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Stick or Carrot? Asymmetric Responses to Vehicle Registration Taxes in Norway

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Abstract
Vehicle registrations have been shown to strongly react to tax reforms aimed at reducing CO_2 emissions from passengers' cars, but are the effects equally strong for positive and negative tax changes? The literature on asymmetric reactions to price and tax changes has documented asymmetries for everyday goods but has not yet considered durables. We leverage multiple vehicle registration tax (VRT) reforms in Norway and estimate their impact on within car-model substitutions. We estimate stronger effects for cars receiving tax cuts and rebates than for those affected by tax increases. The corresponding estimated elasticity is − 1.99 for VRT decreases and 0.77 for increases. As consumers may also substitute across car models, our estimates represent a lower bound.

Keywords CO_2 emissions intensity · New vehicles · Vehicle registration tax · Elasticity · Asymmetric response · Norway

1 Introduction

In the past decade, many European countries have reformed their taxes on vehicle purchases in order to reduce CO_2 emissions rates. Typically, the reforms consisted of positive and/or negative tax incentives, aimed at discouraging the purchase of high CO_2 emitting vehicles in favor of greener ones. Ex-post evaluations of these reforms generally show a quite successful shift toward lower CO_2 emitting vehicles and an increase in diesel shares, but little is known beyond average effects. We ask whether vehicle sales are affected symmetrically, meaning equally strongly, by positive and negative vehicle tax variations.

While these asymmetries have been empirically documented for everyday goods, no clear evidence is available for durables. As we discuss below, it is not obvious whether the results for non-durables may apply to costly goods like vehicles. In general, providing

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evidence on durables is complicated because of high product differentiation and data scarcity for actual transaction prices.

To gain empirical evidence for passenger cars, we leverage the 2007 and 2009 reforms of the Vehicle Registration Tax (VRT) system in Norway. In the relevant time period, registration taxes in Norway for different car models in our sample ranged between 12% and 75% of new vehicles prices. This places the country among those with the highest vehicle taxation in Europe [see Gerlagh et al. (2018) and Runkel et al. (2018) for an overview of similar policies in Europe]. Every car model is available in multiple versions, which differ in their CO_2 emission intensity (i.e. grams of CO_2 produced per kilometer driven) or other characteristics. Within car models, the Norwegian reforms *de facto* decreased vehicle registration taxes on car versions with low CO_2 emissions and increased them for those with higher emissions. We leverage such within-car-model heterogeneity in tax changes induced by the reforms to estimate the (within car model) elasticity of sales to taxes, in the spirit of Klier and Linn (2015). As our estimates only capture substitutions within the car models, they constitute a lower bound on the total effects.

The results highlight a strong asymmetry: while the estimated (within-car-model) elasticity for tax decreases is − 1.99, the elasticity for tax increases is only 0.77. The reform of 2009 additionally introduced a partial rebate for cars emitting less than 120 gCO_2/km.[1] Our estimates point again to a strong asymmetry: sales reactions to tax changes are stronger when the change involves a partial rebate. As we detail below, these results are particularly relevant for policy design: ignoring the higher elasticity of sales to tax reduction may lead to underestimating the impact of similar tax reforms on sales, especially for low emitting vehicles. In the case of Norway, the stronger reaction of sales to tax decreases might help explain the heterogeneous effects of the 2007 reform across different emissions ranges. In an ancillary exercise, we provide evidence of such heterogeneity by isolating within-car-model substitutions around the three CO_2 emission thresholds introduced with the 2007 reform. The patterns we observe are consistent with the reform inducing significant substitutions around the lower thresholds, where the tax on average decreased, and negligible around the highest threshold, where the tax on average increased.

Our work is most closely related to the growing literature on the effects of carbon taxation on passenger vehicles sales and usage in various EU countries and the US. While these can be estimated through structural and semi-structural models of consumers' demand (Berry et al. 1995; Stitzing 2016; Johansen, n.d.), a complementary strand of literature exploits quasi-experimental methods. Our study joins the latter strand, which has the advantage of relying on rather parsimonious assumptions and data requirements (Durrmeyer and Samano 2018; D'Haultfœuille et al. 2014; Gerlagh et al. 2018; Rogan et al. 2011; Alberini and Bareit 2019; Cerruti et al. 2019; Klier and Linn 2015).

The ex-post effects of the Norwegian VRT reforms are also investigated in Ciccone (2018) and Yan and Eskeland (2018). Using a pre-post design Ciccone (2018) shows that, by linking the VRT directly to CO_2 emissions, the 2007 reform contributed to the increase in the market share of new diesel vehicles and a decrease in those of high emitting vehicles. The author argues that this shift may be due to the fact that diesel engines, on average, have lower CO_2 emissions than petrol ones with similar power.

Yan and Eskeland (2018) estimate a negative average elasticity of CO_2 intensity to CO_2 taxes in the fleet and find that this is higher in smaller car segments.

[1] As detailed below, the VRT in Norway has three components: vehicles with very low emissions levels receive a partial rebate on the CO_2 component of the VRT, but the total VRT is never negative.

We complement their findings by studying the potential asymmetry in how sales respond to tax increases and decreases, providing empirical evidence that the elasticity of registrations is higher for tax decreases than increases. This asymmetry is not equivalent to simple heterogeneity across car segments because the reform did not affect the VRT in the same way for all vehicles belonging to the same segment. As a matter of fact, in each segment, the VRT increased for some vehicles and decreased for others. This difference is non-trivial, as the asymmetry goes against classical economics theory and speaks to the risks of overly generous incentives. Indeed, for any given targeted shift in the distribution of registrations by emissions, a VRT reform that ignores the asymmetric response of registrations to tax cuts and increases may result in overly generous tax cuts for low emitting vehicles. For example, in France, the *bonus/malus* reform of 2008 caused a higher than expected increase in total sales, emissions, and governmental expenses (D'Haultfœuille et al. 2014). Switzerland also introduced a bonus/malus system. However, leveraging tax variation over time and across administrative cantons, Alberini and Bareit (2019) find only limited evidence of any asymmetric reactions of sales to such changes. An essential difference between this study and ours is the type of taxes considered. While Alberini and Bareit (2019) focus on annual circulation taxes, we consider vehicle registration taxes, which in Norway are paid upfront and account for around 50% of the price of passenger vehicles. Hence, we expect a more substantial impact on sales and emissions in Norway from potential asymmetric reactions.

Our findings also add to the empirical literature on asymmetric reactions to price and tax changes, which highlights important asymmetries for everyday goods (Bidwell et al. 1995; Dargay 1991; Gately 1992; Dargay and Gately 1997; Gurumurthy and Little 1989; Kalwani et al. 1990; Bonnet and Villas-Boas 2016; Hymel and Small 2015).[2] It is possible that the (a)symmetry of elasticity depends on the price levels. For example, in the soda drinks market, Vespignani (2012) finds asymmetric elasticity for cheaper goods and symmetric for the more expensive ones (respectively, Pepsi and Coca-cola products). In summary, the fact that asymmetries exist for everyday goods does not necessarily imply that we should expect the same for more expensive goods such as vehicles. To the best of our knowledge, the present study is the first to generalize such results to durable goods.

Building on this literature, we additionally discuss several *mechanisms* which might explain the documented asymmetry. Based on (limited) available data, we do not find any evidence that the asymmetry is driven by salience or asymmetric pass-through of tax changes from car dealers to consumers. However, competition among car dealers might have induced them to provide consumers with non-price benefits to compensate them for tax increases.

This paper is structured as follows. We first describe the reforms (Sect. 2) and our data (Sect. 3) and methodology used (Sect. 4). We then present our main results on asymmetric reactions to tax changes with additional empirical evidence in their support (Sect. 5) and discuss possible mechanisms which might explain such asymmetries (Sect. 6). Before concluding, we discuss two critical caveats (Sect. 6.1). First, we document large anticipatory

[2] Specifically, Bidwell et al. (1995), Dargay (1991), Gately (1992), Dargay and Gately (1997) and Gurumurthy and Little (1989) argue that sales react more quickly or more strongly to price increases than decreases for everyday goods such as (respectively) phone calls, coffee and road transport fuel. Kalwani et al. (1990) and Bonnet and Villas-Boas (2016) argue quite the opposite: namely that consumers' demand for coffee reacts more to price decreases than increases. Closer to our context, Hymel and Small (2015) show that the elasticity of distance traveled on motor vehicles to fuel prices is higher in years when gasoline prices are rising than when they are falling.

responses to the announcement of the reform, leading to a + 27% increase in emissions with respect to our counterfactual simulation. Second, in light of the gaps between lab-based and consumers-reported emissions, the overall reduction in emission attributable to the reform might be overestimated by up to 30%.[3]

2 Context

Purchase, ownership, and usage taxes are generally used as economic instruments to affect car purchase and driving decisions. Between 2005 and 2011, many European countries focused their attention on vehicle taxes to reduce CO_2 emissions from road transport. Besides fuel taxes, the most common types of reform implemented in those years involved linking registration or circulation taxes directly to the CO_2 emission intensity of each car, reported by car makers.[4] While circulation and fuel taxes involve relatively small payments deferred in time, the VRT is a large upfront payment. In this sense, if consumers respond to large immediate costs and rewards more than to the discounted value of expected future streams of small expenditures and rewards (Thaler 1981; Laibson 1997), policymakers might prefer using the VRT.

