers are subject to habit persistence in their behavior (see e.g. Ravina, 2005; Scott, 2012) and, therefore, changes in consumption behavior will occur only slowly. In addition, consumers are constrained by the technical features of their vehicles. Given that the stock of vehicles, and consequently also the fuel efficiency of the stock, is fixed in the short term, consumers can only react by changing how they use their vehicle, i.e. by avoiding trips or switching to other modes of transport. Only in the long run consumers can change to more efficient vehicles or sell their car. Taken together, these factors lead to a slow and rather complex adjustment process over time. Consequently, fuel demand should not be modeled in a static framework but in a dynamic model allowing for adjustments over time, disentangling short and long-run effects as well as adjustment processes.

To account for dynamic adjustment mechanisms, we nest expression (1) for the long-run fuel consumption, within a general Autoregressive-Distributed Lag (ADL) model. A specification search suggests that for the sample data at hand the following first-order ADL provides a parsimonious specification of the relevant dynamics[2]:

$$c_{i,t} = \alpha_0 + \alpha_1 c_{i,t-1} + \beta_0 price_{i,t} + \beta_1 price_{i,t-1} + \gamma_0 income_{i,t} + \gamma_1 income_{i,t-1} + \delta_0 stock_{i,t} + \delta_1 stock_{i,t-1} + \mu_i + \epsilon_t + \varepsilon_{i,t} \tag{2}$$

where μ_i is a country-specific effect reflecting unobserved time-invariant heterogeneity between countries, ϵ_t is a year-specific effect that captures the impact of common shocks, and $\varepsilon_{i,t}$ is the error term. The short-run fuel price elasticities are given by the respective coefficients of the price variables β_0 and β_1. The long-run elasticity, or the long-run multiplier (LRM), is given by $(\beta_0 + \beta_1)/(1-\alpha_1)$. It reflects the total effect of fuel price changes on fuel consumption distributed over future time periods.

The ADL representation does not show all information about the adjustment process. Policy makers are likely interested in learning how long it takes for fuel consumption to adjust to price changes and how much of the adjustment happens in early periods. This would

[2] Subject to data limitations, we consider various ADL specifications up to a lag order of two for explanatory and lagged dependent variables. Models are compared using a specific-to-general approach based on F-tests and Arellano-Bond tests for first and second order autocorrelation.

help improve the planning of policy reforms. We transform the ADL model to its Error Correction Model (ECM) form to gain this information

$$\Delta c_{i,t} = \alpha_0 + \alpha_1^{ECM} c_{i,t-1} + \beta_0^{ECM} \Delta price_{i,t} + \beta_1^{ECM} price_{i,t-1} + \gamma_0^{ECM} \Delta income_{i,t} + \gamma_1^{ECM} income_{i,t-1} + \delta_0^{ECM} \Delta stock_{i,t} + \delta_1^{ECM} stock_{i,t-1} + \mu_i + \epsilon_t + \varepsilon_{i,t} \tag{3}$$

with $\alpha_1^{ECM} = (\alpha_1 - 1)$, $\beta_0^{ECM} = \beta_0$ and $\beta_1^{ECM} = \beta_0 + \beta_1$, which applies equivalently to γ_0^{ECM}, γ_1^{ECM} and δ_0^{ECM}, δ_1^{ECM}. In this ECM the short-term price elasticities are given by β_0^{ECM} and $\beta_1^{ECM} - \beta_0^{ECM}$. The long-run multiplier is more readily available as $-(\beta_1^{ECM}/\alpha_1^{ECM})$.

The ECM representation reveals the adjustment speed at which the dependent variable – fuel consumption – returns to its long-run relationship after a change in an independent variable, i.e. price, income and stock. It is reflected in the error correction rate which is estimated by the coefficient of the lagged dependent variable α_1^{ECM}. It tells us how much of the adjustment, to the long-run state, takes place each period after a deviation has occurred. The rate has to be negative and in the range of $-1 < \alpha_1^{ECM} < 0$ for the process to converge to the long-run relationship with non-immediate adjustment. It is important to note that the ECM specification does not require co-integration but can also be estimated based on stationary data (Wickens and Breusch, 1988; De Boef and Keele, 2008). In particular, the inclusion of first differences – in addition to levels – mitigates the danger of spurious regression. With the notable exception of Liddle (2012), the ECM framework for panel data has not been applied in prior analyses of fuel price elasticities.

3.2. Distribution of adjustment dynamics

The dynamic models can reveal further patterns about the distribution of the price effects over time which help to anticipate implications on tax revenues, environmental effectiveness and climate targets.

First, we can determine the cumulative effect over a certain period of time. To fix ideas, consider the ADL in Eq. (2). Assume a permanent price shock of 1 in period r = 0. The immediate response ω_0 to the shock will be a change in fuel demand by β_0, the short-run effect. In period r = 1, this change in r = 0 will be carried further by the direct effect of the lagged price variable β_1 as well as indirectly by the lagged dependent variable, i.e. the additional change in demand is $\omega_1 = \alpha\omega_0 + \beta_1$. From r = 2 onwards, the shock is passed on only through the lagged dependent variable, so that $\omega_r = \alpha\omega_{r-1} = \alpha^{r-1}\omega_1$ for r > 2. Thus, the cumulative effect of the shock realized in period R, φ_R, is obtained by

$$\varphi_R = \sum_{r=0}^{R} \omega_r \tag{4}$$

Second, based on the cumulative effect, we can obtain the median lag length. It provides information on the period in which at least half of the effect has occurred. It is obtained by normalizing the cumulative effect φ_R by the LRM (De Boef and Keele, 2008).

$$m_{ADL} = \frac{\sum_{r=0}^{R} \omega_r}{\sum_{r=0}^{\infty} \omega_r} = \frac{\varphi_R}{LRM} \tag{5}$$

The period R in which the normalized cumulated price effectm exceeds 0.5, constitutes the median lag length.

3.3. Endogeneity of the price

Most studies estimating the fuel price elasticity build on the assumption of exogenous fuel prices. Davis and Kilian (2011), however, argue that feedback effects from fuel demand peaks to fuel prices could result in endogenous prices. Elasticity estimates would then be subject to a bias towards zero. Indeed, identification challenges in estimating demand curves are a long-standing research issue in the literature (Angrist and Krueger 2001; Dahl 1979). Similarly, the choice of an appropriate instrument variable (IV) to address the potential endogeneity is challenging and alternative instruments have been discussed. Davis & Kilian propose to use fuel taxes as instruments.[3] The reasoning is that taxes are correlated with the contemporaneous price level, but likely uncorrelated with contemporaneous fuel demand as taxes can only be implemented with a time lag.

Davis and Kilian (2011) further argue that instrumenting prices with excise taxes has the advantage of identifying the demand response to a pricing policy, i.e. imposing a *tax* increase, rather than general market price changes. As price changes induced by tax changes are both more persistent and more salient (due to media coverage) than other price changes, they may induce larger behavioral responses. Evidence by Scott (2012) corroborates this, showing that changes in fuel taxation result in greater demand responses than changes in total retail prices. Thus, IV estimates based on excise taxes are very likely an overestimate of the true fuel price elasticity. Given our particular interest in the effect of a tax change, we deliberately also apply European data on fuel excise taxes for instrumentation. We, however, caution against generalizing the IV estimates as true estimates.

[3] Burke and Nishitateno (2013) instead propose to use a country's in-ground oil reserves as well as a measure for the international mean import price for crude oil as instruments. Given that domestic oil reserves play a minor role for most European countries, we do not follow this approach.

3.4. Dynamic panel data estimators

To estimate the parameters of the dynamic models in Eqs. (2) and (3), we apply several homogenous dynamic panel estimators.[4] Given our panel structure – with a relatively small number of 16 countries over a moderate number of up to 22 time periods (see Section 4) – there is no single estimator that is particularly well suited and estimation performance remains an empirical issue. While simple *pooled OLS* estimation is biased in the presence of time-invariant unobserved heterogeneity between countries, the *Fixed Effects* (FE) estimator eliminates such country-specific fixed effects but in a dynamic specification with lagged dependent variable it suffers from a simultaneity bias (Nickel bias) that only vanishes with an increasing time dimension (Nickel, 1981). Despite the biases, both OLS and FE can serve to validate other estimators as they provide a range for the true coefficient of the lagged dependent variable (Bond, 2002): while OLS is biased upwards, the FE estimate is biased downwards. In contrast, the *Arellano-Bond estimator* (also called difference GMM; Arellano and Bond, 1991) uses internal instruments to address the simultaneity bias (see Baltagi, 2013 for an overview).[5] In particular, the levels of additional lags of the dependent variable are used as instruments for the differenced lagged dependent variable. However, the Arellano-Bond estimator suffers from weak instruments if variables are highly persistent. To overcome this problem, the *System GMM estimator* (Blundell and Bond, 1998) uses lagged differences as instruments for the lagged dependent variable in a level equation, in addition to lagged levels of the dependent variable instrumenting a differenced equation. A caveat of both GMM estimators is that with growing T the number of instruments can become large relative to sample size, which may render some asymptotic properties invalid (Roodman, 2009).

4. Data and variable definition

Our analysis is conducted on an annual – unbalanced – panel of 16 European countries[6] for the years 1990 to 2012. Detailed information on the data is provided in the Appendix.

4.1. Dependent variables

The two main types of road transport fuel in Europe are petrol and automotive diesel. We obtain our diesel and petrol consumption data from EUROSTAT[7]. For Switzerland, the respective data comes from the World Bank – World Development Indicators[8].

Traditionally petrol has been the main fuel for European passenger cars. Fig. 1, however, reveals that per capita diesel consumption has increased in all sample countries since the 1990s while total petrol consumption has largely declined. Elasticity estimations that do not account for this dieselization would thus yield very misleading results for Europe, overestimating the petrol price elasticity and potentially yielding positive diesel price elasticities. We therefore normalize the diesel and petrol consumption by the stock of vehicles driven by the respective fuel type as proposed by Pock (2010). We will then estimate the respective fuel price elasticity for diesel and petrol vehicles separately.

Moreover, we account for the fact that the consumption data, as reported by EUROSTAT or the World Bank, not only covers passenger cars but also other vehicle types. Disregarding changes in the stock of non-passenger vehicles could cause a bias in the elasticity estimates if the stocks of other vehicles do not develop parallel to the stock of passenger cars; this source of bias is neglected in most previous studies. We therefore additionally compile data on stocks of non-passenger road transport vehicles from EUROSTAT[9].

Fig. 2 highlights that – after the normalization with respective vehicle stocks – both petrol and diesel demand show patterns in line with theoretical expectations, i.e. decreasing fuel consumption with increasing fuel prices (see Fig. A-1 in the Appendix on fuel price development). Most importantly, the figure documents that fuel consumption is highly persistent. This is also consistent with the theory of slow adjustment over time leading to differing long and short-run responses. Not accounting for this persistence in the data can lead to spurious regression results. It is consequently important to apply dynamic estimation techniques (see Section 5).

4.2. Explanatory variables

4.2.1. Fuel price

Data on the price for automotive diesel and petrol, as well as taxes on diesel and petrol per liter, are taken from the International Energy Agency (IEA, 2014). For petrol, we use the price of the most common petrol fuel in Europe, i.e. premium unleaded RON95.

[4] Single country time series analysis or heterogeneous panel estimators could also be applied allowing for heterogeneity in elasticities across countries (Pesaran and Smith, 1995; Pesaran et al., 1999). However, Baltagi and Griffin (1997) as well as Baltagi et al. (2003) show that homogenous estimators taking full advantage of the panel structure outperform heterogeneous estimators which largely suffer from unstable region-specific parameters, even for time dimensions as long as 31 years.

[5] Alternatively, a bias correction for the Least Square Dummy Variable estimator has been proposed for simple dynamic models (see Appendix B).

[6] Sample countries were selected based on data availability. Ireland and Luxembourg were excluded from the sample due to patterns of rising consumption despite increasing fuel prices presumably caused by fuel tourism from neighboring countries.

[7] We use data on gasoline without bio components and gas/diesel oil without bio components for road available at http://ec.europa.eu/eurostat/data/database (nrg_102a). Estimations accounting for bio-diesel and bio-gasoline consumption yield very similar results.

[8] http://data.worldbank.org/indicator/IS.ROD.DESL.KT and http://data.worldbank.org/indicator/IS.ROD.SGAS.KT.

[9] We compiled data from EUROSTAT (road_eqs) on different vehicle types for which sufficient data was available (see Appendix A on details). Our estimation results are consequently based on the stock of petrol passenger cars plus motorcycles for petrol and on the stock of passenger cars and lorries for diesel.

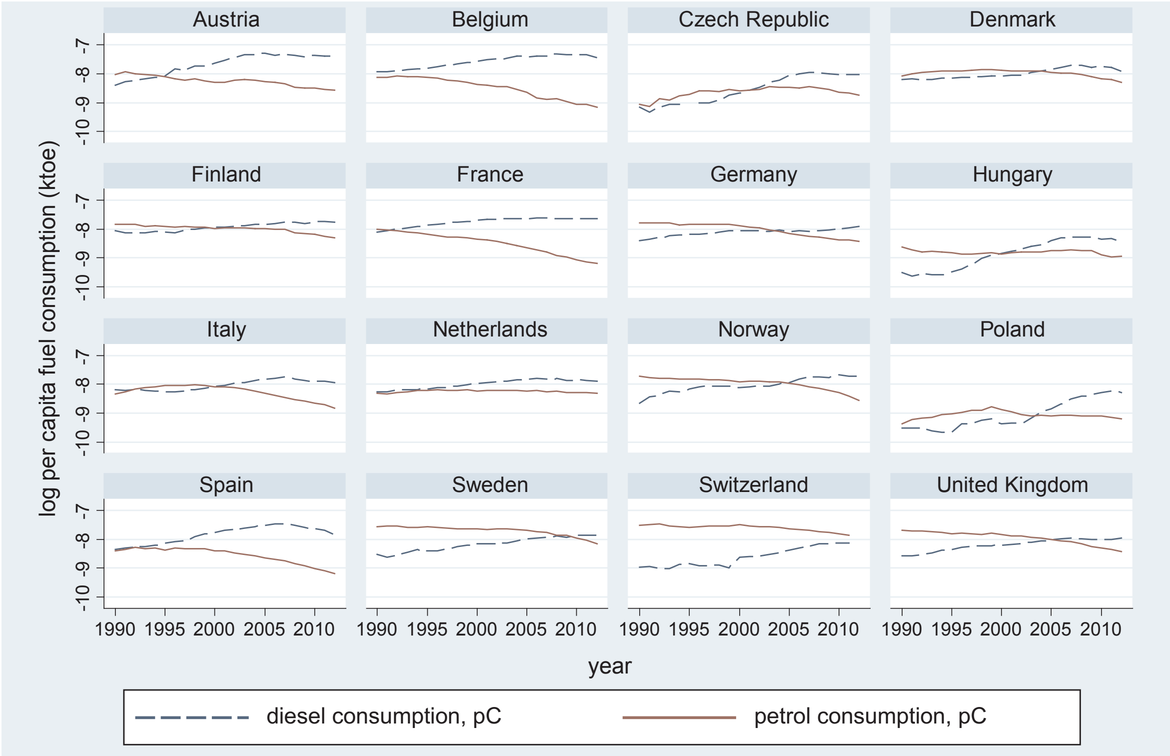

Fig. 1. Road transportation fuel consumption per capita.
Data source: EUROSTAT and WDI World Bank (for Switzerland).

Prices in national currencies have been converted to international Dollars[10]. Diesel and petrol prices over time across countries are shown in Fig. A-1.

We do not include cross-price elasticities or petrol-diesel price differences for four reasons. First, collinearity arises due to similar price developments (see Fig. A-1). Second, as the motor type of a car determines the type of fuel use, substitution between diesel and petrol can only occur in the long run by switching to a car with a different motor type. We indirectly capture this effect by including the total vehicle stock comprising all motor types.[11] Thus, any switch to an alternative motor type shall show up in our estimates: for example, if consumers switch to a diesel car because diesel becomes less expensive, the fuel consumption per petrol car driven would likely go down as trips are substituted with a (less expensive) diesel car. Third, Burguillo-Cuesta et al. (2011) show that the decision of which motor type of car to purchase, is dominated by factors other than the fuel price, such as the purchase price and technological characteristics. Forth, our policy scenarios do not create incentives for switching.

4.2.2. *Vehicle stock*

The stock of vehicles is included to account for the "second car effect" as in Pock (2010) and Baltagi and Griffin (1983). Following Pock (2010), we do not measure the stock of cars *per capita* but rather *per driver* to avoid potential demographical effects. We approximate the number of drivers by data on population and the share of the population aged between 15 and 64 years, both retrieved from the World Bank[12]. We use the aggregate of the total vehicle stock comprising *all* fuel types (in accordance with the definition of the respective dependent variable) to reduce the number of parameters estimated and to account for the small share of alternative motor types.