In Norway, private vehicles are taxed at four levels: (1) the Vehicle Registration Tax (VRT) for new vehicles is a one-time fee paid at the moment of purchase, and it accounts for almost half of the retail price; (2) ownership taxes for passenger cars consist of a flat annual circulation fee; (3) a reclassification fee is applied to used vehicles; and (4) fuel taxes are determined by various factors including the CO_2 content of the fuel. Historically, the first three elements were primarily levied for state revenue, while fuel taxes are meant to compensate for road use, accidents, and other environmental costs. We consider the reforms introduced in January 2007 and 2009, which altered the structure of the VRT but not the other three tax levels. Until 2007 the VRT in Norway had three (stepwise linear) components, based on the vehicle's weight (measured in kg), engine power (measured in kW), and engine displacement (measured in cm^3 and also referred to as cylinder capacity or volume). The reform of 2007 replaced the engine displacement component with a CO_2 component (measured in gCO_2/km). The left panel of Fig. 1, from Ciccone (2018), shows this change.

The right panel shows that the new CO_2 component introduced in 2007 is stepwise-linear in the emission level, with discontinuities at three emission thresholds: 120 g, 140 g, and 180 g of CO_2/km). These thresholds create 4 bands of emissions: in 2007, each gram of CO_2/km up to 120 g is taxed approximately NOK 45, each additional gram up to 140 is taxed NOK 212, each additional gram till 180 is taxed NOK 558, and the remainder is taxed NOK1562 per gram. In addition, each vehicle is also still taxed proportionally to its weight and engine power. In 2009 a new major reform was implemented: a partial rebate of NOK 524 was introduced for all vehicles emitting below 120 g CO_2/km, and the unitary tax per gram of CO_2/km above 250 g was increased. Table 5 in the "Appendix" provides more details about the structure of the VRT and the relative weight of each component.

[3] The latter has received growing attention in the literature (Ewing 2017; Boudette 2017; Tietge et al. 2017; Fontaras et al. 2017a, b).

[4] The tax component is computed based on the official gCO_2/km values reported on a vehicle's matriculation booklet and is hence potentially prone to distortions due to imprecise measurements and unlawful reporting. We discuss this in more detail in Sect. 6.1.

Before the reform of 2007, differences in CO_2 emissions levels explained around 54% of the variation in the VRT due to their correlation with volume displacement, power, and weight. After the introduction of the CO_2 emissions component in the VRT in 2007, the share of variance explained raised to over 69%. With the introduction of fee-bates in 2009, the share slightly increased again (to 72%).

Most of the research evaluating similar policy reforms has focused on average or aggregate effects. In contrast, our empirical analysis in Sect. 5 reveals starkly heterogeneous effects. If the reforms raised awareness of environmental concerns, they could affect other vehicle fleet characteristics and possibly even driving patterns. As the inspection of aggregate data on fleet age, average mileage dimensions, and retirement of old vehicles in Fig. 10 in the "Appendix" reveals no evidence of such effects, in the remainder, we focus exclusively on registrations.

3 Data

The primary data used in this study were provided by the Norwegian Road Federation OFV AS.[5] The dataset contains information about all new passenger vehicles registered in Norway between 2005 and 2011, by month and municipality[6] In what follows, we refer to registrations and sales interchangeably. Our analysis also exploits additional data on the fleet size and total emissions by fuel and year and fleet age and number of scrapped vehicles by year, provided by Statistics Norway (SSB),[7] and monthly average fuel prices and fuel taxes, provided by the Institute of Transport Economics (TØI).[8]

Table 1 shows the evolution over time of the characteristics of new vehicles registered between 2005 to 2011.[9] The total number of new cars sold in a year ranges between 98,640 in 2009 (in the aftermath of the global economic crisis) and 138,312 in 2011. The average weight, engine volume, and power fluctuate but do not show any clear change over time, suggesting that sales did not significantly shift to "smaller" or bigger vehicles.[10]

In 2005, the share of diesel vehicles in Norway (30%) was in line with other European countries (27% in the EU28 area). In general, an improvement in consumers' perception of diesel engines in Norway has been noticed since the early 2000s, in particular in terms of durability, modernity, and user-friendliness, and the lower costs of diesel fuels probably supported this shift (Fridstrom and Østli, 2021).[11] Starting from 2007, diesel shares

[5] OFV AS stands for *Opplysningsrådet for Veitrafikken AS*, more details can be found at http://ofvas.no/.

[6] In the time period which is relevant for our analysis, there were 428 municipalities in Norway. Because electric, gas, hydrogen and hybrid vehicles make up for only about 5% of observations in our data and because our focus is on CO_2 and NO_x emissions, we exclude these fuels from our analysis.

[7] Statistisk Sentralbyrå, www.ssb.no. Each graph and Table lists the specific source of the data.

[8] More information at www.toi.no.

[9] Summary statistics for the entire period of observation, not broken down by year, are shown in Table 8 in the "Appendix".

[10] Ciccone (2018) estimates a small but statistically significant engine size increase right after 2007 associated with the reform, while average weight was virtually unchanged.

[11] Consumers perceptions (and the trend in the market share of diesel vehicles) changed after a significant contamination accident in the city of Bergen in 2011 (Strand et al. 2010), subsequent scientific investigations of the gap between real-world and laboratory-measured NOx emissions (Hagman et al. 2015) and the "dieselgate" of 2015. As a consequence, the VRT was reformed to include a component directed discouraging the purchase of high emitting NOx vehicles (2012). Moreover, local diesel bans and circulation fees for diesel cars were imposed contributing to further deter in diesel sales.

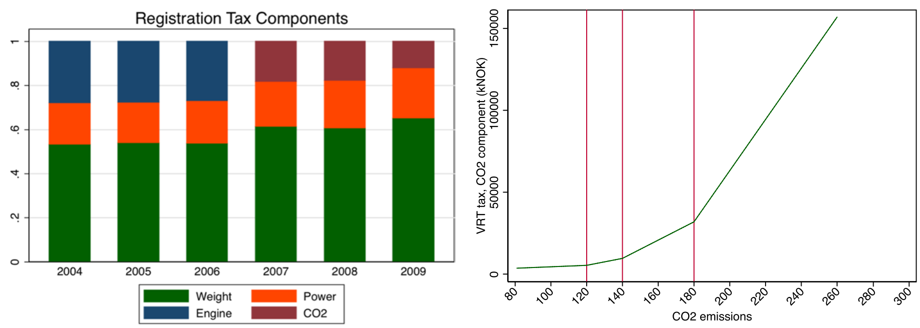

Fig. 1 Tax composition. Left panel shows the VRT replacement of the engine displacement component with the CO_2 component. *Source*: Ciccone (2018). Right panel: the CO_2 component introduced in 2007 is stepwise-linear with three thresholds: 120 g, 140 g, and 180 g of CO_2/km

increased even faster in Norway than in the rest of Europe, reaching a peak of around 80% in 2010 (35% in the EU28 area). We believe that this acceleration is linked, at least in part, to the 2007 VRT reform.[12] While the shift in diesel share is relevant,[13] it does not affect our main findings: even within each fuel category we find evidence of a significant shift towards lower-emitting vehicles and particularly strong reactions to VRT decreases (Fig. 12).[14]

Table 1 also shows a slow and steady decrease over time in the average CO_2 emissions of newly registered cars: in Sect. 6.1 we compare this decrease to the patterns of aggregate emission levels (from both new and old vehicles). Additional fleet characteristics are shown in Table 7 (distribution of relevant vehicle characteristics), Tables 15 and 16 (average and total polluting emissions) and Fig. 7 (total sales of new diesel and petrol passenger cars, by month), Fig. 10 (mileage, scrapped vehicles, and fleet size) and Fig. 11 (distribution of car specifications available for purchase) in the “Appendix”.

As detailed in Table 2, our data covers a total of 431 different models, 5412 different vehicles, and 4765 specifications. We define vehicles as unique combinations of model and CO_2 emissions level, and specifications as unique combinations of model, number of doors, cylinder volume, engine power, gear, and fuel.

[12] As pointed out by Ciccone (2018), by linking the VRT directly to CO_2 emissions, the reform *de facto* promoted the sales of diesel vehicles, which have relatively lower CO_2 emissions, for similar engine power levels. Our analysis offers additional support to this hypothesis: Fig. 8 shows that diesel shares sharply decrease after the announcement of the reform in late 2006 (possibly an anticipatory effect) and increase after its introduction. In addition, Table 9 documents the existence of significant gaps in emission intensities by fuel, when holding other engine characteristics fixed. To the best of our knowledge, fuel taxes and prices remained relatively constant in Norway around 2007 and there was no other policy change that could explain the sharp increase in diesel shares.

[13] Similar effects have also been documented for the EU markets (Gerlagh et al. 2018).

[14] Figure 12 documents a significant shift towards lower emissions for vehicles of each fuel type. Re-estimating our main specifications by fuel type (or further interacting our main regressor “Additional Effect when Tax decreases” with a Diesel indicator) confirms that the asymmetry is not driven by heterogeneous effects by fuel. In other words, even if we focus solely on diesel cars (or solely on petrol ones), the within car-model elasticity of registrations is still higher for vehicles experiencing a tax reduction than for those with a tax increase. Results available upon request.

Table 1 Average characteristics, by year

	Numb. new car	CO_2	Weight	Engine power	Engine size	Share of diesel
2005	109,846	173.434	1306.605	80.800	1689.092	.304
2006	109,098	191.284	1427.421	95.574	1854.377	.373
2007	129,121	155.991	1390.725	84.128	1806.091	.761
2008	110,540	151.357	1393.267	85.386	1766.988	.781
2009	98,640	146.196	1400.483	86.673	1778.966	.748
2010	127,721	135.014	1371.466	83.397	1703.609	.784
2011	138,312	132.324	1389.64	85.255	1690.246	.786
Average	118,787	156.010	1384.771	86.164	1759.202	.645

The table shows the average characteristics, weighted by the number of cars registered, for each year between 2005 and 2011. Given the timeline of the reforms, only data from 2006 till 2009 is used for estimation

In our main analysis, the unit of observation is the model-quarter (15,249 observations from 2005 to 2009), and we aggregate our data at the national level because none of our regressors of interest (tax and fuel prices) varies across municipalities.[15]

In Sect. 5, we focus on narrow emissions ranges and investigate the trends in registrations above and below each emission threshold in 2006 and 2007. In this ancillary analysis, we use non-aggregated data at the model-month-municipality (8668 observations from 2006 to 2007) to avoid small sample bias.[16]

4 Methodology

Our identification strategy exploits within model variation in the size of VRT changes (due to different versions of the same model having different emission levels) to estimate the tax elasticity of registrations of new vehicles through the linear equation in first differences

$$\Delta \ln q_{jt} = \alpha \Delta T_{jt} + \beta \Delta FC_{jt} + \theta_{mt} + \epsilon_{jt}, \tag{1}$$

where q_{jt} is the number of new cars registered for each quarter t and vehicle (j), and Δ denote first differences.[17] The model, to be estimated on data aggregated at the *vehicle* and quarter level, captures the relation between the (first difference) change in total registration tax T and the (first difference) change in the number q of new cars registered (in

[15] Using quarterly observations in our main analysis facilitates the comparison of our results to previous studies and smooths away model-month fluctuations and possible measurement errors, while still preserving most of the tax variation (Klier and Linn 2015).