4.2.3. *Income*

Income is proxied by country data on GDP per capita reflecting the spending capacity of the inhabitants as well as the economic activity. Data on GDP per capita has been taken from the World Bank.[13]

[10] We use the Purchasing Power Parity (PPP) conversion factor for private consumption (LCU per international $) from the World Bank database http://data.worldbank.org/indicator.

[11] Note that the total vehicle stock variable may be influenced by multiple mechanisms, changes in the fuel price of alternative fuel types as well we changes in vehicle prices, limiting the ability to comment on the effect and importance of cross-price elasticities. We thank a referee for highlighting this limitation.

[12] http://data.worldbank.org/indicator/SP.POP.1564.TO.ZS and http://data.worldbank.org/indicator/SP.POP.TOTL.

[13] GDP per capita, PPP (constant 2011 international $), http://data.worldbank.org/indicator/NY.GDP.PCAP.PP.KD.

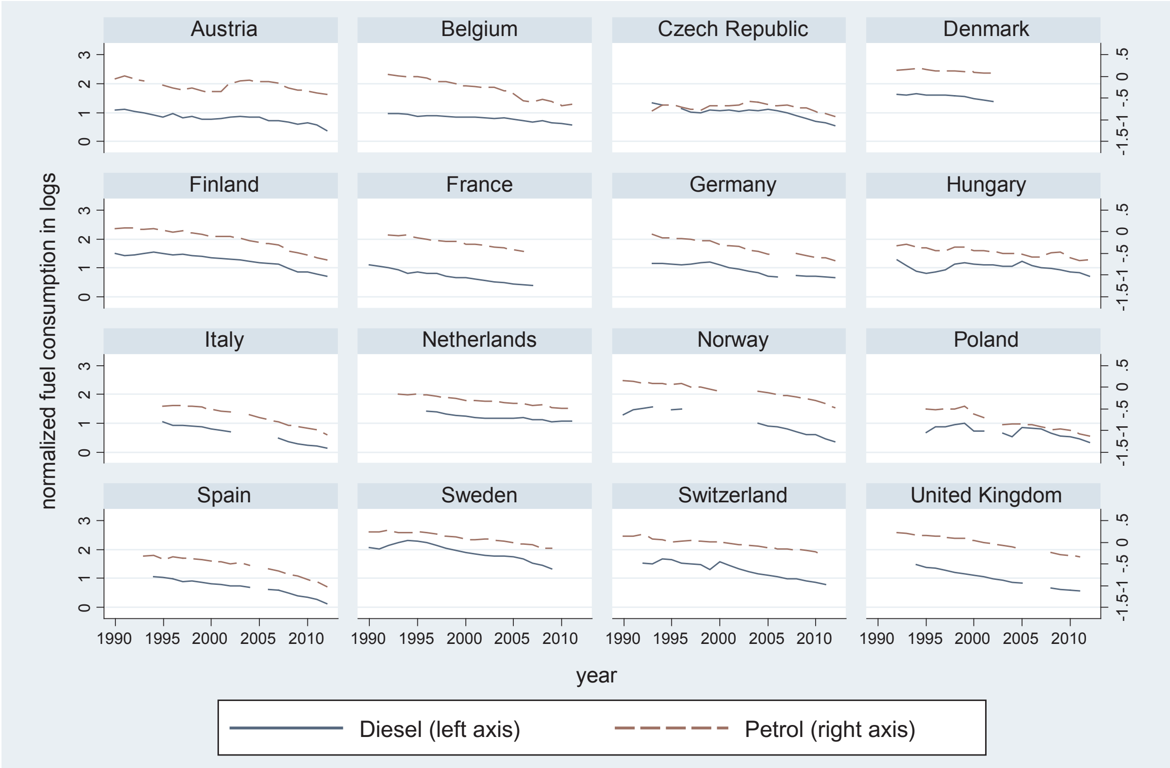

Fig. 2. Diesel and petrol consumption normalized with the respective vehicle stock. Note: Petrol consumption per petrol driven passenger car or motorcycles, diesel consumption per diesel driven passenger car or lorry.
Data source: EUROSTAT for vehicle stocks and fuel consumption data, World Bank WDI for fuel consumption data for Switzerland.

5. Elasticity estimation results

Our estimations for the GMM estimators rely on the one step procedure and forward orthogonal deviations transformation to make best use of our unbalanced panel. To limit instrument count, we restrict the lag length used for instrumentation[14] and collapse the instrument matrix (Roodman, 2009).

5.1. Price elasticity of petrol demand

Table 1 shows the results for petrol demand for the first-order Autoregressive Distributed Lag model as well as its Error Correction form comparing different dynamic estimators. The signs of the estimated effects are in line with expectations, yielding negative price elasticities, positive income elasticities and a negative “second car” effect reflected by the vehicle stock in the short run as well as in the long run (see Appendix C Table C-6 for long-run elasticity estimates for income and vehicle stock).

Let us first discuss the performance of the different estimators. Both Arellano-Bond GMM and System GMM pass the tests for autocorrelation (rejecting the null of no first-order autocorrelation, but not for second-order autocorrelation) as well as the Sargan test on instrument validity. The System GMM also passes the Difference-in-Sargan test on the validity of additional instruments. Yet, both may suffer from a large instrument count compared to the number of sample countries, though the instrument set is already restricted by limiting lag length and collapsing the instrument matrix. The coefficient of the lagged dependent variable shows that petrol consumption behavior is highly persistent, with the true persistence coefficient lying between 0.95 (OLS) and 0.82 (FE). The estimated coefficient for the Arellano-Bond estimator falls outside this range, indicating that this estimation procedure is not well suited for the given highly persistent data, as lagged first differences may provide low power for instrumentation. The System GMM estimator, benefiting from additional information included in the level equation, yields a coefficient estimate that falls inside the OLS-FE range. Interestingly, the point estimates of the other coefficients, as well as the LRM for both Arellano-Bond and System GMM, are similar to those obtained with the FE estimator, indicating that our time dimension is sufficiently large to attenuate the Nickel bias of the FE estimation.

Turning now to the fuel price elasticities and their dynamics, all estimators yield very similar estimates for the short-run as well as

[14] We selected the restriction of the lag length used for instrumentation based on test results for the Arellano-Bond test of autocorrelation, and the Sargan Test of over-identifying restrictions.

Table 1
Estimation results for petrol consumption.

	Autoregressive distributed lag model				*Error correction model*		
	OLS	Fixed Effects	Arellano- Bond GMM	System GMM	Fixed Effects	Arellano-Bond GMM	System GMM
L. consumption per vehicle	0.951***	0.820***	0.732***	0.913***	−0.180**	−0.268^{+}	−0.087
	(0.016)	(0.048)	(0.131)	(0.079)	(0.048)	(0.131)	(0.079)
petrol price	−0.277***	−0.248**	−0.239*	−0.276***			
	(0.070)	(0.079)	(0.083)	(0.059)			
L. petrol price	0.249***	0.144*	0.087	0.228**	−0.105**	−0.152*	−0.048
	(0.072)	(0.067)	(0.106)	(0.069)	(0.032)	(0.065)	(0.040)
D. petrol price					−0.248**	−0.239*	−0.276***
					(0.079)	(0.083)	(0.059)
GDP pC	0.582***	0.622***	0.695**	0.622**			
	(0.141)	(0.129)	(0.213)	(0.181)			
L. GDP pC	−0.573***	−0.455**	−0.471*	−0.594**	0.167*	0.225^{+}	0.027
	(0.139)	(0.137)	(0.172)	(0.151)	(0.064)	(0.111)	(0.045)
D. GDP pC					0.622***	0.695**	0.622**
					(0.129)	(0.213)	(0.181)
total vehicle stock	−0.974***	−1.042***	−1.051***	−1.015***			
	(0.163)	(0.140)	(0.145)	(0.134)			
L. total vehicle stock	0.940***	0.894***	0.848***	0.958***	−0.147**	−0.203^{+}	−0.057
	(0.163)	(0.146)	(0.168)	(0.125)	(0.045)	(0.098)	(0.050)
D. total vehicle stock					−1.042***	−1.051***	−1.015***
					(0.140)	(0.145)	(0.134)
Constant	0.145	−0.838		0.048	−0.810		0.094
	(0.122)	(0.503)		(0.228)	(0.489)		(0.199)
Petrol price shock dynamics							
LRM	−0.572*	−0.580*	−0.565**	−0.554*	−0.580*	−0.565**	−0.554*
period 5 effect φ_5	−0.34***	−0.46**	−0.50***	−0.38**	−0.46**	−0.50***	−0.38**
median lag length	1	1	1	1	1	1	1
# observations	270	270	254	270	270	254	270
# instruments			35	37		35	37
R-squared	0.9896	0.9695					
max IV lag			9	9		9	9
AB-test (AR1)			0.0020	0.0016		0.0020	0.0016
AB-test (AR2)			0.8470	0.8803		0.8470	0.8803
Sargan Test			0.3350	0.1781		0.3350	0.1781
Diff-in-Sargan Test				0.3800			

Notes: Robust standard errors in parentheses. All specifications include year dummies. All variables in logs. Dependent variable: petrol consumption per petrol driven passenger car or motorcycle. Total vehicle stock refers to the sum of all fuel type passenger cars and motorcycles per driver (population age 15–64). L. denotes first lags, D. denotes first differences. For Arellano-Bond and System GMM: one step estimators, Forward Orthogonal Deviations Transformation as well as collapse and small sample option applied, internal instruments restricted from t-2 to maximum lag indicated for all variables. In System GMM the standard instruments are used for the levels equation only. Arellano-Bond-Test for first and second order serial correlation in transformed errors, H_0: no serial correlation of respective order. Sargan Test on over-identifying restrictions, H_0: instruments used are not correlated with the residuals. Difference-in-Sargan Test on the validity of additional instruments in System GMM. *p*-values reported for specification tests. For the FE estimation, the R-squared refers to the within R-squared.

Significance level for parameters:

$^{+}$ $p < 0.10$.

* $p < 0.05$.

** $p < 0.01$.

*** $p < 0.001$.

long run (LRM) responsiveness of fuel consumption to price changes. The immediate effect of a one percent price increase in period t yields a reduction between 0.24% and 0.28% in the petrol consumption in the same period. However, this immediate negative effect is attenuated in the second period by a positive lagged price effect. All estimators clearly suggest that half of the total effect occurs already in period one after the shock, as indicated by the median lag length. The effect in period five ranges between −0.38 and −0.5. The Error Correction form of the model further indicates that a long-run relationship exists with an adjustment behavior back to the equilibrium (statistically significant for FE and Arellano-Bond estimator). For instance, the FE estimates imply that consumption – in response to a 1% fuel price increase – will decline in the long run by 0.58% (LRM) and, more precisely, at an adjustment rate of 18% per year (error correction rate reflected by the coefficient of the lagged consumption). Thus, consumption will decrease by 0.10% in t + 1, by 0.09% in t + 2, by 0.07% in t + 3, and so forth until consumption will have returned to the long-run state after the price shock.

Finally, it is noteworthy that previous studies estimating petrol price elasticities have relied on a restrictive form of the ADL, the Partial Adjustment Model (PAM), which restricts the lagged coefficients of the explanatory variables (i.e. $\beta_1,\gamma_1,\delta_1$ in Eq. (2)) to zero. If these imposed restrictions are invalid, all coefficient estimates of interest will be biased. Our significant lagged coefficient estimates indeed dispute such restrictions and highlight the importance of allowing for first-order dynamics, which inter alia relates to the high

Table 2
Estimation results for diesel consumption.

	Autoregressive distributed lag model				*Error correction model*		
	OLS	Fixed Effects	Arellano- Bond GMM	System GMM	Fixed Effects	Arellano-Bond GMM	System GMM
L. consumption per vehicle	0.970***	0.811***	0.977***	0.966***	−0.189**	−0.023	−0.034
	(0.013)	(0.051)	(0.094)	(0.128)	(0.051)	(0.094)	(0.128)
diesel price	−0.197	−0.169*	−0.206*	−0.195*			
	(0.143)	(0.076)	(0.088)	(0.088)			
L. diesel price	0.138	0.044	0.130	0.136	−0.124*	−0.076*	−0.059*
	(0.135)	(0.092)	(0.107)	(0.092)	(0.054)	(0.029)	(0.025)
D. diesel price					−0.169*	−0.206*	−0.195*
					(0.076)	(0.088)	(0.088)
GDP pC	0.885***	1.058***	0.799***	0.893*			
	(0.243)	(0.184)	(0.182)	(0.392)			
L. GDP pC	−0.919***	−0.921**	−0.819***	−0.926*	0.136	−0.020	−0.033
	(0.242)	(0.255)	(0.184)	(0.317)	(0.190)	(0.162)	(0.086)
D. GDP pC					1.058***	0.799***	0.893*
					(0.184)	(0.182)	(0.392)
Total vehicle stock	−1.357***	−1.294***	−1.433***	−1.356***			
	(0.255)	(0.229)	(0.290)	(0.285)			
L. total vehicle stock	1.313***	1.230***	1.420***	1.311***	−0.065	−0.013	−0.046
	(0.261)	(0.232)	(0.271)	(0.216)	(0.148)	(0.119)	(0.113)
D. total vehicle stock					−1.294***	−1.433***	−1.356***
					(0.229)	(0.290)	(0.285)
Constant	0.688*	−0.743		0.691**	-0.864		0.691**
	(0.294)	(1.194)		(0.225)	(1.239)		(0.225)
Price shock dynamics							
LRM	−1.933	−0.659	−3.251	−1.753	−0.659	−3.251	−1.753
period 5 effect φ_5	−0.45*	−0.49*	−0.55**	−0.44*	−0.49*	−0.55**	−0.44*
median lag length	20	2	27	17	2	27	17
# observations	253	253	237	253	253	237	253
R-squared	0.9799	0.9346					
# instruments			35	38		35	38
max IV lag			9	10		9	10
AB-test (AR1)			0.0125	0.0059		0.0125	0.0059
AB-test (AR2)			0.1403	0.1439		0.1403	0.1439
Sargan Test			0.2760	0.2135		0.2760	0.2135
Diff-in-Sargan Test				0.3878			

Notes: Robust standard errors in parentheses. All specifications include year dummies. All variables in logs. Dependent variable: log diesel consumption per diesel driven passenger car or lorry. Total vehicle stock refers to the sum of all fuel type passenger cars, motorcycles and lorries per driver (population age 15–64). L. denotes first lags, D. denotes first differences. For Arellano-Bond and System GMM: one step estimators, Forward Orthogonal Deviations Transformation as well as collapse and small sample option applied, internal instruments restricted from t-2 to maximum lag indicated for all variables. In System GMM the standard instruments are used for the levels equation only. Arellano-Bond-Test for first and second order serial correlation in transformed errors, H_0: no serial correlation of respective order. Sargan Test on over-identifying restrictions, H_0: instruments used are not correlated with the residuals. Difference-in-Sargan Test on the validity of additional instruments in System GMM. *p*-values reported for specification tests. For the FE estimation, the R-squared refers to the within R-squared.
Significance level for parameters:
$^{+}p < 0.10$.
* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

autocorrelation of the explanatory variables. In Appendix (Table C-2), we further show that the PAM *under*estimates the short-run and slightly *over*estimates the long-run petrol price effect compared to the ADL model. This particularly implies that the potential of fuel tax reforms in influencing short-run fuel demand has been underestimated in most prior studies relying on PAM.

5.2. Price elasticity of diesel demand

Table 2 shows the corresponding results for the diesel price elasticity. As for petrol, the coefficient of lagged diesel consumption estimated by Arellano-Bond falls outside the range defined by FE and OLS. The System GMM estimate, however, remains inside the range although it is very close to the upper bound, indicating a very high persistence. Across estimation procedures, the point estimates for contemporaneous and lagged price effects are again close to each other. The immediate effect of a one percent price increase for diesel in period t yields a reduction between 0.17% and 0.21% in the diesel consumption in the same period. The effect is again partially offset in the second period through the positive effect of the lagged price. However, the long-run price elasticity (LRM) estimate differs strongly between estimators. This finding is due to the high persistence in the lagged dependent variable, which results in very high long-run effects. For instance, the System GMM estimate amounts to −175%. The implausible long-lasting

Table 3
Comparing dynamics for petrol price elasticity estimates for ADL assuming exogenous prices with ADL accounting for endogeneity of prices.