[16] In this ancillary analysis, we restrict the sample to registrations in the time period 2006–2007 and in the emissions ranges 115–125, 135–145, and 175–185 gCO_2/km. For this exercise, aggregating data at the model-quarter level would leave us with a limited sample size. Hence, we use data at the model-month-municipality level. Although taxes do not vary across municipalities, there is still variation in the number of registrations. This variation is valuable as the focus of the ancillary analysis is on the description of changes in registrations trends, and not on explicitly estimating the impact of taxes.

[17] *Vehicles* are defined by unique combinations of brand, model, and CO_2 emission. As we discuss in the Results section, estimating the equation in levels yields qualitatively similar results (estimates available from the authors upon request).

Table 2 Sample composition

Aggregation level	No. observations
No. of models	431
No. of models/CO_2 emission level combinations	5412
No. of specifications	4765

Data for the entire period of observation (2001–2011). A *specification* is defined as a unique combination of model, number of doors, cylinder volume, engine power, gear, and fuel. Given the timeline of the reforms, only data from 2006 till 2009 is used for estimation

logarithm). It does not separately identify changes in demand and supply. The vector θ_{mt} contains model-year-quarter fixed effects, FC_{jt} is the (first difference) change in fuel cost of a vehicle (per 100 km). The residuals (ϵ_{jt}) are clustered at the segment-quarter level to allow for correlation within quarter and market segment.[18] The tax coefficient (α) is identified off variation in VRT within car models (1) over time (by first differences) and (2) across different versions of the same car model (by car model fixed effects). By comparing registrations across different versions of the same car model, we address the concern that the VRT might correspond to a higher share of the total price for low emitting cars.[19]

Section 5 presents estimates of the above equation for our entire sample and for the subsamples of (1) vehicles whose VRT increased and (2) vehicles whose VRT decreased. To explicitly test whether the tax effect differs across the two subsamples, we then extend the equation as follows:[20]

$$\Delta \ln q_{jt} = \alpha \Delta T_{jt} + \lambda \Delta T_{jt} \cdot TaxDown_{jt} + \beta \Delta FC_{jt} + \theta_{mt} + \epsilon_{jt}, \tag{2}$$

where the binary variable *TaxDown* takes value 1 for vehicles whose VRT decreased with respect to the previous year, and zero for those whose VRT increased. The tax effect on registrations is captured by the coefficient α for vehicles whose VRT increased, and by $\alpha + \lambda$ for vehicles whose VRT decreased. If equilibrium registrations react to tax decreases more (less) than to tax increases, we expect λ to be negative (positive).[21]

If registrations react to VRT reductions more than to increases, they might react even more to the partial rebates introduced in January 2009 for cars emitting less than 120 g CO_2 per kilometer. To check this prediction, we further interact the tax and a binary variable for partial rebates:

[18] Segments and models are relevant because differences across vehicle segments explain about half of the variation in VRT across vehicles, and differences across models around 80% (the model captures a good portion of the variability in weight and power).

[19] Because such effect is common to all versions of the same car model, it is captured by the car-model fixed effects in θ_{mt}.

[20] In addition, we also estimated the following version of Eq. 2:

$$\Delta \ln q_{jt} = \alpha \Delta T_{jt} + \kappa \cdot TaxDown_{jt} + \lambda \Delta T_{jt} \cdot TaxDown_{jt} + \beta \Delta FC_{jt} + \theta_{mt} + \epsilon_{jt},$$

which yields qualitatively similar results, available upon request.

[21] By including car-model fixed effects, we identify variations in equilibrium sales with respect to the car-model average over time. To the extent that different versions of the same car model are substitutes, the VRT increase on one specific version might affect demand and sales for the other versions of the same car model, and possibly for different models. In terms of evaluating the overall impact of the reform, we focus on the resulting sales and not on the patterns of substitution within and across car models.

$$\Delta \ln q_{jt} = \alpha \Delta T_{jt} + \pi \Delta T_{jt} \cdot feebate_{jt} + \beta \Delta FC_{jt} + \theta_{mt} + \epsilon_{jt} \tag{3}$$

The main coefficients of interest are α, capturing the average change in log sales in response to tax changes for all vehicles not receiving a partial rebate, and π, capturing the extra effect for vehicles receiving a partial rebate.[22]

For the first time in Norway, the reform of 2007 introduced the use of CO_2 emission thresholds. In an ancillary analysis, we leverage its piece-wise linear structure to show that its effects were highly heterogeneous across CO_2 emissions levels. More precisely, we estimate the number of registrations for each vehicle i and month t from January 2006 to December 2007 via ordinary least squares on the following equation

$$\begin{aligned} q_{imt} =& \alpha \cdot AboveC_c + \gamma \cdot After2007 + \delta \cdot (AboveC_c \cdot After2007) \\ &+ \beta X_i + \Theta_{ijt} + \mu_{imt}, \end{aligned} \tag{4}$$

To exploit the discontinuity of VRT at the thresholds 120, 140, and 180 g CO_2, we estimate the equation separately for vehicles emitting in the ranges 115–125, 135–145 and 175–185 gCO_2/km.[23] In the equation, c is the relevant CO_2 threshold, $AboveC_c$ is a binary variable taking value one if the emission rate of the given vehicle is within 5 g above the cut-off C_c, and zero if it is within 5 g below it. The binary variable $After2007$ equals one for all months in 2007, and zero for those in 2006. The matrix X_i includes vehicle characteristics and the matrix Θ_{ijt} includes county, month-and-year, segment, and model-by-quarter fixed effects.[24] The inclusion of model-by-quarter fixed effects implies that our identification exploits variations in emissions (and therefore in the reform effect on the VRT) within models and quarters. In other words, we identify substitutions across different versions of the same car model, which is a lower bound on the total effect of the reform. Our estimates do not capture any substitutions across different vehicle models (or even across segments, from SUV to compact cars, for example) possibly induced by the reform. To confirm that our estimates capture a general pattern that also characterizes the choice across different car models, in "Appendix 3" we replicate the estimation including only segment-quarter fixed effects. Additional robustness checks, with logarithmic transformations and with larger CO_2 emissions ranges across each threshold are presented in "Appendix".

5 Results

As previously pointed out, our methodology does not aim to separately identify the demand or supply reactions, but rather the response of equilibrium registrations of new passenger cars to increases and decreases in the VRT. We do so by estimating Eqs. 1, 2, and 3 on data aggregated at the vehicle-quarter level.

[22] In this specification, tax increases and decreases are captured by ΔT_{ij} and their (symmetric) effect is hence given by α.

[23] While we could theoretically repeat the same analysis for the reform of 2009, graphical inspection suggests a violation of the parallel trends assumption in 2008, possibly due to longer-run effects of the 2007 reform. We, therefore, prefer not to use our simple econometric model, which relies on parallel trends, to quantify the effect of the reform of 2009.

[24] County fixed-effects absorb any regional differences which are stable over time and the month-and-year fixed effects capture the general time trends and isolate them from the effect of the reform.

Estimates for Eq. 1 on the entire sample, covering registrations from January 2006 to December 2009, are reported in Column (1) of Table 3. The estimated tax coefficient is − 0.008 and is significant at the 1% level. In absolute values, the corresponding elasticity of car registrations at the sample means is equal to − 1.37, implying that, on average, a 1% increase in VRT corresponds to a 1.37% decrease in registrations.[25]

Let $\overline{T}$ represent the average VRT in the sample. Under standard assumptions of symmetry and given our estimates, we should then expect registrations to increase by 1.37% if the VRT decreases from $\overline{T}$ to $\overline{T} - 1\%$, and to decrease by the same 1.37% amount if the VRT increases from $\overline{T} - 1\%$ to $\overline{T}$. As we mention in the introduction and discuss in more detail in Sect. 6, there are many reasons to expect elasticity to be asymmetric in our context.

Re-estimating Eq. (1) on the subsample of vehicles experiencing an increase in VRT yields the estimates in Column (2) of Table 3. The estimated α (− 0.004) appears smaller than the estimate in Column (1). On the other hand, the estimates for the subsample of vehicles experiencing a decrease in VRT, shown in Column (3), suggest a higher sensitivity to VRT changes (− 0.012). The resulting estimated elasticities of registrations (in absolute values) are 0.77 for the subsample of passenger vehicles affected by a VRT increase and 1.99 for those affected by a decrease.