	Exogenous price			*Price instrumented with tax*		
	Fixed Effects	Arellano-Bond GMM	System GMM	FE-IV	Arellano-Bond GMM	System GMM
Short-run	−0.248**	−0.239*	−0.276***	−0.391***	−0.252	−0.066
	(0.079)	(0.083)	(0.059)	(0.114)	(0.201)	(0.209)
Long run (LRM)	−0.580*	−0.565**	−0.554*	−0.742***	−0.572**	−0.460*
	(0.221)	(0.141)	(0.236)	(0.204)	(0.178)	(0.201)
Effect in period 5	−0.457**	−0.497***	−0.378**	−0.609***	−0.521**	−0.323
	(0.144)	(0.109)	(0.112)	(0.146)	(0.144)	(0.215)
Median lag length	1	1	1	0	1	3

Results for the short-run and long-run price elasticity for petrol, based on the Autoregressive Distributed Lag Model with first-order dynamic assuming exogenous prices (Table 1) and instrumenting price endogeneity by petrol excise taxes (Table C-3 in the Appendix). Petrol excise tax used as external instrument for the endogenous contemporaneous price variable. Robust standard errors in parentheses.
Significance levels:
$^{+}p < 0.10$.
* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

adjustment processes implied by the large estimated median lag lengths further reveal that both GMM estimators suffer from weak internal instruments. The range between estimators, however, narrows down considerably to between –0.44 and –0.55 for the effect in period five.

For diesel, the Error Correction term, as expected, is also negative, indicating an adjustment process back to the long-run relation. However, it is only statistically significant for FE and it is very close to zero for Arellano-Bond and System GMM due to the high persistence. While the estimated effects for the vehicle stock are in line with expectation, only the FE estimator yields the expected positive long-run income effect (see Table C-6 in the Appendix for LRM estimates of income and vehicle stock). The counterintuitive results for the income elasticity in combination with implausibly high long-run price elasticities, indicate that there might be deeper methodological issues when estimating diesel demand. We will address these in the next section.

5.3. *Accounting for fuel price endogeneity*

To address concerns that the assumption of exogenous fuel prices might be violated due to feedback effects triggered by demand peaks, in Tables 3 and 4 we contrast our previously obtained price elasticity estimates with estimates that instrument contemporaneous fuel prices with excise tax rates to account for the potential endogeneity (see also Appendix Tables C-3 and C-4). The first stage regression results for the FE-IV as well as the Stock-Yogo test suggest that for both fuels the excise tax rates are not weak instruments (see Appendix Table C-5).

For petrol consumption (Table 3), the short-run and long-run price elasticity, as well as the 5-year effect, are higher in absolute value based on FE-IV estimation. While for Arellano-Bond, the results differ only slightly, the System GMM estimates are lower if endogeneity is accounted for. For both GMM estimates, the short-run elasticity turns insignificant as the estimation accounting for

Table 4
Comparing dynamics for diesel price elasticity estimates for ADL assuming exogenous prices, with ADL accounting for endogeneity of prices.

	Exogenous price			*Price instrumented with tax*		
	Fixed Effects	Arellano-Bond GMM	System GMM	FE-IV	Arellano-Bond GMM	System GMM
Short-run	−0.169*	−0.206*	−0.195*	−0.654**	−0.616***	−0.720**
	(0.076)	(0.088)	(0.088)	(0.234)	(0.138)	(0.220)
Long-run (LRM)	−0.659	−3.251	−1.753	−1.131*	−1.290	−1.037
	(0.403)	(12.944)	(6.236)	(0.457)	(0.924)	(1.059)
Effect in period 5	−0.487*	−0.546**	−0.439*	−0.945**	−0.967*	−0.855*
	(0.221)	(0.185)	(0.197)	(0.296)	(0.372)	(0.397)
Median lag length	2	27	17	0	1	0

Results for the short-run and long-run price elasticity for diesel, based on the Autoregressive distributed Lag Model with first order dynamic assuming exogenous prices (Table 2) and instrumenting price endogeneity by diesel excise taxes (Table C-4 in the Appendix). Diesel excise tax used as external instrument for the endogenous contemporaneous price variable. Robust standard errors in parentheses.
Significance levels:
$^{+}p < 0.10$.
* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

price endogeneity is less efficient. Overall, the results with and without instrumentation of fuel prices do not seem to show consistent indications that petrol price endogeneity is indeed an issue for our data. This is probably due to the fact that we use yearly data. Davis and Kilian (2011) indeed use monthly petrol consumption data for U.S. states, which is more likely to reflect short-run seasonal price hikes mainly caused by public holidays. In annual data the feedback effect of such recurring holiday price hikes are mitigated through aggregation over the year.

For diesel consumption (Table 4), the price elasticity estimates, with and without diesel tax instrumentation, differ more strongly than those for petrol. The short-run elasticity estimates are much higher in absolute terms for all estimators accounting for endogeneity. The estimates for the long-run multiplier, which exhibit a wide spread without instrumentation, lie in a more plausible and closer range when controlling for endogeneity. This can be explained by the lower point estimates for the lagged dependent variable with instrumentation (see Table C-4 in the Appendix), which is in contrast to the very high persistence implied by the exogenous models. Finally, the 5-year effect almost doubles in magnitude if endogeneity is accounted for, indicating that elasticity is likely to be biased towards zero in estimations that assume exogenous diesel prices. While the FE-IV LRM is significant, the GMM estimate for the LRM remains insignificant. However, the 5-year effect is significant for all models.

While the different point estimates for the diesel and petrol price elasticity differ, the confidence intervals often overlap. Therefore, we use a simple z-test (that abstracts from the between-model covariance of parameter estimates and should be interpreted in the light of this limitation) in order to test for parameter equality. The test indicates that the short-run and 5-year diesel price elasticity is statistically greater than the respective petrol price elasticity, at least at the 10% significance level; the long-run elasticities of petrol and diesel are statistically not different.

To summarize, our findings provide evidence that endogeneity concerns might be more relevant for diesel than for petrol demand. While petrol consumption primarily reflects the behavior of private passenger car users,[15] the share of lorries in the diesel vehicle fleet is much more substantial, for example with temporarily over 65% in Denmark (see Appendix Table A-2), and it seems fair to argue that lorries are mostly used by businesses. Moreover, many companies prefer diesel passenger cars due to their favorable fuel efficiency over long distances. The diesel demand might therefore be affected by business specific factors that cause feedback effects on the diesel price. An explanation for diesel demand being more price elastic, apart from the endogeneity bias, is that instrumenting with diesel excise taxes yields elasticity estimates that reflect the demand response to a tax increase as opposed to general price fluctuations. Recall that the consumer reaction to tax increases is likely stronger as tax changes are often (i) accompanied by high media coverage raising awareness and (ii) perceived to be of higher persistence (Scott, 2012). Owners of commercial diesel-driven vehicles probably account for fuel tax increases in their cost calculations and may consider changing to other modes of transport. Private households with petrol cars may, in contrast, be more bound by habit persistence in their price response.

6. Emission impacts of fuel tax reform scenarios

Two recent events – the Paris Agreement on Climate Change and the diesel emission scandal – motivate us to exploit the obtained information on fuel price elasticities in order to evaluate the effect of two hypothetical fuel pricing policy scenarios on emissions of fine particulate matter ($PM_{2.5}$), nitrogen oxides (NO_x) and carbon dioxide (CO_2). This study does not intend to project the air pollution levels for 2020, instead we assess the policy reform induced changes in emissions based on a ceteris paribus assumption. We also estimate the corresponding tax revenues of the policies.

First, at the climate negotiations in Paris in December 2015, the EU and Norway[16] submitted Intended Nationally Determined Contributions (INDCs) committing to an economy wide reduction in total domestic GHG emissions of at least 40% by 2030 compared to 1990 (European Union, 2015; Norway, 2015). Although the sectoral distribution of mitigation efforts, as well as the effort sharing between countries, remain to be discussed, it is clear that the transport sector will need to make a major contribution given its large share in total emissions. The EEA TERM report concludes that decarbonizing the transport sector will require complementary pricing policies stimulating behavioral changes (EEA, 2015, p.59).

Second, the fraud scandal in diesel car test cycles, followed by the discovery that the majority of diesel vehicles on the road fail to meet air pollution emission standards, has relaunched a debate about environmental and health concerns with respect to diesel (New York Times, 2016; Reuters, n.d.; EEA, 2015). In the light of a higher fuel efficiency of diesel cars, many countries in Europe have supported the dieselization process by granting favorable tax treatments to diesel in recent decades. Yet, in fact, the carbon content of one liter of diesel is higher than that of petrol, rendering tax breaks *per liter* diesel highly questionable from a climate perspective (Harding, 2014).[17] Moreover, despite improvements in technology and catalytic converters, diesel cars emit more NO_x and $PM_{2.5}$ per liter than petrol vehicles (see Table D-2 in the Appendix). The EU's emissions standards for air pollution from road transport have shown limited success in meeting concentration limits in many cities, and discrepancies between real driving conditions and approval tests have even increased (ICCT, 2014, 2015b; Carslaw et al., 2011).

[15] Note, however, that our data does not allow the fuel consumption of passenger cars to be distinguished from consumption by commercial vehicles.

[16] Norway states that it will achieve its INDC either jointly with the EU or separately.

[17] Table D-1 (Appendix) shows that the CO_2 content per liter of fuel is actually higher for diesel compared to petrol. Yet, due to their higher fuel efficiency, diesel vehicles tend to emit less CO_2 *per kilometer* driven compared to a petrol vehicle of similar size and weight. However, diesel vehicles tend to be bigger, heavier and driven longer distances, which almost outweighs efficiency advantages per kilometer (Schipper and Fulton, 2013).

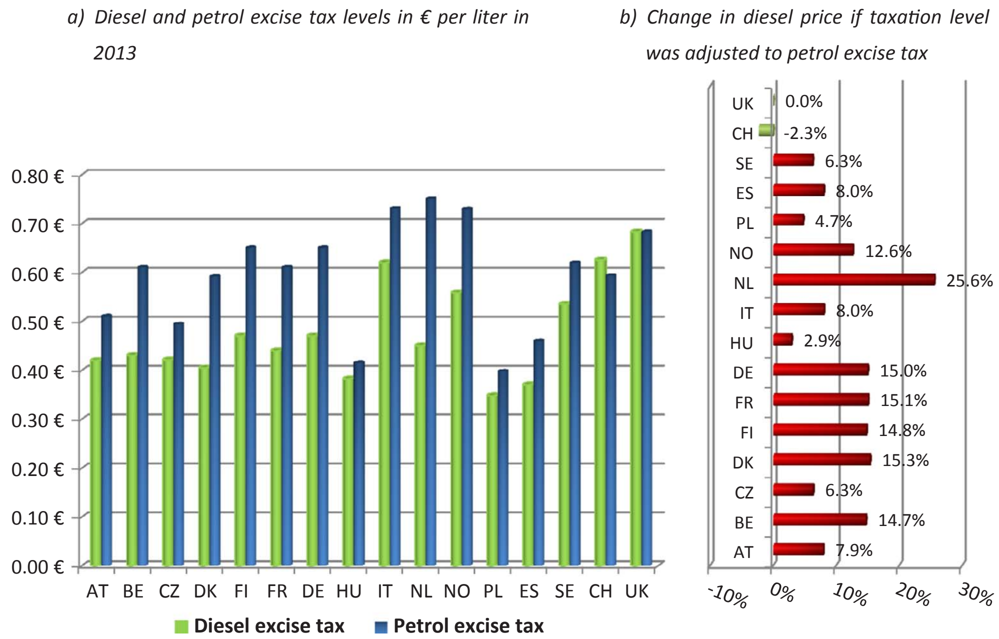

Fig. 3. Tax advantages for diesel. Current excise tax levels on diesel and petrol (2013) and resulting price change if excise taxes for diesel were adjusted to petrol taxation levels. Note: Price changes include the increase in the absolute Value Added Tax (VAT) due to the increase in the excise tax level accounting for country-specific VAT tax rates.
Data Source: (IEA 2014).

6.1. The policy scenarios

This section presents two policy scenarios of two distinct hypothetical fuel tax reforms in more detail, with scenario A focusing on diesel taxation and scenario B focusing on the carbon content of the fuels.

6.1.1. Policy scenario A: Abandoning tax advantages for diesel

In reaction to the diesel scandal, several authorities have called to abandon the favorable tax treatment of diesel. For instance, the French government has recently announced plans to phase out diesel tax breaks within the next 5 years (Reuters, 2015). Similarly, the German Umweltbundesamt (UBA) has proposed an adjustment of the diesel excise tax level to that for petrol (Umweltbundesamt, 2015). Inspired by such proposals, we assess a tax reform scenario of abandoning diesel tax breaks in 2015.

Fig. 3a) shows that in most sample countries excise tax levels are lower for diesel than for petrol (UK and Switzerland are the exception). Fig. 3b) depicts the diesel price increases required to adjust the excise tax level for diesel to that of petrol, accounting for national value added taxes (VAT). Due to its high tax differential, the highest diesel price increase would take place in the Netherlands, amounting to over 25% of the 2013 diesel price while most East European countries exhibit much lower tax differentials. Diesel taxes for Switzerland and the UK remain unchanged in this scenario.

6.1.2. Policy scenario B: Introducing a CO_2 –content based tax

In our second policy scenario, we assume that each sample country introduces a carbon content based tax per liter of diesel and petrol of 50€/tCO_2 in addition to the pre-existing tax level.[18] Given the different carbon content of both fuels this would correspond to a CO_2 tax of 0.12€/liter for petrol and 0.13€/liter for diesel. While the appropriate magnitude of such corrective CO_2 taxes remains disputed, our assumed CO_2 tax lies well within the range of estimates on the Social Costs of Carbon (SCC), i.e. the welfare loss associated with an additional ton of CO_2 emitted (Pearce, 2003; Anthoff and Tol, 2013; Tol, 2011, 2008). The Fifth Assessment Report (AR5) of the IPCC documents average SCC estimates of around 241 USD per ton of carbon for studies published after 2007 (post-AR4) (Arent et al., 2014; IPCC, 2014). This corresponds to around 65 USD/tCO_2 or 50€/tCO_2 (2013). The resulting price changes for each country are shown in the Table D-5 (Appendix).

6.2. Assessment approach

To calculate the effect of the two policy reforms on emissions of $PM_{2.5}$, NO_x and CO_2, we proceed in two steps that are subsequently explained.

[18] For the analysis, we assume that pre-existing excise taxes are prompted by reasons other than climate change considerations. However, some countries may already partly capture the climate externality in their tax rates.

6.2.1. Step 1: Fuel tax-induced price changes and associated demand responses

First, we exploit our estimated petrol and diesel price elasticities from Section 5 to project the relative change in diesel and petrol demand in response to the hypothetical price changes derived from our two policy scenarios. The short-run effect reflects the immediate policy response. We use the cumulative five-year effect (φ_R) to anticipate the demand response for the year 2020, assuming that the policies are introduced in 2015. To reduce complexity, the demand response is presented only on the basis of the Fixed Effects estimator mainly because it provides a moderate elasticity estimate (between Arellano-Bond GMM and System GMM).[19] Given the revealed endogeneity concerns for diesel, we use the FE-IV estimates for diesel but standard FE estimates for petrol. Generally, the projections should not be seen as an exact prediction but rather as an indication of the expected effect compared to the status quo.[20] Fig. 4 illustrates the cumulative fuel demand response over time for a 1% increase in the respective fuel price.

In addition, we have data for the total diesel and petrol consumption up to the year 2013. Combined with the price-induced relative consumption changes in the short-run and 2020, we can calculate the corresponding absolute reduction in consumption of diesel and petrol in each sample country. Note that the simulation assumes that income, as well as vehicle stocks, remain unchanged (at their country-specific level in 2013). This choice is motivated by the fact that (i) forecasting future changes in GDP and vehicle stocks is very challenging and (ii) GDP and vehicle stock projections would no longer allow differentiating the price effect from the GDP and stock effects. The results should, thus, be interpreted as changes compared to a business-as-usual scenario, i.e. without tax reform. Moreover, we assume that fuel substitution effects are negligible for the time scale under consideration.[21]

6.2.2. Step 2: Impact on carbon emissions and air pollution exhaust

Second, using the projected absolute fuel consumption reduction, we calculate the expected impact of the fuel tax reform scenarios on carbon emissions and air pollution.

For CO_2 emissions, we apply constant emission factors shown in Table D-1 in the Appendix. The expected change in CO_2 emissions is compared to the emission level resulting from the reported fuel consumption for 2013 (‘status quo’). Moreover, we assess how the policy scenario would contribute to achieving the EU’s 2020 climate policy targets.

For NO_x and $PM_{2.5}$, the calculation of expected emission changes is less straight forward, as emission factors depend on various factors such as combustion technology, motor temperature, driving behavior and catalytic converters. However, using data-based model estimates, the EEA-EMEP provides average vehicle type emission factors based on the country-specific vehicle fleet composition for each European country (Ntziachristos and Samaras, 2014). Exploiting our data of the vehicle stock composition from EUROSTAT,[22] we can use these vehicle type emission factors. Emissions factors per kg of fuel are presented in Table D-2 (Appendix).