To test whether the two coefficients are statistically different, we estimate Eq. (2) and report the results in Column (4) of Table 3: the estimated VRT effect for vehicles experiencing a tax increase is captured by α (estimated to be − 0.006, statistically significant at the 1% level), while for tax decreases it is the sum of $\alpha + \lambda$. The estimated λ is − 0.008, only statistically significant at the 10% level, making the total effect of a unitary tax decrease − 0.014.We interpret this as further (statistically weak) evidence that registrations react more to VRT decreases than to increases. Re-estimating Eqs. (1) and (2) in levels (rather than first differences) yields qualitatively similar results: the tax effect on sales is significantly larger for vehicles experiencing a tax decrease.[26]

Given such evidence, we estimate Eq. 3 on our sample to check whether registrations react more strongly to partial rebates. While a tax decrease implies that the buyer of a specific vehicle (model-emission) would pay a lower tax than the one applied on the same vehicle one quarter earlier, a partial rebate implies that the buyer would not pay any CO_2 component of the VRT and even receive a transfer. The latter can be more salient to the buyer. Column (5) of Table 3 shows the resulting estimates: a tax change of 1NOK is associated with a 0.8% increase (captured by coefficient $-\alpha$) in registrations, while a 1NOK rebate is associated with a 5.3% ($-\alpha - \pi$) increase.

While our results underline a statistically significant asymmetry in reactions to tax increases and cuts or rebates, one might wonder whether this makes any quantitative

[25] The elasticity is computed by multiplying the tax coefficient by the average tax in the estimation sample. Our estimated coefficient and elasticity in Column (1) of Table 3 are comparable to those obtained in the literature on similar data covering registrations in Norway between 2006 and 2014 (Yan and Eskeland 2018). As a means of comparison, structural model estimates of own-price elasticity for diesel and petrol vehicles in Norway are around − 3.43 (Johansen, n.d.). When comparing our estimates to those obtained from structural models, it should however be noted that the latter typically estimate the elasticity of demand, while our method identifies the elasticity of sales in equilibrium. Furthermore, our method captures substitutions within car models, while structural models can differ, depending on the specific modeling assumptions.

[26] A direct comparison of estimated coefficients is complicated by the fact that while taxes and sales are always positive, changes in either of the two can take any sign. For this reason, we do not report the estimates from the models in levels, but these results are available upon request.

Table 3 Asymmetric tax response

	(1) Eq. (1)	(2) Tax up	(3) Tax down	(4) Eq. (2)	(5) Eq. (3)
Tax effect (α)	– 0.008***	– 0.004***	– 0.012***	– 0.006***	– 0.008***
	(0.003)	(0.001)	(0.004)	(0.002)	(0.003)
Fuel costs	– 0.002	– 0.016	0.016	0.013	– 0.005
	(0.023)	(0.028)	(0.038)	(0.027)	(0.024)
Additional tax effect when tax down=1 (λ)				– 0.008*	
				(0.004)	
Additional tax effect when feebate=1 (π)					– 0.084***
					(0.020)
Constant	– 0.110***	– 0.185***	– 0.117***	– 0.155***	– 0.113***
	(0.004)	(0.018)	(0.028)	(0.017)	(0.004)
No. observations	15,249	3,923	5,060	8,983	15,249
R^2	0.068	0.184	0.102	0.096	0.068
Average tax	170.4	185.16	162.9	–	–
Elasticity	– 1.37	– 0.77	– 1.99	–	–

Dependent variable: natural logarithm of the number of new passenger cars registered, by model, CO_2 emission, and quarter. By construction, Columns (2), (3), and (4) only include vehicles observed in two consecutive quarters between 2006 and 2009, while Column (1) exploits the entire sample for 2006–2009. Standard errors, in parentheses, are clustered at the segment-quarter level

$^*p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$

difference from a policy perspective. To answer this question, in Fig. 2, we present a “goodness of fit” plot for new vehicle registrations. The three lines show the residual registrations (defined as actual registrations minus estimated registrations) based on our baseline model (Eq. 1, estimates shown in Column (1) of Table 3), the asymmetric model for tax cuts (Eq. 2, estimates shown in Column (3) of Table 3) and the model with fee-bates (Eq. 3, estimates shown in Column (5) of Table 3).

The graph suggests that the baseline model tends to underestimate vehicle registrations and that both asymmetric models (and the fee-bate model in particular) fit the registrations better. The improvement is particularly striking for low emission vehicles, most of which experienced VRT tax cuts and partial rebates, and has important implications for the optimal design of VRT schedules.

We can compare alternative VRT reform schedules based on their effect on tax returns and pollution. In light of our findings, for any given targeted shift in the distribution of registrations by emissions, a VRT reform that ignores the asymmetric response of registrations to tax cuts and increases will result in overly-generous tax cuts for low emitting vehicles. Therefore, the resulting tax returns on such vehicles will be too low, with respect to an “ideal” reform that takes into account the asymmetry.

5.1 Additional Supporting Evidence

This section offers graphical and then econometric support of heterogeneous effects of the 2007 reform in the emission ranges around the thresholds. Figure 3 compares the time series of new registrations for passenger vehicles emitting within a range of 5 gCO_2/km

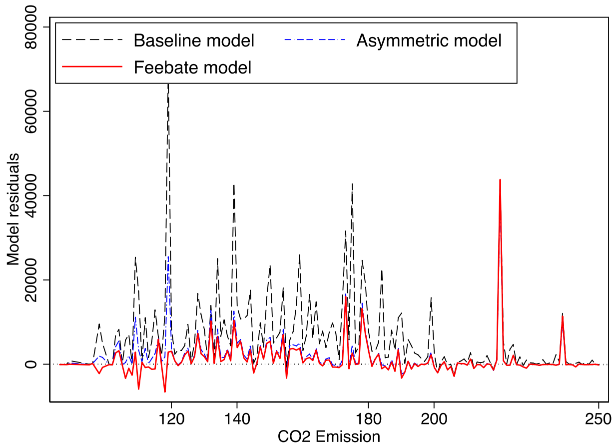

Fig. 2 Goodness of Fit: Actual and Predicted registrations, by CO_2 Emissions. *Note*: The graph shows the actual and predicted sales of vehicles in the period 2006–2009, by CO_2 emission level. Specifically, the *Baseline model* is the difference between actual registrations and the predicted values from the baseline model without interaction terms, the *Asymmetric model* is the difference between actual registrations and predicted values from Eq. 2, and the *Feebate model* is the difference between actual registrations and predicted values from Eq. 3

below and above each of the three thresholds, between January 2006 and December 2007, where each panel corresponds to one threshold. The top panel hence includes vehicles emitting in the range 115–125 CO_2/km (most sold model: Volkswagen Golf) and the bottom one those in the range 175–185 gCO_2/km (most sold model: Mitsubishi Outlander). In 2006, about 22% of all new passenger vehicles sold were in these ranges, in 2007 about 28%. It should be noted that, on average, the registration tax decreased for cars in the top two panels and increased for those in the bottom panel. The average change in tax for each emission range 2006 and 2007 is reported in brackets in the legend of Fig. 3 (for example, for cars emitting between 115 and 120 gCO_2/km, it is -15,000 NOK). Based on our findings on asymmetric reactions to tax changes, we should therefore expect to notice a larger reaction to the reform in the top two panels.

Looking at each of the three panels separately and comparing the time series for cars below and above the thresholds, we notice approximately parallel trends up to 2007 and a divergence afterward, which we interpret as due to the reform. Clearly, both sales above and below the threshold may be (and likely are) affected by the reform, and neither of the two is interpreted as a counterfactual. By comparing sales above and below the thresholds, we do not intend to (quantitatively) estimate the impact of the reform. However, the comparison provides suggestive (and qualitative) evidence that the reform had opposite effects on either side of each threshold, consistent with substitution happening from vehicles above the thresholds towards vehicles below them. Furthermore, such divergence is especially apparent for the lower emissions ranges (top two panels), where VRT on average decreased. This pattern is consistent with our finding that sales react to tax decreases more than to increases.[27]

The OLS estimates for Eq. 4 in Table 4 confirm this impression.[28] In this difference-in-difference-inspired approach, the estimated coefficients are not to be interpreted as an

[27] Specifically, in each of the two top panels we notice mostly parallel trends above and below the thresholds until 2007. In the same panels in 2007 we notice an increase in sales of cars below the thresholds with respect to those above. In the bottom panel, the dynamic appears to be different: in 2007 there is no jump for sales of cars below the threshold, but a sharp decrease for those above the threshold.

[28] Registrations are by definition non-negative and their distribution is therefore censored at zero, introducing non-linearity in the model, which we ignore in our preferred specification. We also estimate Eq. 4 via tobit, getting qualitatively similar results, available on request.