6.3. Implications for CO_2 emissions and EU climate policy targets

6.3.1. Changes compared to status quo (2013) CO_2 emission levels from road transportation

The first column of Fig. 5 shows the expected reductions in CO_2 emissions for Scenario A (diesel excise tax adjustment) and B (50€/tCO_2 carbon tax) relative to the CO_2 emission levels in 2013 from diesel and petrol use. In Scenario A, countries with the highest price differential between diesel and petrol excise taxation (most notably, the Netherlands) would experience the highest reduction in carbon emissions, of up to −14.7%, in 2020. Belgium and France could also reduce CO_2 emissions considerably due to their large share of diesel consumption in total fuel consumption[23]. As diesel tax breaks are much less pronounced in the Eastern-European sample countries, emissions reduction would remain limited in these countries. In contrast, in Scenario B, the expected CO_2 emissions reductions would be distributed more evenly, ranging between −7.2% in Sweden and around −10% in France, Spain and Poland. In this policy scenario the Eastern-European countries would also face significant CO_2 reductions. The latter finding highlights that a diesel tax reform (Scenario A) would shift the burden away from these economically weaker countries. Another interesting finding from the comparison of Scenarios A and B is that in many countries the phase out of diesel tax breaks can have as strong an effect on CO_2 as the 50€/tCO_2 carbon tax.

Note that similar findings emerge if we compare the impacts on CO_2 emissions in absolute terms – as reductions in tCO_2 per capita (see Fig. D-1 and Table D-6, Appendix). A notable difference is, however, that the highest absolute emissions reduction for Scenario B would stem from Austria (−0.25tCO_2/capita in 2020); this is mainly due to the country’s relatively high per capita fuel consumption. In Scenario A, the Netherlands would still exhibit the highest absolute reductions with −0.27tCO_2/capita due to its large price change for diesel. Belgium and France would also exhibit relatively high reductions in their absolute CO_2 emissions per capita,

[19] Moreover, the range of results indicates that the Nickel bias in the Fixed Effects estimator is not severe due to the relatively large time dimension.

[20] Note that the strong price adjustments to level some of the large diesel-petrol tax differential may interfere with the applicability of elasticity estimates, which reflect the response for *marginal* changes in prices.

[21] The demand changes are presented in the Appendix. Table D-4 shows the relative and absolute changes in diesel consumption for scenario A. Table D-5 shows the CO_2 tax induced fuel price changes (accounting for VAT adjustments) and the expected impact on fuel consumption for Scenario B.

[22] We assume that shares of vehicle types (passenger cars, motorcycles, lorries, buses and heavy duty vehicles) reflect fuel consumption shares. This assumption is a necessary simplification which may underestimate the true emission factors, as larger (mostly commercial) vehicles are likely to be covering more kilometers and consuming more fuel per kilometer; but at the same time they exhibit higher emission factors per kg of fuel. Moreover, note that the EMEP-EEA emission factors are based on 2005 vehicle fleet composition (Ntziachristos and Samaras, 2014) while we apply most recent available data (mostly 2011) for vehicle shares.

[23] See Table D-3 on shares of diesel and petrol use in aggregated fuel consumption.

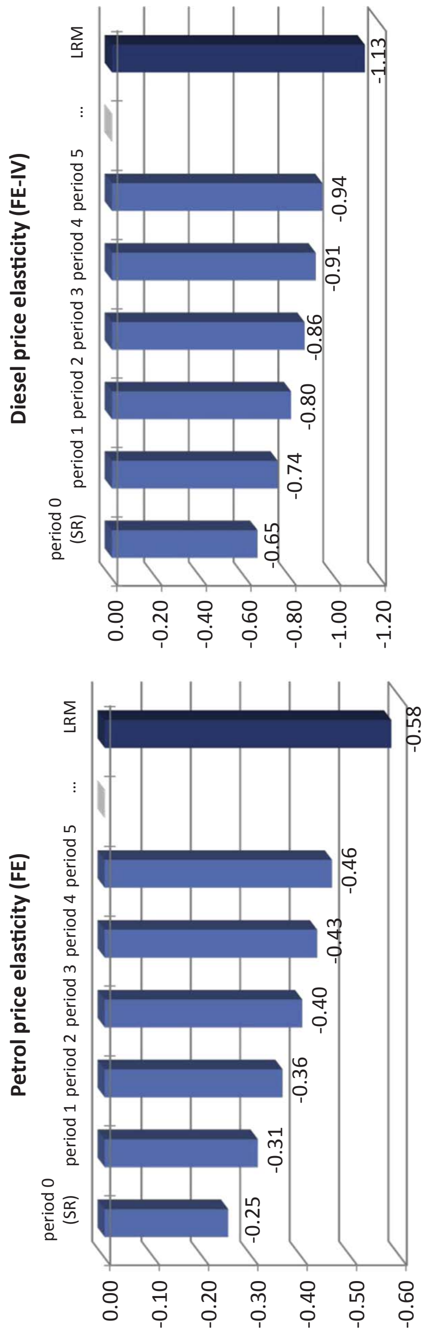

Fig. 4. Petrol and diesel price elasticity dynamics for different periods after the price change (based on FE results for petrol and FE-IV for diesel).

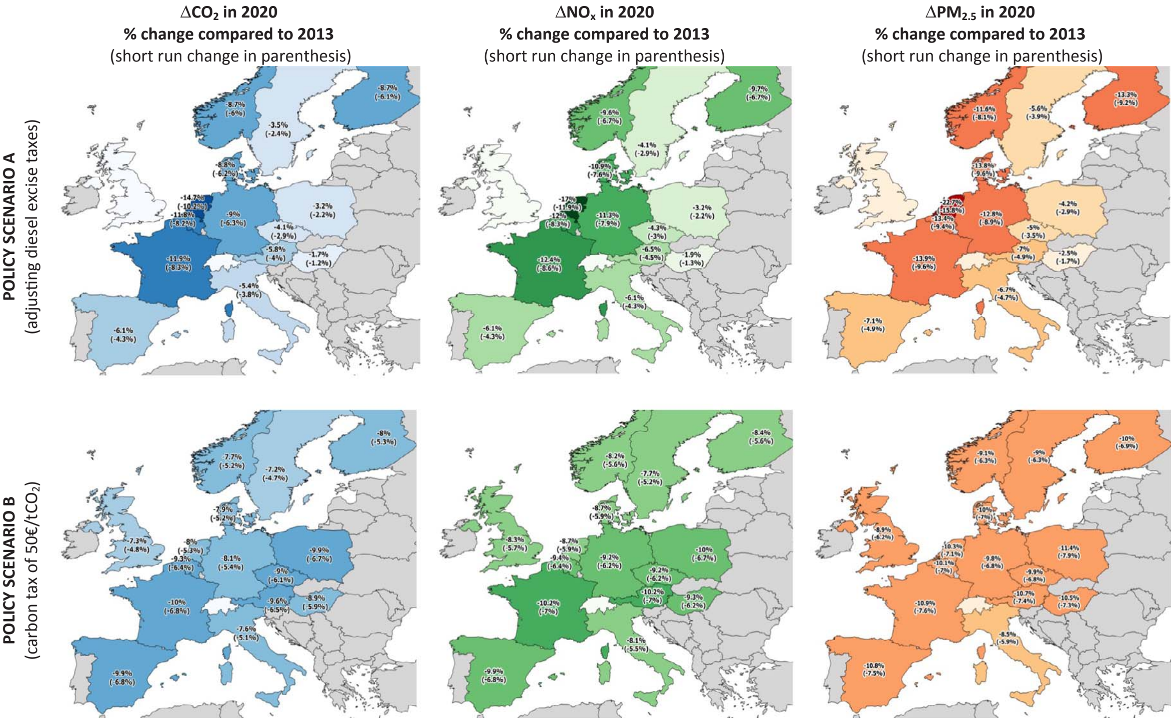

Fig. 5. Relative emission level changes in 2020 compared to status quo (2013) for CO_2, NO_x and $PM_{2.5}$ for each policy scenario, respectively. Note: Results refer to calculated emissions from diesel and petrol consumption for road transport based on EUROSTAT fuel consumption data for 2013, own elasticity estimates and emission factors per liter (see the Appendix D). Reported changes assume that GDP per capita and vehicle stocks per driver remain unchanged. Changes in emissions refer to annual emissions, i.e. in 2020 and not to accumulated emission reductions up to 2020.

amounting to $-0.25tCO_2$ (BE) and $-0.21tCO_2$ (FR), which can mainly be attributed to their large share of diesel use (see Table D-3 in the Appendix).

6.3.2. Contribution of fuel tax reforms to EU climate policy targets

How do the policy scenarios perform with respect to the EU's climate change mitigation targets for the year 2020? Answering this question is complicated by the fact that there are two different EU reduction targets with relevance to the transport sector.

First, the 2020 EU climate and energy package defines GHG emission reduction targets for the year 2020 compared to 2005 emissions, defining a specific target for sectors not covered by the EU ETS which is relevant for road transport. In its Effort Sharing Decision (ESD) the EU member states have agreed on country specific emission targets varying between -20% and $+20\%$ based, inter alia, on relative GDP per capita; the EU-28 wide target is $ESD_{2005}^{2020} = -10\%$ (EU Parliament and EU Council, 2009).

Second, in its 2011 White Paper (WP) for the Transport Sector (European Commission, 2011b) the European Commission states that, in order to achieve the EU's 2 °C long-term target (European Commission, 2011a), the transport sector must reduce GHG emissions by at least 60% by 2050 compared to 1990 ($WP_{1990}^{2050} = -60\%$); country-specific reduction targets are not specified. Assuming equal absolute emission reductions per year (from 2015 onwards) until 2050, the corresponding targets for 2020 for different baselines would be $WP_{2013}^{2020} = -9.3\%$, $WP_{2005}^{2020} = -17.8\%$ and $WP_{1990}^{2020} = +3.7\%$. Comparing $WP_{2005}^{2020} = -17.8\%$ to $ESD_{2005}^{2020} = -10\%$, it is obvious that the ESD targets for 2020 are not sufficient in order to limit temperature increase to well below 2 °C as agreed in the Paris Accord.

A comparison of 2013 emissions and ESD_{2005}^{2020} targets in Table 5 shows that the majority of EU countries in the sample would currently not fulfill their targets. Only the Czech Republic, Hungary, Italy and Spain can already over-fulfill their targets; these countries have been strongly affected by the recent economic crisis and have not yet fully recovered. Adjusting diesel excise tax levels to petrol taxation (PS A) would bring most countries that are currently falling short of ESD goals much closer to their targets. The Netherlands, France, Denmark and Belgium could then over-fulfill their targets and only Poland would still significantly miss its emission goal. In contrast, introducing a CO_2 tax of 50€/tCO_2 (PS B) would help to bring Poland much closer to fulfilling its ESD_{2005}^{2020} target. The UK and Sweden would also meet their ESD_{2005}^{2020} targets in Scenario B. Interestingly, the 50€/tCO_2 tax would not be sufficient in Finland, Germany and the Netherlands to enable them to meet their targets even in the absence of economic growth and vehicle stock effects. Assuming that most countries in the sample will exhibit GDP growth in the years to 2020, and experience rising vehicle stocks, meeting the ESD_{2005}^{2020} targets will likely require stronger policies for most countries.

While the ESD_{2005}^{2020} targets are measured against a 2005 baseline – i.e. a period before the economic crisis with GHG emissions at high levels – the White Paper (as well as the EU's INDC) refers to 1990 as baseline. The last three columns of Table 5 illustrate the development of emissions with respect to this baseline. While Germany seems to underperform compared to the 2005 baseline, it is one of the few countries in our sample, together with the UK, that exhibits an actual decrease in emissions in 2013 compared to 1990

Table 5
Change in CO_2 emissions from petrol and diesel combustion compared to the respective baseline.

	Baseline 2005 CO_2 emissions				Baseline 1990 CO_2 emissions		
	in 2013	in 2020			in 2013	in 2020	
	Status Quo	*ESD targets*	PS A equal diesel tax	PS B CO_2 tax of 50€/tCO2	Status Quo	PS A equal diesel tax	PS B CO_2 tax of 50€/tCO2
Austria	−8.21%	*−16%*	−13.52%	−17.04%	64.75%	55.22%	48.91%
Belgium	−5.66%	*−15%*	−16.77%	−14.44%	20.51%	6.31%	9.29%
Czech Republic	−7.36%	*9%*	−11.20%	−15.71%	118.49%	109.43%	98.78%
Denmark	−15.55%	*−20%*	−23.02%	−22.20%	11.81%	1.92%	3.01%
Finland	−4.48%	*−16%*	−12.82%	−12.12%	3.11%	−5.90%	−5.14%
France	−7.84%	*−14%*	−18.77%	−17.03%	5.49%	−7.02%	−5.03%
Germany	−2.20%	*−14%*	−10.99%	−10.14%	−3.80%	−12.46%	−11.61%
Hungary	−16.55%	*10%*	−18.01%	−23.95%	24.08%	21.92%	13.08%
Italy	−21.30%	*−13%*	−25.57%	−27.30%	0.12%	−5.32%	−7.52%
Netherlands	−7.03%	*−16%*	−20.65%	−14.45%	34.28%	14.61%	23.56%
Poland	28.41%	*14%*	24.33%	15.68%	106.71%	100.15%	86.22%
Spain	−22.60%	*−10%*	−27.36%	−30.29%	37.72%	29.26%	24.04%
Sweden	−10.94%	*−17%*	−14.06%	−17.35%	4.72%	1.05%	−2.81%
United Kingdom	−9.83%	*−16%*	−9.83%	−16.41%	−1.56%	−1.56%	−8.74%
All EU countries in sample	−9.63%	*−10%**	−15.89%	−17.40%	11.08%	3.39%	1.53%

* ESD target for EU-28. Effort Sharing Decision (EU Parliament and EU Council, 2009).

levels. For the Czech Republic and Poland, CO_2 emission levels have more than doubled since 1990, although from a comparably low level. Adjusting diesel excise taxes (PS A) would help Finland, France, and Italy to reduce emissions relative to 1990 levels. The tax of 50€/tCO_2 (PS B) would additionally push Sweden below its 1990 levels.

6.4. *Implications for air pollution*

The second and third column of Fig. 5 illustrate the expected impacts of both fuel tax reform scenarios on exhaust emissions of NO_x and fine particulate matter, relative to the status quo.[24] By ending diesel tax breaks (scenario A), the Netherlands could benefit from 17% lower NO_x and over 22% lower $PM_{2.5}$ exhaust emissions in 2020. France, Germany, Belgium, Finland, Norway and Denmark could also achieve considerable emission reductions for both air pollutants of around −10% in 2020. For Finland this is mainly driven by comparably high emission factors for both NO_x and $PM_{2.5}$. In Belgium and France, the high share of diesel in fuel use substantially contributes to the considerable reductions of −12% in NO_x and over −13% for $PM_{2.5}$. Again countries with low diesel tax breaks would benefit least in terms of reduced air pollution, despite relatively high emission factors in Eastern-European countries. In contrast, with the introduction of a carbon tax (Scenario B) all countries would benefit more evenly from considerable exhaust reductions ranging from −7.7% for NO_x in Sweden up to −11.4% for $PM_{2.5}$ in Poland in 2020. Finally, it is noteworthy that both tax reforms could considerably reduce air pollution exhaust already in the short term.

When comparing changes in air pollutant emissions in *absolute* terms per capita (see Fig. D-1 Appendix), differences in country characteristics become more visible. Most notably, in Scenario A, despite lower diesel tax breaks, Finland joins the Netherlands in benefiting from very high absolute reductions as Finland exhibits very high emission factors especially for $PM_{2.5}$. When introducing a carbon tax (Scenario B), Austria stands out regarding the highest NO_x reductions, while the Czech Republic would exhibit the highest absolute reduction in $PM_{2.5}$.

Note that tax-induced behavioral changes may additionally lead to a reduction in distances driven, thereby also reducing the non-exhaust emissions of PM stemming from, for example, dust swirl, road abrasion and wear of brakes and tires. Moreover, the formation of secondary PM is impacted by the concentration of precursor gases like NO_2, which is part of the family of Nitrogen Oxides (NO_x).

6.5. *Implications for tax revenues*

Implementing fuel tax reforms would also have an impact on tax revenues. Table 6 shows estimates of additional tax revenues in excise taxes in the short term. We estimate that by ending diesel tax breaks, Germany and France could gain as much as €4 billion in the year of the tax reform. Italy, Spain and the Netherlands could raise their budgets by more than €1 billion. The introduction of a carbon tax of 50€/tCO_2 would yield more than €5 billion for Germany, €4 billion for France and €3.8 billion for the UK. In the carbon tax case, Poland could also earn €1.4 billion in tax revenues. These additional tax revenues, especially in the short term, could contribute substantially to financing public transport or clean infrastructure. Likewise revenues could be invested in research and development or the health system.

[24] Tables D-7 and D-8 in the appendix compile all numbers on absolute and relative changes for NOx and $PM_{2.5}$.

Table 6
Additional excise tax revenues for tax reform scenarios (short run effect).