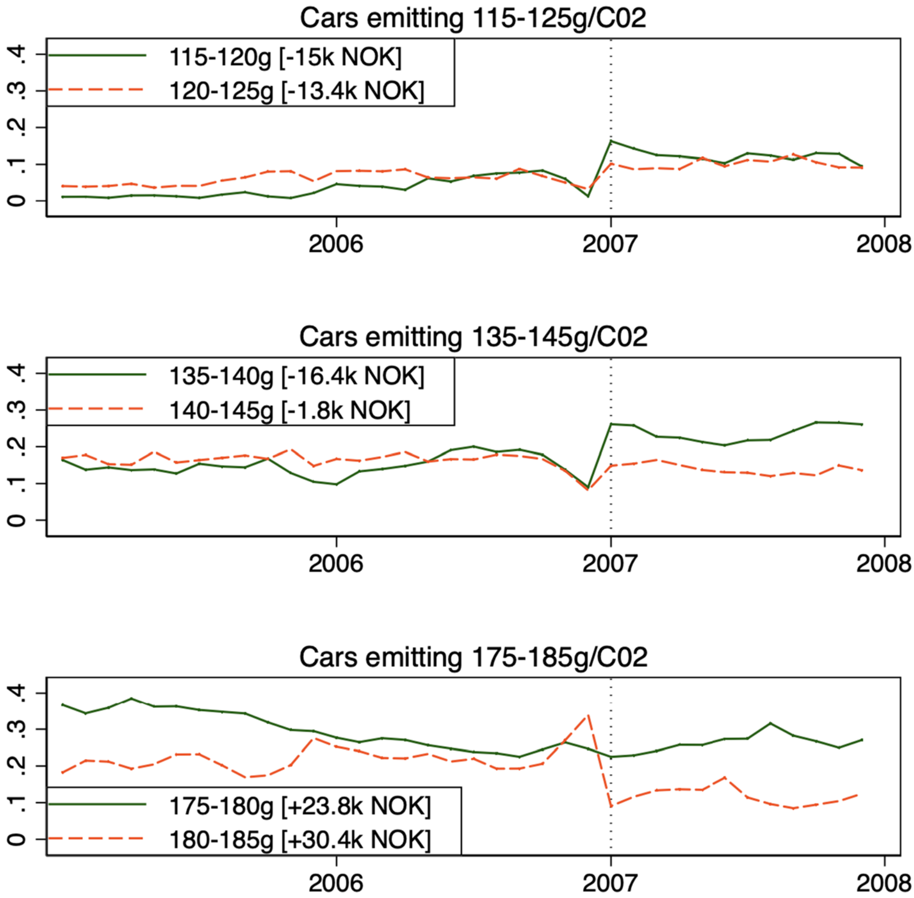

Fig. 3 Market share of new vehicles registered, by CO_2 intensity category. *Note*: Categories are defined around the three thresholds used for the registration tax: 120 ± 5, 140 ± 5 and 180 ± 5 g CO_2. The average change in VRT, weighted by new registrations, is displayed in brackets in the panel legend. In 2007, the best-selling models in each top panel are: Peugeot 207 (top panel, emission range 115–125 gCO_2/km), Volkswagen Golf (mid panel, emission range 135–145 gCO_2/km), and Mitsubishi Outlander (bottom panel, emission range 175–185 gCO_2/km). The vertical axis shows the market share for each emission range

average treatment effect of the reform. Rather, we interprete them as the difference in trends for vehicles above and below each threshold while holding the observable characteristics in Θ and X fixed (all characteristics are listed in the table). Given the presence of Quarter*Model fixed effects, Eq. 4 identifies substitutions across different versions of each car model.

The coefficients α and γ capture the simple differences. Namely, γ captures the average difference in registrations between 2007 and 2006 for cars below the threshold (solid green lines in Fig. 3), and α the pre-reform differences between vehicles just below and just above each threshold (the gap between the dashed orange and the solid green lines in each panel of Fig. 3, before 2007). The coefficient δ captures the double-difference. The double-difference is the change from 2006 to 2007 in the difference of registrations of vehicles

Table 4 Impact on registrations around the tax thresholds, 2006–2007

Eq. (4): $Sales = \alpha AboveC + \gamma \cdot After2007 + \delta \cdot (AboveC \cdot After2007) + \delta \cdot X + \mu$

	Subsample: 120 g±5		Subsample: 140 g±5		Subsample: 80 g±5	
δ	− 0.29*	− 0.30**	− 0.30***	− 0.14*	− 0.04	0.08
	(0.12)	(0.11)	(0.08)	(0.06)	(0.07)	(0.09)
α	− 0.00	− 0.13	0.26**	0.10	0.02	− 0.06
	(0.08)	(0.09)	(0.08)	(0.08)	(0.07)	(0.09)
γ	0.35*	0.36*	0.03	0.01	− 0.63	− 0.59
	(0.15)	(0.15)	(0.19)	(0.19)	(0.45)	(0.43)
Constant	1.22***	5.07***	1.27***	3.59***	2.38***	− 2.09***
	(0.27)	(1.10)	(0.31)	(0.72)	(0.40)	(0.62)
County FE	✓	✓	✓	✓	✓	✓
Month FE	✓	✓	✓	✓	✓	✓
Quarter*model FE	✓	✓	✓	✓	✓	✓
Segment FE	✓	✓	✓	✓	✓	✓
No. of doors FE		✓		✓		✓
Gear FE		✓		✓		✓
Brand FE		✓		✓		✓
Body FE		✓		✓		✓
Driving axel FE		✓		✓		✓
Weight		✓		✓		✓
Power KW		✓		✓		✓
No. obs.	8668	8668	16,504	16,504	18,757	18,757
No. car specifications	81	81	172	172	259	259
R^2	0.10	0.11	0.08	0.09	0.12	0.13

Dependent variable: number of vehicles sold, by municipality and month

*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$. Standard errors, in parentheses, are clustered at the municipality level.

just below and just above the relevant threshold (the change in the gap between the orange dashed line and the green solid line, from before to after the reform of 2007). The negative sign of the estimated δ can be due to an increase in sales above the thresholds, a decrease in sales below the thresholds, or both. The fact that the estimated δ is statistically significant in Columns (1) to (4) is consistent with within-car-model substitution from vehicles emitting above the 120 and 140 gCO_2/km thresholds towards vehicles emitting below them. For vehicles emitting around the 180 gCO_2/km we find no supportive evidence of a similar substitution. To the extent that the substitutions can be interpreted as due to the reform, the results in Table 4 are consistent with the expectation that the reform has stronger effects on sales for cars experiencing a tax decrease (emission ranges 115–125 and 135–145 gCO_2/km) than for those experiencing an increase (emission range 175–185 gCO_2/km).[29]

[29] It is worth stressing that these estimates, like the previous ones, capture the impact on new registrations in equilibrium, rather than an impact on consumers demand, because the availability of palatable substitute cars and the marketing strategies of sellers also play a role in determining sales and registrations, and are unobservable. However, the average number of versions available per car model is not driving the fact that most substitutions are found in the lower two ranges: if anything, the average number of versions available for each car model is higher in the 175–185 g range of CO_2 emissions.

6 Discussion

Our estimates provide evidence that sales react to changes in VRT in a highly asymmetric fashion: the percentage change in new registrations linked to unitary VRT cuts is bigger than the percentage change in sales linked to unitary VRT increases. In addition, the relatively small rebates had a large impact on registrations. As our estimates are based on within-car model comparisons, it should be clear that such asymmetries cannot be driven by differences across market segments or car attributes.

In this section, we first discuss several possible interpretations of the asymmetry and then focus on the environmental impact of the reforms.

A review of the literature on promotions, marketing, and car markets suggests several mechanisms that could explain the asymmetry and have different economic and policy consequences. We group these mechanisms in three categories, depending on the main actors they involve: consumers, who might exhibit behavioral biases; manufacturers, who might alter production in response to the reforms; car dealers, who might alter their marketing behavior. While available data does not allow a systematic test of these mechanisms, we discuss suggestive evidence for each.

Consumers The economics and psychology literatures suggest several reasons why consumers may react asymmetrically to tax increases and decreases. As our data suggest stronger reactions to tax decreases, we ignore the mechanisms predicting the opposite (such as prospect theory).[30] Among the mechanisms compatible with our evidence, the main one is salience: sales might react more to tax decreases if these are more salient to consumers than tax increases. However, salience probably did not play a decisive role in our setting, since total prices shown at purchase include the VRT and, as we detail in Sect. 6.1, the media widely covered the reforms. Therefore, we believe that consumers were well aware of the reforms and their effects on the VRT.[31]

Car Producers The reaction to tax decreases might be amplified by producers' response. Specifically, if producers start offering more car versions that qualify for tax cuts (Klier and Linn 2015), this would result in more options to satisfy consumers' non-pecuniary tastes and potentially more sales. While this mechanism may play a role in countries with

[30] Prospect theory posits that the utility associated with a bundle depends on the consumer's individual reference point and on whether such bundle is a loss or gain relative to such reference point. Typically, loss aversion is observed: consumers react to perceived losses more than to gains. In our context, prospect theory could explain the asymmetries we observe if the reference points were such that tax cuts are perceived as losses. As it is more likely that consumers perceive tax increases as losses and tax reductions as gains, we do not believe loss aversion to be the driving mechanism in our context.

[31] The importance of salience in shaping consumers' responsiveness has been underlined in empirical and laboratory evidence on everyday goods (Chetty et al. 2009; Finkelstein 2009; Blattberg et al. 1995) and for private vehicles (Busse et al. 2013). In particular, Chetty et al. (2009) find that consumers' demand underreacts to tax adjustments when the sale tax is not highlighted but decreases by nearly the same amount as an equivalent price increase when the sales tax is listed in the price tag (making it more salient). Similarly, Finkelstein (2009) finds that driving is less elastic under electric than under manual toll collection, with the second being arguably more salient. Busse et al. (2013) show that retail consumers devote limited attention to used vehicle mileage so that the first digit of an odometer reading is more salient than the subsequent digits. Somewhat related to salience is the possibility that car dealers might have advertised tax cuts and increases differently: we come back to this possibility below.

local car manufacturers, Norway is a small market with no domestic producer. Therefore, it is unlikely that the availability of car versions shifted in response to the reform, especially in the short-medium run. Indeed, graphical (Fig. 11) and econometric (Table 14) analyses of the distribution of available vehicles over time offer no evidence that suppliers reacted to the VRT reform by offering a greater variety or number of qualifying vehicle versions.[32]

Car Dealers and Intermediaries may pass on tax incentives to consumers asymmetrically to capture a share of the surplus created by tax incentives if they have better information or higher bargain power than consumers. However, the resulting asymmetry would be the opposite of what we observe, with stronger reactions of sales to tax increases. Analogous asymmetries were documented in the pass-through of discounts for the car market, and of changes in taxes and production costs for non-durable everyday goods.[33] To empirically test whether the pass-through of tax incentives on prices is higher for tax decreases than increases, we focus on the within-model correlation between changes in prices and changes in VRT, which we interpret as a proxy for pass-through.[34] The hypothesis is empirically rejected since the estimated correlation is statistically the same (and numerically higher) for the subsample of vehicle specifications experiencing a VRT increase as in the sample experiencing a VRT decrease (Table 13 in the "Appendix").