	PS A: adjusting diesel taxes	PS B: carbon tax of 50€/tCO_2
	in Mio €	in Mio €
Austria	409	799
Belgium	918	857
Czech Republic	212	573
Denmark	305	403
Finland	314	421
France	4046	4089
Germany	4131	5470
Hungary	58	373
Italy	1735	3143
Netherlands	1218	1133
Norway	312	371
Poland	383	1424
Spain	1510	2760
Sweden	255	727
United Kingdom	0	3800

Note: Estimates refer to excise tax revenues only, additional revenues due to value added taxation (VAT) are not included here.

7. Concluding remarks and policy implications

Given the multiple negative externalities caused by road transportation, it is in the public interest to address fuel consumption behavior by setting corrective economic incentives. In this paper, we provide tangible evidence on the demand response of petrol and diesel consumption to pricing policies. A flexible dynamic specification of fuel demand allows us to scrutinize the consumption response to price changes over time. We find that ignoring endogeneity may mask diesel elasticity estimates, while petrol estimates by and large remain unchanged if we instrument prices by excise taxes. Our results indicate that diesel and petrol demand – when first-order dynamics, potential endogeneity and dieselization are accounted for – are more price elastic in the short run than previous estimates for Europe imply. We provide first evidence that the diesel demand in Europe tends to be more price elastic than petrol demand, especially in the short run.

So far, emission and efficiency standards introduced in Europe have shown only limited success in reducing air pollution and CO_2, due to slow turn-over rates of vehicle fleets (Kageson, 2005), limited compliance under real-driving conditions, a lack of incentives to reduce distances driven and potential rebound effects. Introducing complementary fuel tax reforms would in contrast already yield significant effects in the short run. Findings from Bonilla (2009) for the UK confirm such advantages of taxes over standards.

Our evaluation of the impacts of fuel pricing policies on CO_2, $PM_{2.5}$ and NO_x emissions from road transport further documents that complementary fuel taxes could make a significant contribution to reducing exhaust emissions of health damaging air pollutants while at the same time contributing substantially to achieving climate change mitigation goals. Both (i) a removal of the preferential tax treatment for diesel or (ii) an introduction of a carbon content based tax of 50€/tCO_2 per liter would allow achieving the EU climate policy goals for 2020 for the current level of income and vehicle stock. However, the estimated positive income elasticity as well as observed trends of steeply increasing vehicle stocks in some countries suggest that fuel taxation policies would probably need to be more ambitious to outweigh future GDP growth and car purchases if climate targets are to be met. Yet, both scenarios may induce faster switching towards cleaner technologies which could render the future vehicle stock less emission intensive.

Given pre-existing fuel taxes in all sample countries, which at least partially aim to internalize negative externalities, national governments will have to decide on how to restructure fuel taxation based on more research on country-specific circumstances. In contrast with standards, the revenues raised through taxation can be earmarked for reinvestment into public transport, clean transport infrastructure (e.g. bike lanes, e-mobility), the health system, research and development for clean technologies or to mitigate potential regressive effects of fuel taxation. Though taxation is finally decided by national governments, to avoid competitive disadvantages and "leakage" of fuel purchase to neighboring countries, the coordination of fuel pricing policies within Europe seems to be the preferable option (Frondel et al., 2011). The EU could build on its European Energy Tax Directive (Energy Tax Directive 2003/96/EC) to adjust minimum taxation requirements for fuel, especially for diesel. As taxation is imposed *per liter*, the fuel efficiency advantage of diesel cars per km is fully appropriated by the vehicle user, rendering additional tax advantages for diesel unjustified both from an air pollution as well as a climate perspective (Harding, 2014). The withdrawal of the European Commission's proposal to reform the 2003 European Energy Tax Directive with a carbon and energy content based fuel taxation, however, indicates considerable political barriers in achieving an agreement between EU member states. Nonetheless, new negotiations on such reform proposals seem to be necessary in view of the recent Paris Agreement and the diesel emissions scandal.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Appendix A. Data

We compiled data on passenger cars, motorcycles, lorries, busses and motor coaches as well as road tractors differentiated by motor energy type based on the information in EUROSTAT (road_eqs). Data on special purpose vehicles is only available from 2008 onwards and is therefore not included. For motorcycles, no information is available on motor energy type. As petrol is the dominant fuel for motorcycles, we assume that all motorcycles are petrol driven. For road tractors, busses and motor coaches the amount of missing values is considerable. As the share of road tractors and busses/motor coaches in total stocks is very low and mostly develops in parallel to other stocks, we decided to exclude these data in order to minimize the amount of data loss due to missing values. Our estimation results are consequently based on the stock of petrol passenger cars plus motorcycles for petrol and on the stock of passenger cars and lorries for diesel.

Missing values in the vehicle stock data have been filled only if other available information allowed a reasonable assumption. For example, if the total stock and the number of diesel passenger cars was available, however, the stock of petrol passenger cars exhibited a missing, this has been filled by calculating the difference in total and diesel stock. Moreover, obvious data errors such as decimal point faults have been corrected.

A few data points constituting extreme outliers have been set to missing values to not distort overall estimation results by potential errors in the data. This affects the diesel consumption of the Czech Republic for the year 1995, the motorcycle stock in Austria in 1994, and the stock of lorries in the Netherlands for the years 1993, 1994 and 1995.

Table A-1
Descriptive statistics for the variables.

Variable	Unit of measurement		Mean	Std. Dev	Min	Max	Observations
Diesel consumption per diesel driven passenger car or lorry	Tons of oil equivalent per diesel driven passenger car or lorry	Overall	3.08	1.50	1.13	10.19	N = 293
		Between		1.26	1.94	6.85	n = 16
		Within		0.83	−0.73	6.83	T-bar = 18.3125
Petrol consumption per petrol driven passenger car or motorcycle	Tons of oil equivalent per petrol driven passenger car or motorcycle	Overall	0.78	0.23	0.32	1.32	N = 306
		Between		0.21	0.47	1.14	n = 16
		Within		0.13	0.44	1.22	T-bar = 19.125
Total petrol price (RON95)	International $ PPP (LCU)	Overall	1.25	0.47	0.47	2.97	N = 367
		Between		0.33	0.75	1.98	n = 16
		Within		0.35	0.42	2.48	T-bar = 22.9375
Total diesel price	International $ PPP (LCU)	Overall	1.10	0.48	0.44	3.02	N = 369
		Between		0.30	0.80	1.78	n = 16
		Within		0.38	0.33	2.51	T-bar = 23.0625
GDP per capita	Constant 2011 international $	Overall	35082.24	10914.39	9395.13	65780.91	N = 383
		Between		10338.49	15583.95	57417.76	n = 16
		Within		4366.12	20960.42	43445.39	T-bar = 23.9375
Total stock of passenger cars and motorcycles (all fuel types) per driver	Number per 1000 inhabitants aged 15–64	Overall	680.75	160.00	268.21	1127.39	N = 331
		Between		136.55	394.58	958.56	n = 16
		Within		85.83	453.82	959.15	T-bar = 20.6875
Total stock of passenger cars, motorcycles & lorries (all fuel types) per driver	Number per 1000 inhabitants aged 15–64	overall	758.46	172.51	309.16	1230.63	N = 326
		between		145.00	443.19	1068.69	n = 16
		within		97.84	514.48	1074.63	T-bar = 20.375
Excise tax on petrol (RON95)	international $ PPP (LCU)	overall	0.58	0.16	0.20	1.36	N = 367
		between		0.12	0.38	0.81	n = 16
		within		0.11	0.26	1.14	T-bar = 22.9375
Excise tax on diesel	international $ PPP (LCU)	overall	0.43	0.15	0.12	0.98	N = 369
		between		0.12	0.30	0.65	n = 16
		within		0.10	0.01	0.76	T-bar = 23.0625

Note: The table reports variables in levels while regression uses logs. N: total. n = number of countries. T-bar: mean number of time periods.

Table A-2
Descriptive Statistics – Share of diesel-driven lorries in the diesel-driven vehicle fleet (in %).

year	AT	BE	CZ	DK	FI	FR	DE	HU	IT	NL	NO	PL	ES	SE	CH	UK
1990	29.7	.	.	.	56.4	35.2	.	87.3	.	.	75.8	.	.	52.1	.	.
1991	28.7	.	.	.	57.0	34.7	20.8	.	.	.	74.9	.	.	52.3	.	.
1992	27.2	19.5	.	73.0	57.6	33.3	.	60.0	.	.	73.7	.	.	53.1	55.0	.
1993	25.5	18.9	45.6	73.4	57.7	31.5	24.5	51.0	.	12.3	71.6	.	.	53.0	54.3	.
1994	23.8	18.5	44.8	74.1	57.8	28.0	24.7	47.8	.	11.9	.	.	51.3	52.9	51.8	46.5
1995	22.1	18.2	44.9	74.4	58.0	29.0	25.2	46.9	40.0	11.6	70.5	42.4	49.5	52.1	51.2	45.5

(continued on next page)

Table A-2 *(continued)*

year	AT	BE	CZ	DK	FI	FR	DE	HU	IT	NL	NO	PL	ES	SE	CH	UK
1996	20.3	18.4	44.9	74.7	57.4	28.1	25.6	47.7	44.8	43.0	69.6	42.3	47.4	50.6	50.7	42.1
1997	19.1	18.5	43.6	74.9	57.0	26.9	26.3	48.9	44.1	44.3	.	43.6	45.2	48.6	50.1	42.5
1998	18.1	18.4	41.7	74.9	56.3	31.3	27.3	49.6	42.5	45.3	.	44.0	42.7	46.8	49.7	41.8
1999	17.1	18.6	38.9	73.6	55.6	30.9	27.8	50.3	40.7	45.7	.	47.3	40.4	47.3	49.1	41.6
2000	16.3	18.6	36.7	72.0	54.3	30.5	26.8	51.1	38.4	45.9	.	49.0	38.5	48.7	47.3	41.4
2001	15.4	18.8	35.4	70.1	53.9	29.8	25.4	50.4	36.3	45.8	.	47.4	36.9	53.4	44.8	40.9
2002	14.6	18.6	34.0	67.8	53.4	28.8	23.7	48.9	34.4	45.9	.	.	35.5	55.2	41.2	39.4
2003	14.0	18.5	32.2	.	52.2	27.8	22.1	46.3	.	45.9	.	50.4	34.3	56.6	37.5	38.1
2004	13.5	18.3	31.8	.	53.7	26.9	20.6	44.0	.	45.6	56.3	37.5	32.9	58.0	34.5	36.8
2005	13.2	18.4	31.9	.	52.1	26.2	19.0	45.9	.	43.9	52.7	46.3	.	58.9	32.3	35.5
2006	12.9	18.1	32.1	.	50.7	25.4	18.2	41.8	.	42.2	49.6	42.1	31.0	56.6	29.9	.
2007	12.9	17.7	32.6	.	49.4	25.1	.	40.3	22.7	41.4	45.0	37.8	30.3	51.5	28.4	.
2008	13.0	17.4	32.3	.	46.7	.	17.5	38.6	22.0	41.3	41.9	34.0	29.6	48.3	26.6	32.2
2009	13.0	17.1	30.4	.	45.4	.	17.1	38.9	21.3	40.9	38.9	32.4	28.9	45.3	25.2	30.6
2010	12.9	16.8	28.6	.	43.7	.	16.8	38.3	20.8	40.5	35.8	31.6	28.2	.	24.3	29.2
2011	13.0	16.6	27.0	.	42.7	.	16.6	37.4	20.3	39.6	33.4	30.3	27.6	36.9	23.5	28.1
2012	27.6	.	25.2	.	41.7	.	16.2	36.1	19.8	.	31.8	29.0	27.0	.	22.5	.

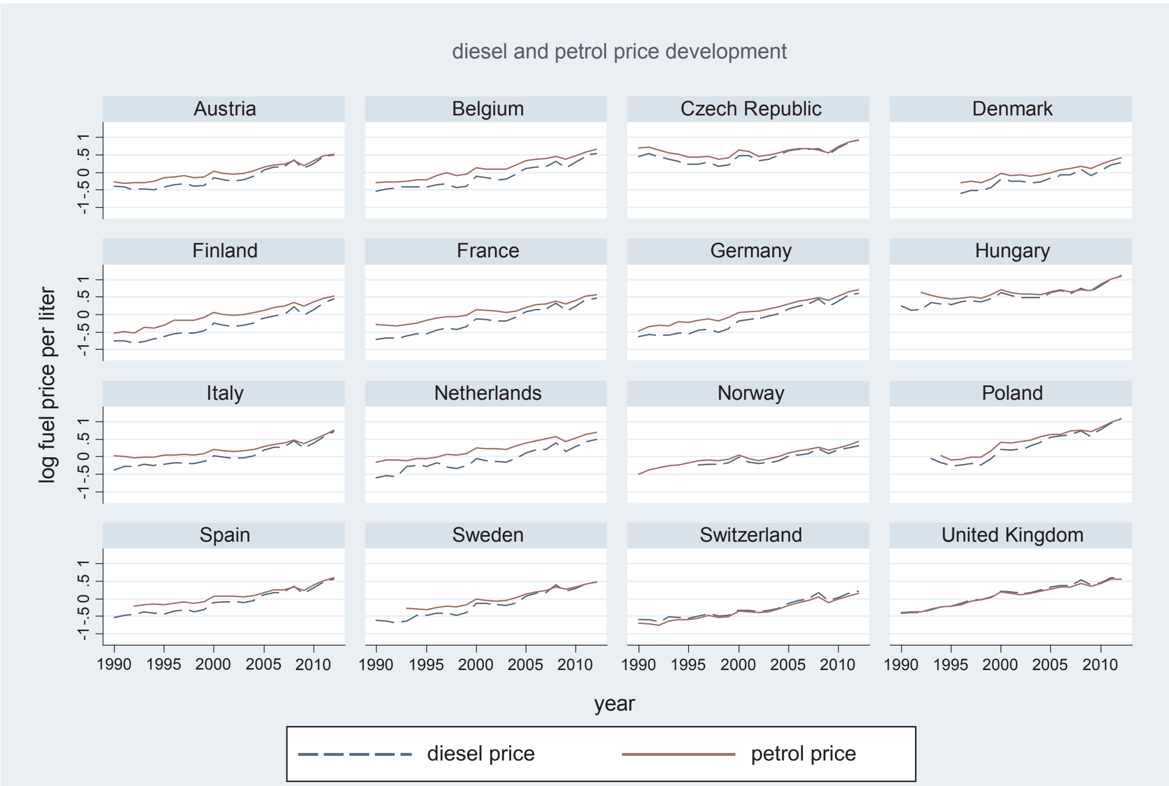

Fig. A-1. Development of petrol and diesel prices (in logs). Note: Petrol price is the premium unleaded RON95.
Data Source: IEA (2014).

Appendix B. Bias corrected Least Square Dummy Variable estimator (LSDVc)

A bias corrected Least Squares Dummy Variable estimator (LSDVc) has been proposed for macro panels with medium N and large time dimensions to address the Nickel bias (see Bun and Kiviet, 2003; Judson and Owen, 1999; Bruno, 2005a for an extension). The LSDVc estimator is based on Monte Carlo simulation results assessing the magnitude of the Nickel bias for simple dynamic Partial Adjustment models. Based on derived bias approximation formulas[25] the estimator has been frequently applied in previous studies

[25] The formula has been derived for three different levels of accuracy of bias-approximation (Bruno, 2005b).

using Partial Adjustment models. However, the reliability of the bias approximation of the LSDVc estimator in more complex dynamics models including lagged explanatory variables or in the presence of high persistence has not yet been explored sufficiently to our knowledge. We therefore present results for the LSDVc estimator only for robustness analysis as additional results and only for the partial adjustment model (see Table C-1) as this has been the focus of bias correction simulation studies.

Appendix C. Additional tables on regression results

As most of the previous literature estimating petrol price elasticities has relied on the more restrictive Partial Adjustment Model (PAM), in Table C-2 we contrast our estimates that allow for first-order dynamics with those from the widely applied PAM (see Table C-1 for point estimates). The short-run effect in the PAM is indeed much lower due to the exclusion of the lagged price variable. As described above, the first-order dynamics ADL model reveals a strong immediate price response which is then attenuated in the following period. While the PAM seems to *under*estimate the short-run effect, it seems to slightly *over*estimate the long-run effect compared to the results based on the first-order dynamics ADL model. This shows that imposing invalid restrictions on dynamics causes a bias in the estimated fuel price elasticities, both in the short and the long run.

Table C-1
Partial Adjustment Model estimates for petrol consumption per passenger car or motorcycles.