Price is, however, only one of the marketing tools that car dealers can utilize. We speculate that faced with low demand for vehicles affected by a VRT increase, car dealers might have tried to support sales by offering accessory services, such as financing, extra benefits, or after-sales services. By compensating consumers for the VRT increase, such ancillary services might have *de facto* reduced the elasticity of sales to VRT changes. As such behavior is not observable in listed prices, we cannot provide any empirical evidence in favor or against this hypothesis.

6.1 Environmental Impact

At first glimpse, it would appear that the reforms introduced between 2007 and 2009 could have had a beneficial impact on polluting emissions by shifting sales of new cars in favor of vehicles emitting less CO_2. Indeed, between 2005 and 2011, the *average* emission

[32] Figure 11 compares the distribution of new car versions registered for the six most popular brands in Norway, by CO_2 emission level, in the 24 months before and after the VRT reform of 2007. The generalized shift towards lower-emitting vehicles is similar to most European car markets and relatively smooth. Supply response to the reforms should induce lumps around the VRT reforms thresholds (120, 140, and 180 gCO_2 per km), with more vehicles below each threshold. This is not observed in the graph. To gather econometric evidence, we estimate an ancillary regression where the dependent variable is the number of distinct car specifications (unique combinations of brand, model segment, and CO_2 emission level) within 5g CO_2 below any of the three VRT reform thresholds. Controlling for segment and threshold specific linear time trends, the binary regressor *Post 2007* has no significant impact on the dependent variable (Table 14). In summary, we find no evidence of a supply response.

[33] In the US market for new cars, for example, it has been noted that the share of surplus retained by car dealers is higher with dealer discounts than with consumer rebates, possibly because consumers are better informed about the latter (Busse et al. 2006). In the context of everyday goods, Benzarti et al. (2017) identify asymmetric pass-through of changes in taxes in wholesale markets and Peltzman (2000) and Blattberg et al. (1995) present evidence of asymmetric reactions to changes in production costs and to marketing promotions in retail markets.

[34] A similar approach has been followed for example in Busse et al. (2006) and Yan and Eskeland (2018). Ideally, pass through would be computed using actual transaction prices, but these are unfortunately not observed. Official listing prices are available for about half of our sample. The actual price paid by consumers might differ significantly from the official price listed: in this sense, our evidence on pass-through should be interpreted as purely suggestive.

intensity from new vehicles decreased by 40 g per kilometer (or about 23%, data reported in Table 15 in “Appendix 4”). In this section, we provide evidence that while *average* CO_2 emission intensities from *new* vehicles decreased, *total* CO_2 emissions from *all* vehicles still increased from 2005 to 2011. To make things worse, the growing gap between lab-based and road-based estimates of CO_2 emissions suggests that the decrease in average emissions might be overestimated. In addition, we also document an increase in NOx emissions from new vehicles and a surge in sales of highly polluting vehicles following the announcement of the 2007 reform.

Figure 4 shows the total emissions of CO_2 (left panel) and NOx (right panel) from all vehicles and from new vehicles, by fuel and year.[35] The first thing to notice is that total CO_2 emissions from all passenger cars (black solid lines, values shown on the right vertical axis in each graph) increased by 2% for CO_2 (from 5100 in 2005 to 5200 thousand tonnes in 2011), thanks to the increase in emissions from diesel vehicles as a result of their increasing market shares. In particular, the increase in CO_2 emissions from diesel vehicles is observed both for *new* vehicles (dashed blue line in the left panel of Fig. 4) and for *all* vehicles (solid blue line).[36]

The second observation is that total NOx emissions from all vehicles (solid black line in the right panel of Fig. 4) decreased by 7% (from 16.2 in 2005 to 15 thousand tonnes in 2011). This is possibly driven by the reduction in emissions from petrol vehicles (dashed and solid red lines in the right panel, for new and all petrol vehicles). Although the market share of diesel vehicles increased over time, the average NOx emissions for new diesel cars in the Norwegian market decreased from 0.25 to 0.15 g/km (un-weighted average) between 2005 and 2011. This is likely due to technological improvements in diesel engines: as reported in Table 15 in the “Appendix”, the average emissions of CO_2 per km driven for diesel cars decreased from 176 g to 137 between 2005 and 2011.

The increase in CO_2 emissions is associated with global health and social costs and the decrease in NOx to a saving in local public health costs. For CO_2, the EU Emission Trading System (ETS) indicates a price range of €10 to €30 per tonne between 2005 and 2007 (Duong 2009). For NOx, Samstad et al. (2010) suggest an estimated cost between €5 and €20 per kg, depending on local population density.[37] Using these unitary costs, between 2005 and 2011, the public health costs associated with CO_2 pollution increased by 1–3

[35] Total emissions from new vehicles and from all vehicles in 2005 and 2011, by fuel, are also reported in Table 16 in the “Appendix”. Total emissions for new vehicles are computed based on our registration records data as the sum of each vehicle specification’s emissions (as reported on the registration records) times the number of sold vehicles, multiplied by the average mileage of passenger vehicles, by fuel, and year. As data on mileage is not available by vehicle age, we must abstract from differences in mileage between old and new vehicles and use common average mileage estimates provided by SSB, *Table 12577: Road traffic volumes, by vehicle type, type of fuel, contents, and year.* Total emissions from the entire passenger fleet, by fuel and year, are provided by Statistic Norway (SSB), *Table 08940: Greenhouse gases, by source (activity), pollutant, contents, and year*. Note that even though the official average per-km-emissions by new vehicles decreased, total emissions also depend on the total number of (new and old) vehicles in the fleet and on their mileage. Figure 10 in “Appendix 2” provides evidence that between 2005 and 2011 the average age of the fleet remained approximately constant, the total and average number of km driven on petrol vehicles declined and the total number of kilometers driven on diesel vehicles strongly increased because of the wide increase in the number of diesel cars in the fleet (while the estimated average number of kilometers driven on each of the diesel vehicles in the fleet slightly declined).

[36] The fact that the market share of diesel among new vehicles increased between 2005 and 2011 can be appreciated both in Table 1 above and in Fig. 10 in “Appendix 2”.

[37] The price value we are using is reported in Table 10 in Samstad et al. (2010), a report written in Norwegian with a short summary in English.

million Euros, while those associated with NOx decreased by 6–24 million, depending on whether the lower or higher unitary costs are used for each pollutant.[38]

CO_2 emissions for new vehicles are based on official lab-based emission estimates reported by car producers. As recent scandals have highlighted, they can be pretty far from "real" emissions. An alternative approach to estimate CO_2 emissions relies on users' reports of fuel consumption (Tietge et al. 2017). Using this approach, we calculate that the reduction in average CO_2 emissions from new passenger vehicles is 27 g/km, or 33% lower than the 40 g/km reduction computed using official lab-based estimates. Hence relying on official emissions leads to an overestimation of the reduction of CO_2 intensity and of total CO_2 emissions (additional evidence and details are reported in "Appendix 4").

6.1.1 Anticipation Effect

The reform of 2007 was announced approximately three months before its introduction and received significant coverage in the media. For example, the number of articles about the vehicle registration tax in the national newspaper (*Aftenposten*) abruptly increased in 2006 (Fig. 6 in the "Appendix"). Our main analysis captures the overall impact of the reform, in the way it was implemented and announced. While the reform was certainly effective, in this section we argue that its premature announcement resulted in a spike in the registrations of highly polluting vehicles in the last trimester of 2006, reducing the reform's potential impact on CO_2 emissions.

The time series of monthly average CO_2 emissions between 2005 and 2008 indeed exhibits a sharp peak in the last trimester of 2006, when the reform was announced, and a decline in January 2007, when the reform was implemented (Fig. 5). To put this in perspective, we compare the observed average emissions in the last trimester of 2006 to those of the last trimester of 2005, and the observed emissions in the first trimester of 2007 to those of the first trimester in 2008, after adjusting for the yearly difference in average levels. In light of the strong seasonality of the car market, we consider this to be a good comparison. The corresponding "counterfactual" time series is represented with a dashed line in Fig. 5.[39]

This comparison suggests that a temporary increase in emissions accompanied the announcement of the reform. Based on the trends we observed in Fig. 3, we attribute the

[38] In comparing such costs, it should be noticed that by definition they are bared by different entities: CO_2 emissions are a global issue associated with climate change and global warming, while NOx emissions strongly affect public health at the local level.

[39] The yearly difference in average levels between 2005 and 2006 is computed as the difference between average emissions in the first three trimesters of 2005 and 2006. Similarly, to approximate the yearly trend between 2007 and 2008 we compute the difference in average emissions between the last three trimesters of 2007 and the corresponding period in 2008. This approximation is meant to correct for the major drop in emissions observed at the beginning of 2007, which has been attributed to the reform of 2007 Ciccone (2018). The resulting estimators are

$$\theta = \Delta Emissions_{(QIV2005,QIV2006)} - \Delta Emissions_{(QI,II,III2005,QI,II,III2006)}$$

for the increase in emissions in the last trimester of 2006, and

$$\theta = \Delta Emissions_{(QI2007,QI2008)} - \Delta Emissions_{((QII,III,IV2007),(QII,III,IV2008))}$$

for the reduction in emissions in the first trimester of 2007. These can be interpreted as difference-in-difference estimators.