	(1)	(2)	(3)	(4)	(5)
PETROL	OLS	Fixed-Effects	Arellano-Bond GMM	System GMM	LSDVc
L. consumption per vehicle	0.953***	0.778***	0.806***	0.868***	0.836***
	(0.017)	(0.051)	(0.110)	(0.074)	(0.058)
Petrol price	-0.027	-0.140**	-0.125+	-0.075+	-0.099+
	(0.018)	(0.041)	(0.065)	(0.036)	(0.054)
GDP pC	0.023+	0.196*	0.177	0.063	0.162+
	(0.014)	(0.089)	(0.111)	(0.052)	(0.086)
Total vehicle stock	-0.055***	-0.255***	-0.238*	-0.106+	-0.214**
	(0.016)	(0.062)	(0.096)	(0.055)	(0.083)
Constant	0.051	-0.463		0.005	
	(0.162)	(0.879)		(0.281)	
Year dummies	Yes	Yes	Yes	Yes	Yes
LRM	-0.581	-0.629	-0.645	-0.568	-0.607
# observations	273	273	257	273	273
# instruments			29	31	
Max IV lag			6	6	
AB-test (AR1)			0.0052	0.0021	
AB-test (AR2)			0.7561	0.6845	
Sargan Test			0.4530	0.2160	
Diff-in-Sargan Test				0.2847	

Standard errors in parentheses.
Estimation results for petrol consumption per passenger car or motorcycle, robust standard errors in all specifications except LSDVc. All variables in logs. For Arellano-Bond and System GMM: one step estimators, Forward Orthogonal Deviations Transformation as well as collapse and small sample option applied, internal instruments restricted from t-2 to maximum lag indicated. In System GMM the standard instruments are used for the levels equation only. Difference-in-Sargan Test on the validity of additional instruments in System GMM, p-values reported. For LSDVc: Bias correction up to order O(1/NT) based on Arellano-Bond estimator, standard errors bootstrapped with 100 repetitions (based a method proposed by Kiviet and Bun (2001).
+ $p < 0.10$.
* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

Table C-2
Comparing dynamics for petrol price elasticity estimates of first-order ADL and PAM.

PETROL	*ADL with first-order dynamics*			*Partial Adjustment Model*		
	Fixed Effects	Arellano-Bond GMM	System GMM	Fixed Effects	Arellano-Bond GMM	System GMM
Short-run	−0.248**	−0.239*	−0.276***	−0.140**	−0.125+	−0.075+
	(0.079)	(0.083)	(0.059)	(0.041)	(0.065)	(0.036)
Long-run (LRM)	−0.580*	−0.565**	−0.554*	−0.629*	−0.645*	−0.568*
	(0.221)	(0.141)	(0.236)	(0.215)	(0.261)	(0.203)
Error Correction Rate	−0.180**	−0.268+	−0.087			
	(0.048)	(0.131)	(0.079)			

Results for the short-run and long-run price elasticity, based on the Autoregressive Distributed Lag (ADL) Model with first-order dynamics (Table 1) and the Partial Adjustment Model (Table C-1), including additional estimation results for the bias corrected Least Square Dummy Variable Estimator. Standard errors in parentheses.
Significance levels:
+ $p < 0.10$.
* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

Table C-3
Petrol estimation results accounting for price endogeneity – petrol excise taxes used as instruments.

PETROL	*exogenous price*	*endogenous price*	*exogenous price*	*endogenous price*	*exogenous price*	*endogenous price*
	Fixed Effects	Fixed-Effects IV	Arellano-Bond GMM	Arellano-Bond GMM	System GMM	System GMM
L. consumption per vehicle	0.820***	0.824***	0.732***	0.693***	0.913***	0.810***
	(0.048)	(0.035)	(0.131)	(0.124)	(0.079)	(0.099)
Petrol price	−0.248**	−0.391***	−0.239*	−0.252	−0.276***	−0.066
	(0.079)	(0.114)	(0.083)	(0.201)	(0.059)	(0.209)
L. petrol price	0.144*	0.260**	0.087	0.076	0.228**	−0.022
	(0.067)	(0.099)	(0.106)	(0.209)	(0.069)	(0.195)
GDP pC	0.622***	0.650***	0.695**	0.732**	0.622**	0.679*
	(0.129)	(0.156)	(0.213)	(0.183)	(0.181)	(0.273)
L. GDP pC	−0.455**	−0.492**	−0.471*	−0.482*	−0.594**	−0.594*
	(0.137)	(0.159)	(0.172)	(0.180)	(0.151)	(0.239)
Total vehicle Stock	−1.042***	−1.067***	−1.051***	−1.058***	−1.015***	−1.084***
	(0.140)	(0.117)	(0.145)	(0.149)	(0.134)	(0.203)
L. total vehicle stock	0.894***	0.929***	0.848***	0.831***	0.958***	0.966***
	(0.146)	(0.117)	(0.168)	(0.171)	(0.125)	(0.184)
Constant	−0.838	−0.785+			0.048	−0.205
	(0.503)	(0.441)			(0.228)	(0.401)
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes
LRM	−0.580	−0.742	−0.565	−0.572	−0.554	−0.460
# observations	270	270	254	254	270	270
# instruments		1	35	43	37	46
Max IV lag			9	9	9	9
AB-test (AR1)			0.0020	0.0025	0.0016	0.0013
AB-test (AR2)			0.8470	0.8581	0.8803	0.7445
Sargan Test			0.3350	0.2162	0.1781	0.0157
Diff-in-Sargan Test					0.3800	

Notes: Robust standard errors in parentheses. All specifications include year dummies. All variables in logs. Dependent variable: petrol consumption per petrol driven passenger car or motorcycle. Total vehicle stock refers to the sum of all fuel type passenger cars and motorcycles per driver (population age 15–64). GDP per capita. L. denotes first lags, D. denotes first differences. The “exogenous price”-columns refer to estimation results assuming prices to be exogenous without instrumentation, while “endogenous price”-columns assume prices to be endogenous if not instrumented. Petrol excise tax used as external instrument for the endogenous contemporaneous price variable. For Arellano-Bond and System GMM: one step estimators, Forward Orthogonal Deviations Transformation as well as collapse and small sample option applied, internal instruments for L. consumption and endogenous price restricted from t-2 to maximum lag indicated. In System GMM the standard instruments are used for the levels equation only. Arellano-Bond-Test for first and second order serial correlation in transformed errors, H_0: no serial correlation of respective order. Sargan Test on over-identifying restrictions, H_0: instruments used are not correlated with the residuals. Difference-in-Sargan Test on the validity of additional instruments in System GMM. *p*-values reported for specification tests.
Significance level for parameters:
+ $p < 0.10$.
* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

Table C-4
Diesel estimation results accounting for price endogeneity – diesel excise taxes used as instruments.

DIESEL	*exogenous price*	*endogenous price*	*exogenous price*	*endogenous price*	*exogenous price*	*endogenous price*
	Fixed Effects	Fixed-Effects IV	Arellano-Bond GMM	Arellano-Bond GMM	System GMM	System GMM
L. consumption per vehicle	0.811***	0.828***	0.977***	0.863***	0.966***	0.894***
	(0.051)	(0.045)	(0.094)	(0.086)	(0.128)	(0.108)
Diesel price	−0.169*	−0.654**	−0.206*	−0.616***	−0.195*	−0.720**
	(0.076)	(0.234)	(0.088)	(0.138)	(0.088)	(0.220)
L. diesel price	0.044	0.460*	0.130	0.439**	0.136	0.611*
	(0.092)	(0.208)	(0.107)	(0.146)	(0.092)	(0.213)
GDP pC	1.058***	1.071**	0.799***	1.013***	0.893*	1.112***
	(0.184)	(0.327)	(0.182)	(0.191)	(0.392)	(0.255)
L. GDP pC	−0.921**	−0.974**	−0.819***	−0.946***	−0.926*	−1.134***
	(0.255)	(0.344)	(0.184)	(0.233)	(0.317)	(0.200)
Total vehicle stock	−1.294***	−1.364***	−1.433***	−1.387***	−1.356***	−1.550***
	(0.229)	(0.264)	(0.290)	(0.290)	(0.285)	(0.291)
L. total vehicle stock	1.230***	1.336***	1.420***	1.368***	1.311***	1.449***
	(0.232)	(0.264)	(0.271)	(0.300)	(0.216)	(0.334)
Constant	−0.743	−0.640			0.691**	0.982***
	(1.194)	(0.940)			(0.225)	(0.215)
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes
LRM	−0.659	−1.131	−3.251	−1.290	−1.753	−1.037
# observations	253	253	237	237	253	253
# instruments		1	35	43	38	48
Max IV lag			9	9	10	10
AB-test (AR1)			0.0125	0.0085	0.0059	0.0054
AB-test (AR2)			0.1403	0.2449	0.1439	0.3469
Sargan Test			0.2760	0.1708	0.2135	0.1636
Diff-in-Sargan Test					0.3878	

Notes: Robust standard errors in parentheses. All specifications include year dummies. All variables in logs. Dependent variable: log diesel consumption per diesel driven passenger car or lorry. Total vehicle stock refers to the sum of all fuel type passenger cars, motorcycles and lorries per driver (population age 15–64). L. denotes first lags, D. denotes first differences. The "exogenous price"-columns refer to estimation results assuming prices to be exogenous without instrumentation, while "endogenous price"-columns assume prices to be endogenous if not instrumented. Diesel excise tax used as external instrument for the endogenous contemporaneous price variable. For Arellano-Bond and System GMM: one step estimators, Forward Orthogonal Deviations Transformation as well as collapse and small sample option applied, internal instruments for L. consumption and endogenous price restricted from t-2 to maximum lag indicated. In System GMM the standard instruments are used for the levels equation only. Arellano-Bond-Test for first and second order serial correlation in transformed errors, H_0: no serial correlation of respective order. Sargan Test on over-identifying restrictions, H_0: instruments used are not correlated with the residuals. Difference-in-Sargan Test on the validity of additional instruments in System GMM.*p*-values reported for specification tests.
Significance level for parameters:
$^{+}p < 0.10$.
* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

Table C-5
First stage estimation results for the FE-IV estimation for petrol and diesel respectively.

dependent variable	PETROL *petrol price*		DIESEL *diesel price*
L. consumption per vehicle	−0.049+	L. consumption per vehicle	0.025
	(0.029)		(0.022)
L. petrol price	0.515***	L. diesel price	0.642***
	(0.045)		(0.050)
GDP pC	0.068	GDP pC	0.136
	(0.133)		(0.197)
L. GDP pC	−0.164	L. GDP pC	−0.301
	(0.133)		(0.200)
Vehicle stock	−0.143	Vehicle stock	−0.071
	(0.111)		(0.150)
L. vehicle stock	0.119	L. vehicle stock	0.186
	(0.117)		(0.158)
Petrol excise tax	0.337***	diesel excise tax	0.200***
	(0.036)		(0.036)
Year dummies	Yes	Year dummies	Yes

(continued on next page)

Table C-5 *(continued)*

dependent variable	PETROL *petrol price*		DIESEL *diesel price*
# observations	270	# observations	253
R-squared	0.990	R-squared	0.989
Weak identification test:		Weak identification test:	
Kleibergen-Paap rk Wald F statistic	89.855	Kleibergen-Paap rk Wald F statistic	31.282
Stock-Yogo weak ID test critical values: 10% maximal IV size	16.38	Stock-Yogo weak ID test critical values: 10% maximal IV size	16.38

Robust standard errors in parentheses. First stage estimation results for FE-IV estimation. Dependent variable is petrol and diesel price respectively. All variables in logs. Consumption per vehicle is either log petrol consumption per petrol driven passenger car or motorcycle or log diesel consumption per diesel driven passenger car or lorry. Total vehicle stock refers to the sum of all fuel type passenger cars and motorcycles per driver (population age 15–64) (petrol estimation) and additionally lorries per driver (population age 15–64) (diesel estimation).

$^{+}$ $p < 0.10$.
* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

Table C-6
Short and long run (LRM) elasticities for income and vehicle stock per driver for diesel and petrol.

	exogenous prices			*price instrumented with tax*		
	Fixed Effects	Arellano-Bond	System GMM	Fixed Effects- IV	Arellano-Bond	System GMM
Petrol						
Income (SR)	0.622***	0.695**	0.622**	0.650***	0.732**	0.679*
	(0.129)	(0.213)	(0.181)	(0.156)	(0.183)	(0.273)
Income (LRM)	0.923**	0.838**	0.314	0.899**	0.814**	0.446*
	(0.313)	(0.264)	(0.282)	(0.304)	(0.236)	(0.204)
vehicle stock (SR)	−1.042***	−1.051***	−1.015***	−1.067***	−1.058***	−1.084***
	(0.140)	(0.145)	(0.134)	(0.117)	(0.149)	(0.203)
vehicle stock (LRM)	−0.817**	−0.757**	−0.651***	−0.783**	−0.739**	−0.623***
	(0.236)	(0.212)	(0.155)	(0.277)	(0.206)	(0.129)
Diesel						
Income (SR)	1.058***	0.799***	0.893*	1.071**	1.013***	1.112***
	(0.184)	(0.182)	(0.392)	(0.327)	(0.191)	(0.255)
Income (LRM)	0.723	−0.848	−0.989	0.568	0.489	−0.205
	(0.897)	(9.239)	(6.266)	(0.685)	(1.172)	(0.972)
vehicle stock (SR)	−1.294***	−1.433***	−1.356***	−1.364***	−1.387***	−1.550***
	(0.229)	(0.290)	(0.285)	(0.264)	(0.290)	(0.291)
vehicle stock (LRM)	−0.344	−0.554	−1.359	−0.160	−0.143	−0.954*
	(0.744)	(4.838)	(1.955)	(0.610)	(0.944)	(0.340)

Robust standard errors in parentheses. Estimation results for petrol consumption per passenger car or motorcycle and for diesel consumption per passenger car or lorry. Income is measured in GDP per capita. For Arellano-Bond and System GMM: one step estimators, Forward Orthogonal Deviations Transformation as well as collapse and small sample option applied, internal instruments (for L. consumption and price if endogenous) restricted. In System GMM the standard instruments are used for the levels equation only. External instrumentation with fuel excise tax levels in the models assuming endogenous prices.

$^{+}$ $p < 0.10$.
* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

Appendix D. Emission reduction calculation

Table D-1 shows the emission factors for CO_2. Due to the chemical process of burning fossil fuel, the carbon content of a liter of diesel and petrol reduces to a constant. The amount of CO_2 emitted per liter of fuel, assuming complete combustion, thus only depends on the type of fuel, and not on other external factors such as vehicle type or temperature. We concentrate on CO_2, since other GHGs play only a minor role with respect to road transport.

Fig. D-1 compares changes in air pollutant emissions in *absolute* terms per capita. As stated in Section 6.4, differences in country characteristics become more visible. Most notably, in Scenario A, despite lower diesel tax breaks, Finland joins the Netherlands in benefiting from very high absolute reductions as Finland exhibits very high emission factors especially for $PM_{2.5}$. When introducing a carbon tax (Scenario B), Austria stands out regarding the highest NO_x reductions, exhibiting the highest absolute emission reductions per capita driven mostly by its high share of diesel use and its high per capita fuel consumption. Denmark and Finland would yield large NO_x reductions as they both exhibit relatively high NO_x emission factors for diesel due to their car fleet composition. For $PM_{2.5}$ (in Scenario B), the Czech Republic would exhibit the highest absolute reduction in fine particulate matter exhaust per capita due to

Table D-1
Emission Factors and conversion rates for CO_2 from fuel combustion exhaust.

	CO_2 emission factors		conversion of metrics
Fuel type	kg CO_2/kg fuel[a]	kg CO_2/liter fuel	liter fuel/kg fuel[b]
Petrol	3.16	2.37	1.33
Diesel	3.17	2.66	1.19

[a] Emission factors in EMEP/EEA emission inventory guidebook 2013 updated Sept 2014, Appendix 1 in chapter 1A3b (Ntziachristos and Samaras, 2014).
[b] http://www.bdbe.de/daten/Umrechnung_und_Formeln.

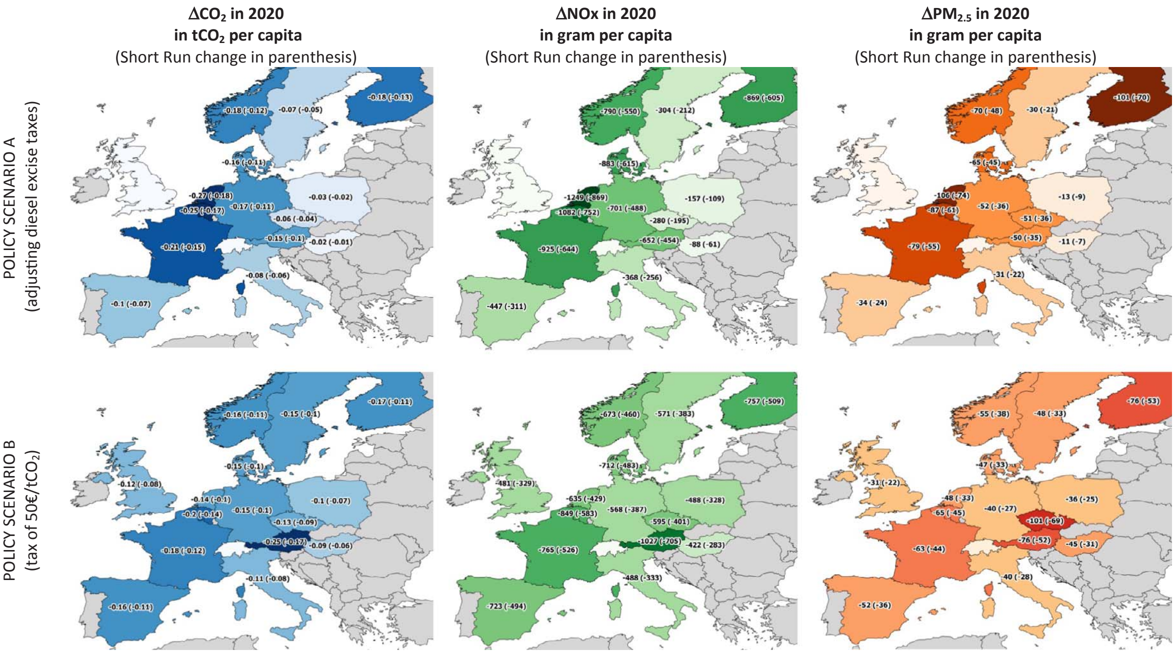

Fig. D-1. Changes in CO_2, NO_x and $PM_{2.5}$ in absolute terms (per capita) compared to the status quo (2013). Note: Emissions refer to calculated emissions from diesel and petrol consumption for road transportation based on EUROSTAT fuel consumption data for 2013, own elasticity estimates and emission factors per liter. Reported changes assume that GDP per capita and vehicle stocks per driver remain unchanged.

Table D-2
Country specific emission factors for air pollutant exhaust (in gram per kg fuel). Emission factors weighted by country vehicle fleet shares.

	CO		NOx		NMVOC		CH_4		PM ($PM_{2.5}$)	
	petrol	diesel	petrol	diesel	petrol	diesel	petrol	diesel	petrol	diesel
Austria	129.24	3.62	7.10	13.70	17.62	0.74	1.30	0.07	0.22	1.05
Belgium	169.44	3.36	12.27	13.75	20.79	0.80	1.65	0.06	0.18	1.11
Czech Republic	239.28	8.68	12.27	14.54	88.52	1.87	2.52	0.24	1.10	2.66
Denmark	104.54	5.95	8.87	17.03	13.26	1.45	1.03	0.13	0.08	1.26
Finland	138.88	6.50	11.24	15.14	18.91	1.48	1.31	0.13	0.14	1.76
France	110.32	4.56	10.39	13.94	16.69	0.97	1.20	0.10	0.13	1.20
Germany	101.01	3.27	5.83	13.46	16.15	0.81	1.09	0.06	0.18	0.99
Hungary	129.32	7.66	12.07	16.13	31.46	1.65	1.59	0.21	0.33	1.96
Italy	193.15	4.13	8.47	14.44	31.57	0.84	2.04	0.08	0.40	1.23
Netherlands	102.45	4.44	9.51	14.90	14.24	1.00	1.03	0.07	0.11	1.26
Norway	111.78	4.78	8.86	14.21	11.56	1.06	1.09	0.07	0.08	1.25
Poland	208.51	6.27	15.22	15.76	29.31	1.31	1.78	0.16	0.19	1.31
Spain	177.13	4.85	14.31	14.40	26.27	0.85	1.61	0.09	0.29	1.11
Sweden	96.08	5.08	8.56	13.65	11.46	1.26	1.09	0.13	0.10	1.33
Switzerland	123.32	3.32	6.91	13.64	14.88	0.73	1.22	0.06	0.26	0.85
United Kingdom	89.94	3.44	4.75	14.27	7.18	0.73	0.82	0.07	0.07	0.99

Note: calculations based on Emission Factors in EMEP/EEA (2013) emission inventory guidebook 2013 update Sept 2014 (http://www.eea.europa.eu/publications/emep-eea-guidebook-2013. (Ntziachristos and Samaras, 2014) Appendix 1 in Chapter 1 A3b) and EUROSTAT vehicle stock data assuming that shares in stocks reflect shares in fuel consumption. Bulk emission factors refer to 2005.

Table D-3
Share of diesel and petrol use in aggregated fuel consumption and fuel consumption per capita.

	Share in total consumption (2013)		Fuel consumption per capita (diesel and petrol)
	petrol share	diesel share	in ktons per 1000 inhabitants
Austria	22.59%	77.41%	0.82
Belgium	14.88%	85.12%	0.67
Czech Republic	30.39%	69.61%	0.47
Denmark	38.74%	61.26%	0.59
Finland	37.21%	62.79%	0.66
France	16.26%	83.74%	0.56
Germany	36.18%	63.82%	0.58
Hungary	36.12%	63.88%	0.31
Italy	28.20%	71.80%	0.47
Netherlands	39.11%	60.89%	0.57
Norway	27.22%	72.78%	0.64
Poland	28.52%	71.48%	0.31
Spain	18.42%	81.58%	0.51
Sweden	40.61%	59.39%	0.64
Switzerland	.	.	.
United Kingdom	36.57%	63.43%	0.54

Table D-4
Policy Scenario A – adjusting diesel excise taxes to petrol taxation level: Changes in diesel consumption.

	Change in diesel consumption			
	Short Run		in 2020	
	in %	in Mt	in %	in Mt
Austria	−5.19%	−0.28	−7.46%	−0.40
Belgium	−9.62%	−0.61	−13.83%	−0.88
Czech Republic	−4.14%	−0.14	−5.95%	−0.20
Denmark	−10.04%	−0.20	−14.43%	−0.29
Finland	−9.67%	−0.22	−13.89%	−0.31
France	−9.85%	−3.05	−14.16%	−4.38
Germany	−9.80%	−2.92	−14.08%	−4.20
Hungary	−1.90%	−0.04	−2.73%	−0.05
Italy	−5.25%	−1.07	−7.55%	−1.54
Netherlands	−16.72%	−0.98	−24.03%	−1.41
Norway	−8.26%	−0.20	−11.88%	−0.28
Poland	−3.09%	−0.26	−4.44%	−0.38
Spain	−5.24%	−1.01	−7.53%	−1.45
Sweden	−4.10%	−0.15	−5.90%	−0.21

Note: All changes compared to 2013 levels, ceteris paribus. Potential impacts of GDP or vehicle stock changes are not accounted for. Based on elasticity estimates from FE-IV estimation for diesel. For Switzerland and the UK, taxes have remained unchanged for the policy scenario.

Table D-5
Policy Scenario B – tax of 50€/tCO_2: Price changes and resulting changes in petrol and diesel consumption.

	Petrol					Diesel				
	change in price	change in consumption due to price change				change in price	change in consumption due to price change			
		Short Run		2020			Short Run		2020	
	in %	in %	in kt	in %	in kt	in %	in %	in kt	in %	in kt
Austria	10.23%	−2.54%	−40	−4.71%	−74	11.75%	−7.68%	−415	−11.04%	−597
Belgium	8.69%	−2.16%	−24	−4.00%	−44	10.89%	−7.12%	−453	−10.23%	−651
Czech Republic	10.30%	−2.55%	−38	−4.74%	−70	11.58%	−7.57%	−258	−10.89%	−371
Denmark	8.74%	−2.17%	−28	−4.02%	−51	10.96%	−7.17%	−145	−10.31%	−208
Finland	9.01%	−2.24%	−30	−4.15%	−55	10.93%	−7.15%	−161	−10.28%	−231
France	9.20%	−2.28%	−137	−4.23%	−254	11.80%	−7.71%	−2385	−11.09%	−3429
Germany	8.81%	−2.19%	−370	−4.05%	−686	11.08%	−7.25%	−2161	−10.41%	−3107
Hungary	10.71%	−2.66%	−30	−4.93%	−55	11.79%	−7.71%	−152	−11.08%	−218

(continued on next page)

Table D-5 *(continued)*

	Petrol					Diesel				
	change in price	change in consumption due to price change				change in price	change in consumption due to price change			
		Short Run		2020			Short Run		2020	
	in %	in %	in kt	in %	in kt	in %	in %	in kt	in %	in kt
Italy	8.21%	−2.04%	−163	−3.78%	−302	9.72%	−6.36%	−1294	−9.14%	−1860
Netherlands	8.24%	−2.04%	−77	−3.79%	−143	11.35%	−7.42%	−435	−10.66%	−625
Norway	7.86%	−1.95%	−17	−3.61%	−32	9.87%	−6.46%	−153	−9.28%	−221
Poland	11.16%	−2.77%	−94	−5.14%	−175	12.57%	−8.22%	−701	−11.81%	−1008
Spain	10.03%	−2.49%	−108	−4.61%	−200	11.85%	−7.75%	−1491	−11.13%	−2142
Sweden	8.92%	−2.21%	−55	−4.11%	−102	9.90%	−6.47%	−235	−9.30%	−338
United Kingdom	9.01%	−2.24%	−281	−4.15%	−521	9.69%	−6.34%	−1382	−9.11%	−1987

Note: change refer to reference year 2013, price change including adjustment in value added tax (VAT) due to excise tax increase.

Table D-6
Absolute and relative changes in CO_2 emissions compared to the status quo (2013) for both policy scenarios.

	ΔCO_2 short run						ΔCO_2 in 2020					
	$MtCO_2$		tCO_2/capita		in % (to 2013)		$MtCO_2$		tCO_2/capita		in % (to 2013)	
	PS A	*PS B*	*PS A*	*PS B*	*PS A*	*PS B*	*PS A*	*PS B*	*PS A*	*PS B*	*PS A*	*PS B*
Austria	−0.9	−1.4	−0.10	−0.17	−4.0%	−6.5%	−1.3	−2.1	−0.15	−0.25	−5.8%	−9.6%
Belgium	−1.9	−1.5	−0.17	−0.14	−8.2%	−6.4%	−2.8	−2.2	−0.25	−0.20	−11.8%	−9.3%
Czech Republic	−0.4	−0.9	−0.04	−0.09	−2.9%	−6.1%	−0.6	−1.4	−0.06	−0.13	−4.1%	−9.0%
Denmark	−0.6	−0.5	−0.11	−0.10	−6.2%	−5.2%	−0.9	−0.8	−0.16	−0.15	−8.8%	−7.9%
Finland	−0.7	−0.6	−0.13	−0.11	−6.1%	−5.3%	−1.0	−0.9	−0.18	−0.17	−8.7%	−8.0%
France	−9.7	−8.0	−0.15	−0.12	−8.3%	−6.8%	−13.9	−11.7	−0.21	−0.18	−11.9%	−10.0%
Germany	−9.3	−8.0	−0.11	−0.10	−6.3%	−5.4%	−13.3	−12.0	−0.17	−0.15	−9.0%	−8.1%
Hungary	−0.1	−0.6	−0.01	−0.06	−1.2%	−5.9%	−0.2	−0.9	−0.02	−0.09	−1.7%	−8.9%
Italy	−3.4	−4.6	−0.06	−0.08	−3.8%	−5.1%	−4.9	−6.8	−0.08	−0.11	−5.4%	−7.6%
Netherlands	−3.1	−1.6	−0.18	−0.10	−10.2%	−5.3%	−4.5	−2.4	−0.27	−0.14	−14.7%	−8.0%
Norway	−0.6	−0.5	−0.12	−0.11	−6.0%	−5.2%	−0.9	−0.8	−0.18	−0.16	−8.7%	−7.7%
Poland	−0.8	−2.5	−0.02	−0.07	−2.2%	−6.7%	−1.2	−3.7	−0.03	−0.10	−3.2%	−9.9%
Spain	−3.2	−5.1	−0.07	−0.11	−4.3%	−6.8%	−4.6	−7.4	−0.10	−0.16	−6.1%	−9.9%
Sweden	−0.5	−0.9	−0.05	−0.10	−2.4%	−4.7%	−0.7	−1.4	−0.07	−0.15	−3.5%	−7.2%
Switzerland	0.0	.	0.00	.	0.0%	.	0.0	.	0.00	.	0.0%	.
United Kingdom	0.0	−5.3	0.00	−0.08	0.0%	−4.8%	0.0	−7.9	0.00	−0.12	0.0%	−7.3%

Note: PS A denotes policy scenario A (adjusting diesel excise taxes to petrol taxation levels) and PS B refers to policy scenario B (introducing a carbon-content based tax of 50€/tCO_2 per liter of fuel). Emissions refer to calculated emissions from diesel and petrol consumption for road transportation based on elasticity estimates and emission factors per liter. Reported changes assume that GDP per capita and vehicle stocks per driver remain unchanged.

Table D-7
Absolute and relative changes in NO_x emissions compared to the status quo (2013) for both policy scenarios.

	ΔNO_x Short run						ΔNO_x in 2020					
	in tons NO_x		gr/capita		in % (to 2013)		in tons NO_x		gr/capita		in % (to 2013)	
	PS A	*PS B*	*PS A*	*PS B*	*PS A*	*PS B*	*PS A*	*PS B*	*PS A*	*PS B*	*PS A*	*PS B*
Austria	−3847	−5975	−454	−705	−4.5%	−7.0%	−5529	−8707	−652	−1027	−6.5%	−10.2%
Belgium	−8415	−6518	−752	−583	−8.3%	−6.4%	−12,095	−9492	−1082	−849	−12.0%	−9.4%
Czech Republic	−2049	−4216	−195	−401	−3.0%	−6.2%	−2945	−6254	−280	−595	−4.3%	−9.2%
Denmark	−3451	−2711	−615	−483	−7.6%	−5.9%	−4960	−3998	−883	−712	−10.9%	−8.7%
Finland	−3290	−2768	−605	−509	−6.7%	−5.6%	−4729	−4118	−869	−757	−9.7%	−8.4%
France	−42,449	−34,668	−644	−526	−8.6%	−7.0%	−61,012	−50,424	−925	−765	−12.4%	−10.2%
Germany	−39,330	−31,245	−488	−387	−7.9%	−6.2%	−56,529	−45,809	−701	−568	−11.3%	−9.2%
Hungary	−603	−2803	−61	−283	−1.3%	−6.2%	−866	−4178	−88	−422	−1.9%	−9.3%
Italy	−15,439	−20,065	−256	−333	−4.3%	−5.5%	−22,190	−29,416	−368	−488	−6.1%	−8.1%
Netherlands	−14,600	−7211	−869	−429	−11.9%	−5.9%	−20,984	−10,670	−1249	−635	−17.0%	−8.7%
Norway	−2791	−2335	−550	−460	−6.7%	−5.6%	−4012	−3420	−790	−673	−9.6%	−8.2%

(continued on next page)

Table D-7 *(continued)*

	ΔNO_x Short run						ΔNO_x in 2020					
	in tons NO_x		gr/capita		in % (to 2013)		in tons NO_x		gr/capita		in % (to 2013)	
	PS A	*PS B*	*PS A*	*PS B*	*PS A*	*PS B*	*PS A*	*PS B*	*PS A*	*PS B*	*PS A*	*PS B*
Poland	−4154	−12,489	−109	−328	−2.2%	−6.7%	−5970	−18,550	−157	−488	−3.2%	−10.0%
Spain	−14,510	−23,011	−311	−494	−4.3%	−6.8%	−20,856	−33,719	−447	−723	−6.1%	−9.9%
Sweden	−2033	−3678	−212	−383	−2.9%	−5.2%	−2921	−5482	−304	−571	−4.1%	−7.7%
Switzerland	0	.	0	.	0.0%	.	0	.	0	.	0.0%	.
United Kingdom	0	−21,069	0	−329	0.0%	−5.7%	0	−30,840	0	−481	0.0%	−8.3%

Note: PS A denotes policy scenario A (adjusting diesel excise taxes to petrol taxation levels) and PS B refers to policy scenario B (introducing a carbon-content based tax of 50€/tCO_2 per liter of fuel). Emissions refer to calculated emissions from diesel and petrol consumption for road transportation based on elasticity estimates and emission factors per liter. Reported changes assume that GDP per capita and vehicle stocks per driver remain unchanged.

Table D-8
Absolute and relative changes in $PM_{2.5}$ emissions compared to the status quo (2013) for both policy scenarios.