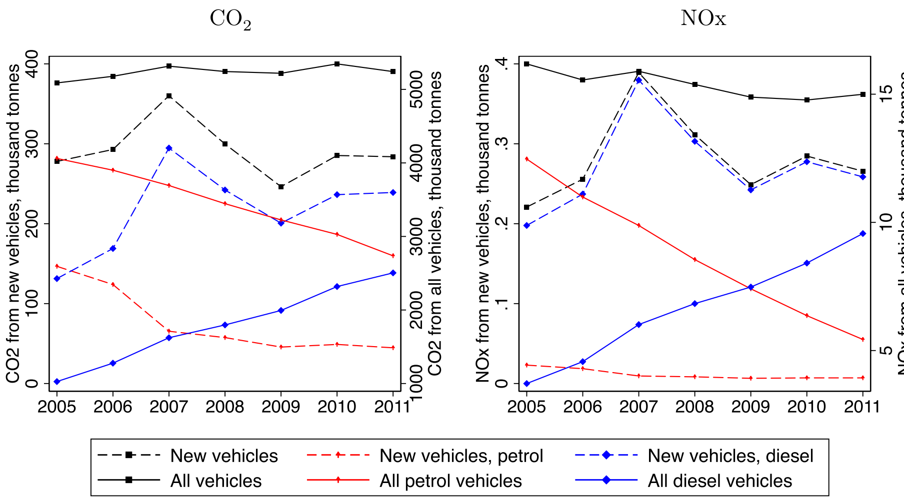

Fig. 4 CO_2 and NOx emissions from passenger cars, by fuel. *Note*: The two graphs show total CO_2 (in the left panel) and NOx (right panel) emissions from new vehicles (dashed lines) and from all vehicles, by fuel. All emissions are expressed in thousand tonnes. We compute total missions from new vehicles using our data on new registrations. The data source for total emissions from all vehicles is SSB *Table 08940 Greenhouses gases, by source (activity, pollutant, contents, and years)*

rise in emissions to the sharp increase of registrations for high CO_2 emitting vehicles (bottom Panel in Fig. 3) and to the decrease in registrations for middle and low emitting vehicles (top and mid Panels in Fig. 3). Adjusting for the positive yearly time trend, the average emission intensity is 47 g/km higher in the last trimester of 2006 than in 2005, and it is 14 g/km lower in the first trimester of 2007 than in 2008. To put these numbers in perspective, 47 g/km amount to 27% of the average emission intensity of the last trimester of 2005, and 14 g/km correspond to 9% of the average emission intensity of the first trimester of 2008.

While previous evaluations of such reforms have highlighted a consequent reduction of CO_2, it is essential to consider the increase in social costs associated with its announcement in the last trimester of 2006.[40] Given the average total mileage in this period (32,206 million km per year), the extra 47 g of CO_2 per km translate to approximately 1503 tonnes per year, for a social cost of 15,000 to 45,000 thousand Euros per year (based on the previously mentioned ETS estimates).

[40] While anticipatory reactions to VRT reforms have not been considered in the literature so far, our evidence is in line with Coglianese et al. (2017)'s finding that buyers increase (delay) gasoline purchases before fuel tax increases (decreases).

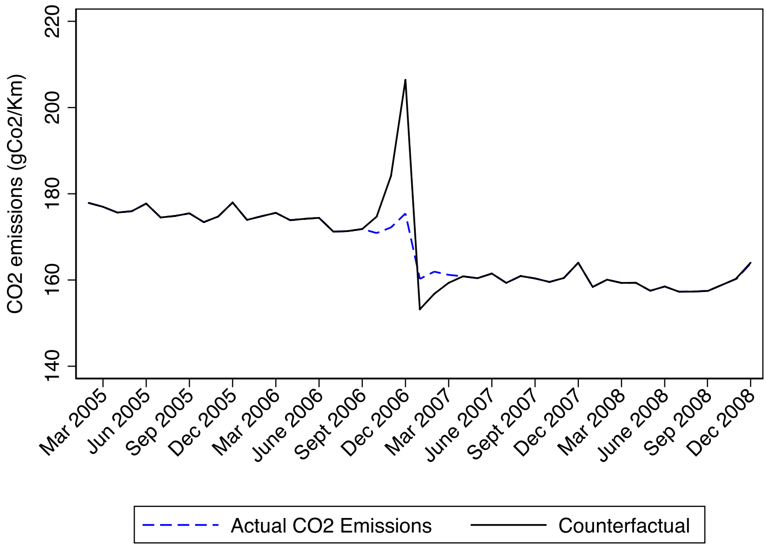

Fig. 5 Monthly average CO_2 intensity of new vehicles

7 Conclusions

In recent years, growing attention has been given to passenger vehicles as determinants of air pollution. To reduce CO_2 emissions many countries, especially in Europe, have modified passenger vehicle taxes linking them to CO_2 intensity. In Norway, this process resulted in the introduction of a series of reforms to the VRT system, with the aim to incentivize the purchase of "greener" new vehicles and discourage that of highly polluting alternatives. Previous studies have documented the overall success of such reforms and the increase in market shares for low emission vehicles, mostly driven by the increase of diesel market shares (Ciccone 2018). For a review of alternative policy levers to reduce emissions from road transport in general and passenger vehicles in particular, see ITF (2008), Fullerton and Gan (2005), and Withana et al. (2013).[41]

In this paper, we exploit the Norwegian reforms implemented in the car market in 2007 and 2009 to study the reaction of new car registrations to tax changes. Our main contribution to the literature is the empirical evidence of stark differences in equilibrium responses to tax changes, depending on the direction of such changes. Our results (1) are confirmed by several variations of our main estimating equation, (2) help improve the fit (in-sample) of the model, (3) could explain the stark heterogeneity in effects for the 2007 VRT reform across emission ranges, and (4) are in line with empirical findings in other contexts, such as fuel taxes and non-durable goods.

The analysis follows the standard empirical methodology in this literature, but we allow the tax elasticity of new car registrations to depend on the direction of the tax change. The resulting estimates suggest that new registrations react significantly (in economic and statistical terms) more strongly for vehicles that receive tax decreases and partial rebates than

[41] In addition, it should be noticed that polluting emissions can also indirectly taxed via fuel taxes (Andersson 2019; Coglianese et al. 2017).

for those receiving tax increases. Such effects are found for diesel and gasoline fuel cars and are hence not directly driven by the stark rise in diesel market shares (Fig. 12).

This result has important policy implications for the design of optimal taxation. Many countries have introduced partial rebates for vehicles with low polluting emissions to shift sales towards low emitting vehicles. To achieve revenue neutrality, such rebates are typically financed, at least in part, through tax revenues from highly emitting vehicles. Ignoring the documented asymmetry might result in overly generous incentives, leading to higher polluting emissions and lower tax revenues than desired. In 2008, France introduced a bonus/malus reform of its vehicle registration tax. The reform led to an unexpectedly large increase in the sales of low emitting vehicles, resulting in a sizable increase in aggregate emissions (both from the production of passenger vehicles and by their use) and to government expenditure well above the targeted revenue neutrality (D'Haultfœuille et al. 2014).

In Norway, the asymmetric response also implies that most of the within-car-model substitutions attributable to the reform are found for vehicles emitting in the lower and middle CO_2 ranges. To demonstrate such heterogeneous effects by emission ranges, we compare the before-after variation in new registrations for vehicles emitting in small adjacent ranges of emissions. Our estimates show that the reform had a large impact on vehicles emitting around 120 and around 140 g of CO_2 per km, but no detectable effect for those emitting around 180 g. As average VRT decreases in the first two ranges and increases (extensively more, in both absolute and relative-to-car-price terms) in the third range, we read this as further evidence of asymmetric response to VRT changes. This pattern is also in line with the finding that sales of relatively "green" vehicles react strongly to tax rebates in Switzerland (Alberini and Bareit 2019) and France (D'Haultfœuille et al. 2014).

To complete our discussion of the VRT reforms' effects, we complement our data with official aggregate statistics from SSB and highlight that total CO_2 emissions from passenger vehicles increased in the aftermath of the 2007 reform, driven by a sharp increase from diesel vehicles. In addition, in the same time window, the total NOx emissions from diesel vehicles also sharply increase. Overall, between 2005 and 2011, total emissions, from both new and older passenger vehicles, slightly increased for CO_2 and decreased for NOx. This change is not purely due to the reform but also to other factors, including technological progress. Based on literature reports of estimated social costs per unit of polluting emissions, the resulting additional costs due to the increase in CO_2 could range between 1 to 3 million Euros, while the public health savings associated with the decrease in NOx would range between 6 and 24 million. We show that the benefits might have been even higher if the 2007 reform had not been so largely publicized in the last trimester of 2006. The announcement of the reform appears to have led to a large spike in sales of vehicles with high CO_2 intensities, for an estimated public health cost of 15–45 thousand Euros per year.

While our main analysis relies on official lab-based estimates of polluting emission data, we also discuss the discrepancy with "real" emissions using road estimates provided by Tietge et al. (2017) and its consequences for Norway. As a result of this gap, the estimated total decrease in CO_2 emissions from new vehicles between 2005 and 2011 is likely to be overestimated by as much as 33%.

Appendix 1: Details of the Reform

Table 5 shows the unitary tax per kg of car weight, per *kW* of engine power, per *ccm* of engine volume (only until 2007) and per g/km of CO_2 (only from 2007), in the time period which is relevant for the study.