	Δ $PM_{2.5}$ Short run						Δ $PM_{2.5}$ in 2020					
	in tons $PM_{2.5}$		gr/capita		in % (to 2013)		in tons $PM_{2.5}$		gr/capita		in % (to 2013)	
	PS A	*PS B*	*PS A*	*PS B*	*PS A*	*PS B*	*PS A*	*PS B*	*PS A*	*PS B*	*PS A*	*PS B*
Austria	−294	−444	−35	−52	−4.9%	−7.4%	−423	−642	−50	−76	−7.0%	−10.7%
Belgium	−679	−506	−61	−45	−9.4%	−7.0%	−975	−730	−87	−65	−13.4%	−10.1%
Czech Republic	−375	−727	−36	−69	−3.5%	−6.8%	−538	−1063	−51	−101	−5.0%	−9.9%
Denmark	−254	−184	−45	−33	−9.6%	−7.0%	−366	−266	−65	−47	−13.8%	−10.0%
Finland	−382	−286	−70	−53	−9.2%	−6.9%	−548	−413	−101	−76	−13.3%	−10.0%
France	−3643	−2872	−55	−44	−9.6%	−7.6%	−5237	−4135	−79	−63	−13.9%	−10.9%
Germany	−2901	−2211	−36	−27	−8.9%	−6.8%	−4170	−3205	−52	−40	−12.8%	−9.8%
Hungary	−73	−308	−7	−31	−1.7%	−7.3%	−105	−446	−11	−45	−2.5%	−10.5%
Italy	−1318	−1659	−22	−28	−4.7%	−5.9%	−1894	−2412	−31	−40	−6.7%	−8.5%
Netherlands	−1236	−557	−74	−33	−15.8%	−7.1%	−1776	−804	−106	−48	−22.7%	−10.3%
Norway	−246	−193	−48	−38	−8.1%	−6.3%	−353	−279	−70	−55	−11.6%	−9.1%
Poland	−345	−938	−9	−25	−2.9%	−7.9%	−497	−1355	−13	−36	−4.2%	−11.4%
Spain	−1117	−1683	−24	−36	−4.9%	−7.5%	−1605	−2433	−34	−52	−7.1%	−10.8%
Sweden	−198	−318	−21	−33	−3.9%	−6.3%	−285	−460	−30	−48	−5.6%	−9.0%
Switzerland	0	.	0	.	0.0%	.	0	.	0	.	0.0%	.
United Kingdom	0	−1385	0	−22	0.0%	−6.2%	0	−1998	0	−31	0.0%	−8.9%

Note: PS A denotes policy scenario A (adjusting diesel excise taxes to petrol taxation levels) and PS B refers to policy scenario B (introducing a carbon-content based tax of 50€/tCO_2 per liter of fuel). Emissions refer to calculated emissions from diesel and petrol consumption for road transportation based on elasticity estimates and emission factors per liter. Reported changes assume that GDP per capita and vehicle stocks per driver remain unchanged.

its very high emission factor for $PM_{2.5.}$ For Scenario A, this effect is masked by the comparably low diesel price differential. While Hungary and Poland also exhibit high emission factors for both pollutants, these do not translate into over-proportionately high emission reductions due to the relatively low per capita fuel consumption in these countries.

References

Angrist, Joshua D., Krueger, Alan B., 2001. Instrumental variables and the search for identification: from supply and demand to natural experiments. J. Econ. Perspect. 15 (4), 69–85.

Anthoff, David, Tol, Richard S.J., 2013. The uncertainty about the social cost of carbon: a decomposition analysis using fund. Clim. Change 117, 515–530. http://dx.doi.org/10.1007/s10584-013-0706-7.

Arellano, M., Bond, Stephen, 1991. Some tests of specification for panel data: Monte Carlo evidence and an application to employment equations. Rev. Econ. Stud. 58 (2), 277–297.

Arent, D.J., Tol, R.S.J., Faust, E., Hella, J.P., Kumar, S., Strzepek, K.M., Tóth, F.L., Yan, D., 2014. "Chapter 10: Key Economic Sectors and Services". In: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., et al. (Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, pp. 1039–1099. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Baltagi, Badi H., 2013. Econometric Analysis of Panel Data, fifth ed. John Wiley Sons Ltd.

Baltagi, Badi H., Griffin, James M., 1983. Gasoline demand in the OECD – an application of pooling and testing procedures. Eur. Econ. Rev. 22, 117–137.

Baltagi, Badi H., Griffin, James M., 1997. Pooled estimators vs. their heterogeneous counterparts in the context of dynamic demand for gasoline. J. Economet. 77 (2), 303–327. http://dx.doi.org/10.1016/S0304-4076(96)01802-7.

Baltagi, Badi H., Bresson, Georges, Griffin, James M., Pirotte, Alain, 2003. Homogeneous, heterogeneous or shrinkage estimators? Some empirical evidence from

French regional gasoline consumption. Empir. Econ. 28 (4), 795–811. http://dx.doi.org/10.1007/s00181-003-0161-9.
Basso, Leonardo J., Oum, Tae Hoon, 2007. Automobile fuel demand: a critical assessment of empirical methodologies. Transp. Rev.: Transnat. Transdicipl. J. 27 (4), 449–484. http://dx.doi.org/10.1080/01441640601119710.
Blundell, R., Bond, S., 1998. Initial conditions and moment restrictions in dynamic panel data models. J. Economet. 87, 115–143.
Bollen, Johannes, Brink, Corjan, 2014. Air pollution policy in Europe: quantifying the interaction with greenhouse gases and climate change policies. Energy Econ. 46 (November), 202–215. http://dx.doi.org/10.1016/j.eneco.2014.08.028.
Bond, Stephen., 2002. D Ynamic P Anel D Ata M Odels. Portuguese Econ. J. 1, 141–162. http://dx.doi.org/10.1007/s10258-002-0009-9.
Bonilla, David., 2009. Fuel demand on UK roads and dieselization of fuel economy. Energy Policy 37 (10), 3769–3778. http://dx.doi.org/10.1016/j.enpol.2009.07.016. Elsevier.
Brons, Martijn, Nijkamp, Peter, Pels, Eric, Rietveld, Piet, 2008. A meta-analysis of the price elasticity of gasoline demand. A SUR approach. Energy Econ. 30 (5), 2105–2122. http://dx.doi.org/10.1016/j.eneco.2007.08.004.
Bruno, G.S.F., 2005a. Approximating the bias of the LSDV estimator for dynamic unbalanced panel data models. Econ. Lett. 87 (3), 361–366. http://dx.doi.org/10.1016/j.econlet.2005.01.005.
Bruno, G.S.F., 2005b. Estimation and inference in dynamic unbalanced panel-data models with small number of individuals. Stata J. 5 (4), 473–500.
Bun, Maurice J.G., Kiviet, Jan F., 2003. On the diminishing returns of higher-order terms in asymptotic expansions of bias. Econ. Lett. 79 (2), 145–152. http://dx.doi.org/10.1016/S0165-1765(02)00299-9.
Burguillo-Cuesta, Mercedes, García-Inés, Marta Jorge, Romero-Jordan, Desiderio, 2011. Does dieselization favour a cleaner transport? Evidence from EU-15. Transp. Rev. 31 (5), 571–589. http://dx.doi.org/10.1080/01441647.2011.566378.
Burke, Paul J., Nishitateno, Shuhei., 2013. Gasoline prices, gasoline consumption, and new-vehicle fuel economy: evidence for a large sample of countries. Energy Econ. 36, 363–370. http://dx.doi.org/10.1016/j.eneco.2012.09.008.
Carslaw, David C., Beevers, Sean D., Tate, James E., Westmoreland, Emily J., Williams, Martin L., 2011. Recent evidence concerning higher NOx emissions from passenger cars and light duty vehicles. Atmos. Environ. 45 (39), 7053–7063. http://dx.doi.org/10.1016/j.atmosenv.2011.09.063.
Chay, Kenneth, Greenstone, Michael, 2003. The impact of air pollution on infant mortality: evidence from geographic variation in pollution shocks induced by a recession. Quart. J. Econ. 118, 1121–1167.
Creutzig, Felix, Mcglynn, Emily, Minx, Jan, Edenhofer, Ottmar, 2011. Climate policies for road transport revisited (I): evaluation of the current framework. Energy Policy 39, 2396–2406. http://dx.doi.org/10.1016/j.enpol.2011.01.062.
Currie, Janet, Neidell, Matthew, 2005. Air pollution and infant health: what can we learn from California's recent experience? Quart. J. Econ. 120, 1003–1030.
Dahl, Carol A., 1979. Consumer adjustment to a gasoline tax. Rev. Econ. Stat. 61 (3), 427–432.
Dahl, Carol A., 2012. Measuring global gasoline and diesel price and income elasticities. Energy Policy 41, 2–13. http://dx.doi.org/10.1016/j.enpol.2010.11.055.
Dahl, Carol., Sterner, Thomas., 1991. Analysing gasoline demand elasticities: a survey. Energy Econ. 13 (3), 203–210. http://dx.doi.org/10.1016/0140-9883(91)90021-Q.
Davis, Lucas W., Kilian, Lutz, 2011. Estimating the effect of a gasoline tax on carbon emissions. J. Appl. Economet. 26 (7), 1187–1214. http://dx.doi.org/10.1002/jae.1156.
De Boef, Suzanna, Keele, Luke, 2008. Taking time seriously. Am. J. Polit. Sci. 52 (1), 184–200.
EEA, 2015. Evaluating 15 years of transport and environmental policy integration – TERM 2015: transport indicators tracking progress towards environmental targets in Europe. http://dx.doi.org/10.2800/214970.
Espey, Molly, 1998. Gasoline demand revisited: an international meta-analysis of elasticities. Energy Econ. 20 (3), 273–295. http://dx.doi.org/10.1016/S0140-9883(97)00013-3.
EU Parliament and EU Council, 2009. Decision No 406/2009/EC on the effort of member states to reduce their GHG emissions to meet the community's GHG reduction commitment up to 2020. Official Journal of the European Union L 140/136, pp. 136–48.
European Commission, 2011a. A roadmap on moving to a Competitive low carbon economy in 2050. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Vol. COM(2011). http://dx.doi.org/10.1017/CBO9781107415324.004.
European Commission, 2011b. White paper – roadmap to a single European transport area – towards a competitive and resource efficient transport system.
European Union, 2015. Submission by Lithuania and the European commission on behalf of the European Union and its member states, intended nationally determined contributions of the EU and its member states.
Fowlie, Meredith, Holland, Stephen P., Mansur, Erin T., 2012. What do emissions markets deliver and to whom? Evidence from Southern California's NOx trading program. Am. Econ. Rev. 102 (2), 965–993.
Frondel, Manuel, Schmidt, Christoph M., Vance, Colin, 2011. A regression on climate policy: the European commission's legislation to reduce CO_2 emissions from automobiles. Transp. Res. Part A: Policy Pract. 45 (10), 1043–1051. http://dx.doi.org/10.1016/j.tra.2009.12.001.
Graham, Daniel J., Glaister, Stephen, 2002. The demand for automobile fuel: a survey of elasticities. J. Transp. Econ. Policy 36 (1), 1–26.
Harding, Michelle, 2014. The diesel differential: differences in the tax treatment of gasoline and diesel for road use. OECD Taxation Working Paper No. 21, OECD Publishing. http://dx.doi.org/10.1787/5jz14cd7hk6b-en.
Havranek, Tomas, Irsova, Zuzana, Janda, Karel, 2012. Demand for gasoline is more price-inelastic than commonly thought. Energy Econ. 34 (1), 201–207. http://dx.doi.org/10.1016/j.eneco.2011.09.003.
ICCT, 2014. Real-world exhaust emissions from modern diesel cars.
ICCT. 2015a. The European real-driving emissions regulation.
ICCT, 2015b. NOx control technologies for euro 6 diesel passenger cars: market penetration and experimental performance assessment (white paper). International Council on Clean Transportation, Washington.
IEA. 2014. "Energy Prices and Taxes - 1Q2014 End-Use Prices". International Energy Agency.
IPCC, 2014. Climate change 2014: Impacts, adaptation, and vulnerability. Part A: global and sectoral aspects. In: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L. L., (Eds.), Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Chapter 10, Table 10.9. Cambridge. Cambridge, United Kingdom and New York, NY, USA.
Johansson, Olof, Schipper, Lee, 1997. Measuring the long-run fuel demand of cars – separate estimations of vehicle stock, mean fuel intensity, and mean annual driving distance. J. Transp. Econ. Policy 31, 277–292.
Judson, Ruth A., Owen, Ann L., 1999. Estimating dynamic panel data models: a guide. Econ. Lett. 65, 9–15.
Kageson, Per, 2005. Reducing CO_2 emissions from new cars: a progress report on the car industry's voluntary agreement and an assessment of the need for policy instruments.
Kim, Young Duk, Han, Hyun Ok, Moon, Young Seok, 2011. The empirical effects of a gasoline tax on CO_2 emissions reductions from transportation sector in Korea. Energy Policy 39 (2), 981–989. http://dx.doi.org/10.1016/j.enpol.2010.11.026.
Liddle, Brantley., 2012. The systemic, long-run relation among gasoline demand, gasoline price, income, and vehicle ownership in OECD countries: evidence from panel cointegration and causality modeling. Transp. Res. Part D: Transp. Environ. 17 (4), 327–331. http://dx.doi.org/10.1016/j.trd.2012.01.007.
Malina, Christiane, Scheffler, Frauke, 2015. The impact of low emission zones on particulate matter concentration and public health. Transp. Res. Part A: Policy Pract. 77, 372–385. http://dx.doi.org/10.1016/j.tra.2015.04.029.
Melo, Patricia C., Ramli, Ahmad Razi, 2014. Estimating fuel demand elasticities to evaluate CO_2 emissions: panel data evidence for the Lisbon metropolitan area. Transp. Res. Part A: Policy Pract. 67, 30–46. http://dx.doi.org/10.1016/j.tra.2014.06.001.
Nam, Kyu-Min, Waugh, Caleb J., Paltsev, Sergey, Reilly, John M., Karplus, Valerie J., 2014. Synergy between pollution and carbon emissions control: comparing China and the United States. Energy Econ. 46 (November), 186–201. http://dx.doi.org/10.1016/j.eneco.2014.08.013.
New York Times, 2016. VW admits cheating in the U.S., but not in Europe. < http://www.nytimes.com/2016/01/22/business/international/vw-admits-cheating-in-

the-us-but-not-in-europe.html?_r=0 > .
Nickel, S., 1981. Biases in dynamic models with fixed effects. Econometrica 49, 1417–1426.
Norway, 2015. Norway's intended nationally determined contributions - submission by Norway to the ADP.
Ntziachristos, Leonidas, Samaras, Zissis, 2014. EMEP/EEA Air Pollutant Emission Inventory Guidebook 2013. EEA Publication. Vol. 1 A 3b-U. http://dx.doi.org/10.2800/92722.
Parry, Ian W.H., 2009. How much should highway fuels be taxed?" Discussion paper – resources for the future, no. RFF DP 09-52.
Pearce, David, 2003. The social cost of carbon and its policy implications. Oxford Rev. Econ. Policy 19 (3), 362.
Pesaran, M. Hashem, Smith, Ron, 1995. Econometrics estimating long-run relationships from dynamic heterogeneous panels. J. Economet. 68, 79–113.
Pesaran, M. Hashem, Shin, Yongcheon, Smith, Ron P., 1999. Pooled mean group estimation of dynamic heterogenous panels. J. Am. Stat. Assoc. 94 (446), 621–634. http://dx.doi.org/10.2307/2670182.
Pock, Markus, 2010. Gasoline demand in Europe: new insights. Energy Econ. 32 (1), 54–62. http://dx.doi.org/10.1016/j.eneco.2009.04.002.
Ramli, Ahmad Razi, Graham, Daniel J., 2014. The demand for road transport diesel fuel in the UK: empirical evidence from static and dynamic cointegration techniques. Transp. Res. Part D: Transp. Environ. 26, 60–66. http://dx.doi.org/10.1016/j.trd.2013.10.010.
Ravina, Enrichetta, 2005. Habit Persistence and keeping up with the joneses: evidence from micro data. < http://papers.ssrn.com/sol3/papers.cfm?abstract_id=1294189 > .
Reuters, 2015. France to consider phasing out diesel tax breaks: minister. < http://www.reuters.com/article/us-France-Diesel-idUSKCN0RY0T120151004 > .
Reuters. n.d. Volkswagen scandal. < http://www.reuters.com/subjects/volkswagen-Scandal > .
Roodman, David, 2009. Practitioners' corner: a note on the theme of too many instruments. Oxford Bull. Econ. Stat. 71 (1), 135–158. http://dx.doi.org/10.1111/j.1468-0084.2008.00542.x.
Schipper, L., Fulton, L., 2013. Dazzled by diesel? The impact on CO_2 emissions of the shift to diesels in Europe through 2009. Energy Policy 54, 3–10.
Scott, K. Rebecca, 2012. Rational habits in gasoline demand. Energy Econ. 34 (5), 1713–1723. http://dx.doi.org/10.1016/j.eneco.2012.02.007.
Tol, Richard S.J., 2008. The social cost of carbon: trends, outliers and catastrophes. Econ.: Open-Access, Open-Assessm. E-J. 2 (25). http://dx.doi.org/10.5018/economics-ejournal.ja.2008-25.
Tol, Richard S.J., 2011. The social cost of carbon. Annu. Rev. Resour. Econ. 3, 419. http://dx.doi.org/10.1146/annurev-resource-083110-120028.
Umweltbundesamt, 2015. Alte Diesel Müssen Schrittweise Raus Aus Der Innenstadt, vol. 48.
WHO Regional Office for Europe, and OECD, 2015. Economic cost of the health impact of air pollution in Europe: clean air, health and wealth. Copenhagen.
Wickens, M.R., Breusch, T.S., 1988. Dynamic specification, the long-run the estimation of transformed models. Econ. J. 98 (390), 189–205.