Table 6 shows the average change in registration tax between 2006 and 2007 for vehicles emitting just below or above each of the CO_2 emission thresholds 120, 140, and 180 g/

Table 5 The VRT components in different years

		2004	2005	2006	2007	2008	2009
Weight (kg)	0–1150	39.52	39.76	39.16	36.82	36.40	36.71
	1151–1400	79.04	79.52	79.45	80.25	79.32	80.02
	1401–1500	158.10	159.05	157.77	160.52	158.67	160.05
	Over 1500	183.87	184.97	183.51	186.68	184.53	186.13
Power (kW)	0–65	152.66	153.58	153.30	133.91	132.37	133.52
	66–90	556.79	560.14	557.24	557.97	551.55	556.35
	91–130	1113.93	1120.63	1115.59	1339.12	1323.71	1335.22
	Over 130	1885.04	1896.37	1886.54	2789.83	2757.73	2781.71
Engine vol (ccm)	0–1200	11.67	11.74	11.68			
	1201–1800	30.55	30.73	30.58			
	1801–2200	71.86	72.29	71.94			
	Over 2200	89.77	90.31	90.42			
gCO_2/km	0-120				44.64	44.13	Feebate: 523.87
	121–140				212.03	209.59	551.11
	141–180				557.97	551.55	556.35
	181–250				1562.30	1544.54	1557.98
	Over 250				1562.30	1544.54	2619.33

Prices are in NOK (2012 currency)

Table 6 Tax change by emission band

	VRT 2006	ΔVRT	$\Delta_{\%}$VRT	Price 2006
115–120	73.85	− 16.26	− 0.08	208.27
	5.11	2.97	0.01	11.21
120–125	83.78	− 12.61	− 0.05	233.77
	12.76	16.70	0.08	16.90
135–140	85.25	− 13.30	− 0.06	219.67
	13.82	12.99	0.05	43.31
140–145	86.17	− 8.61	− 0.05	168.89
	18.54	12.86	0.08	15.90
175–180	135.24	22.29	0.09	316.46
	27.50	27.30	0.10	56.74
180–185	129.42	30.04	0.08	329.10
	13.78	23.16	0.09	48.01

Thousand NOK (2012 currency). Statistics weighted by the number of cars sold in the period 2006–2007 km. In general, the VRT decreased for low emitting vehicles, and more so for those emitting just below 120 and 140 g. While the VRT increased for vehicles emitting below and above the 180 thresholds, the increase was larger above the threshold.

Evidence of Media Coverage Before the Introduction of the Reform

Figure 6 shows that the number of articles containing the Norwegian term for "Vehicle Registration Tax" ("engangsavgift") published on the Aftenposten newspaper's website sharply increased in 2006 with respect to the previous years. This reflects the important media coverage received by the 2007 reform before its implementation.

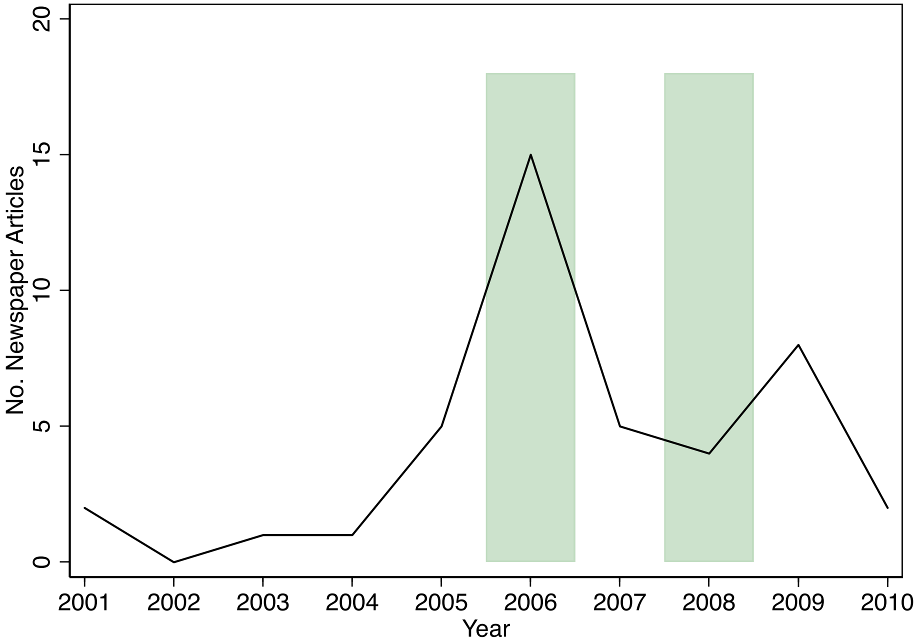

Fig. 6 Number of newspaper articles about the VRT. The graph shows the number of articles containing the word "*engangsavgift*" over time (black line) and the calendar years when a new reform is introduced (green bars). *Source*: *Aftenposten* website (www.aftenposten.no), word search

Appendix 2: Fleet Characteristics

In this section, we present some additional descriptive statistics and graphs for the Norwegian fleet of passenger cars. The fleet size and composition are presented in Figs. 7 (sales by month and year), 9 (number of new cars sold by year and segment), 10 (number of cars scrapped, average and total mileage and fleet size, by fuel) and 11 (distribution of available car specifications, by emission levels), and in Table 7.

In particular, the number of new petrol and diesel vehicles registered each year between 2005 and 2011 fluctuated between 98 and 139 thousand (Fig. 9). The share of diesel among

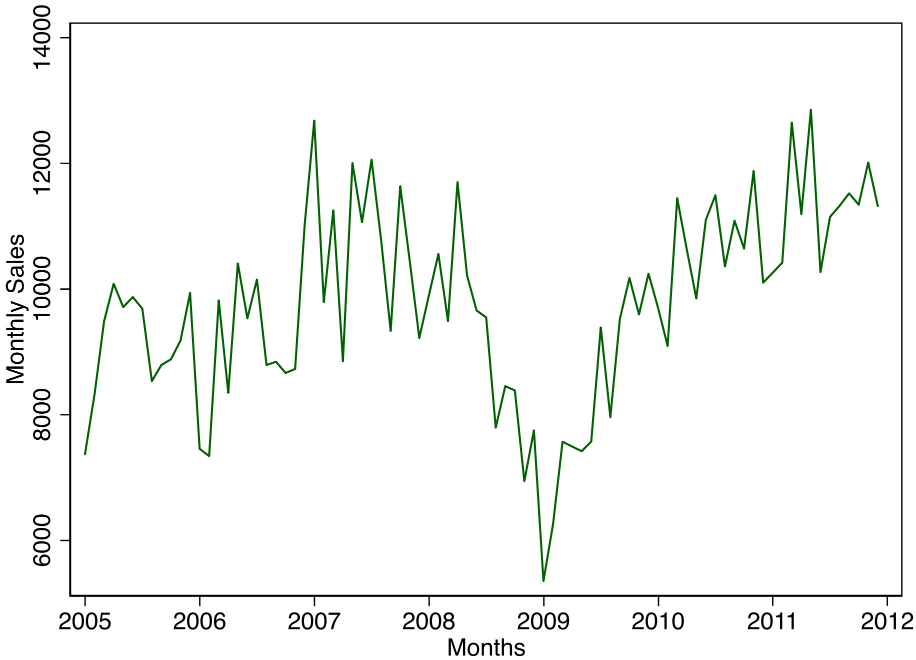

Fig. 7 Monthly sales of new passenger cars

Fig. 8 Market shares of diesel among new passenger cars, monthly time series

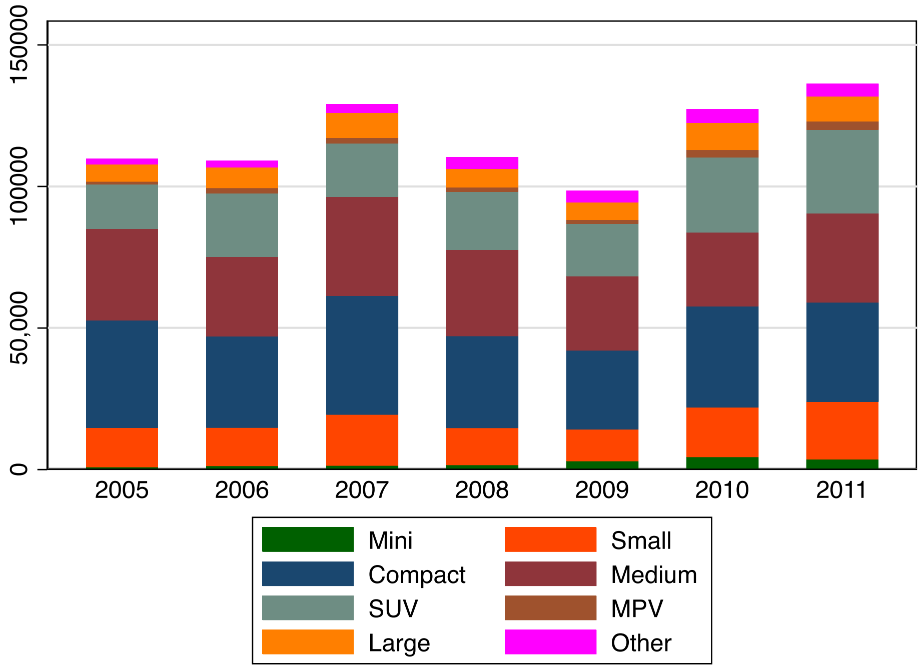

Fig. 9 Number of new diesel and petrol car registered, by year and vehicle segment

new cars increases relatively steadily from 2005 till the end of 2006, it plummets around the announcement of the reform and it then increases very sharply in the first part of 2007 (Fig. 8). These patterns are likely an effect of the fact that the reform *de facto* makes diesel cars cheaper than petrol ones as the former have lower CO_2 emissions, for comparable engine volume and power and vehicle weight and same brand (Table 9). In addition, in 2007 the share of new small, compact and medium vehicles registered increased, at the expense of new SUV vehicles. Table 7 shows the distributions of the following characteristics of newly registered petrol and diesel passenger vehicles registered between 2005 and 2011 in Norway: total registration tax (VRT), estimated CO_2 emissions intensity, vehicle weight, engine power, and cylinder volume. The availability of vehicles does not seem to react to the introduction of emission thresholds, suggesting that, at least in the short run, supply reactions can be ignored (Fig. 11).

Table 8 reports the summary statistics for the sample of data used in our analysis. This includes all new petrol and diesel private passenger vehicles registered between 2005 and 2011. While Table 1 in the main text reports the average characteristics by year of registration, Table 8 shows the average, minimum and maximum values, median, and standard deviation for each characteristic over the entire period 2005–2011. Table 9 shows that, holding other engine and vehicle characteristics fixed, diesel cars emit less CO_2 and more NOx than petrol ones.

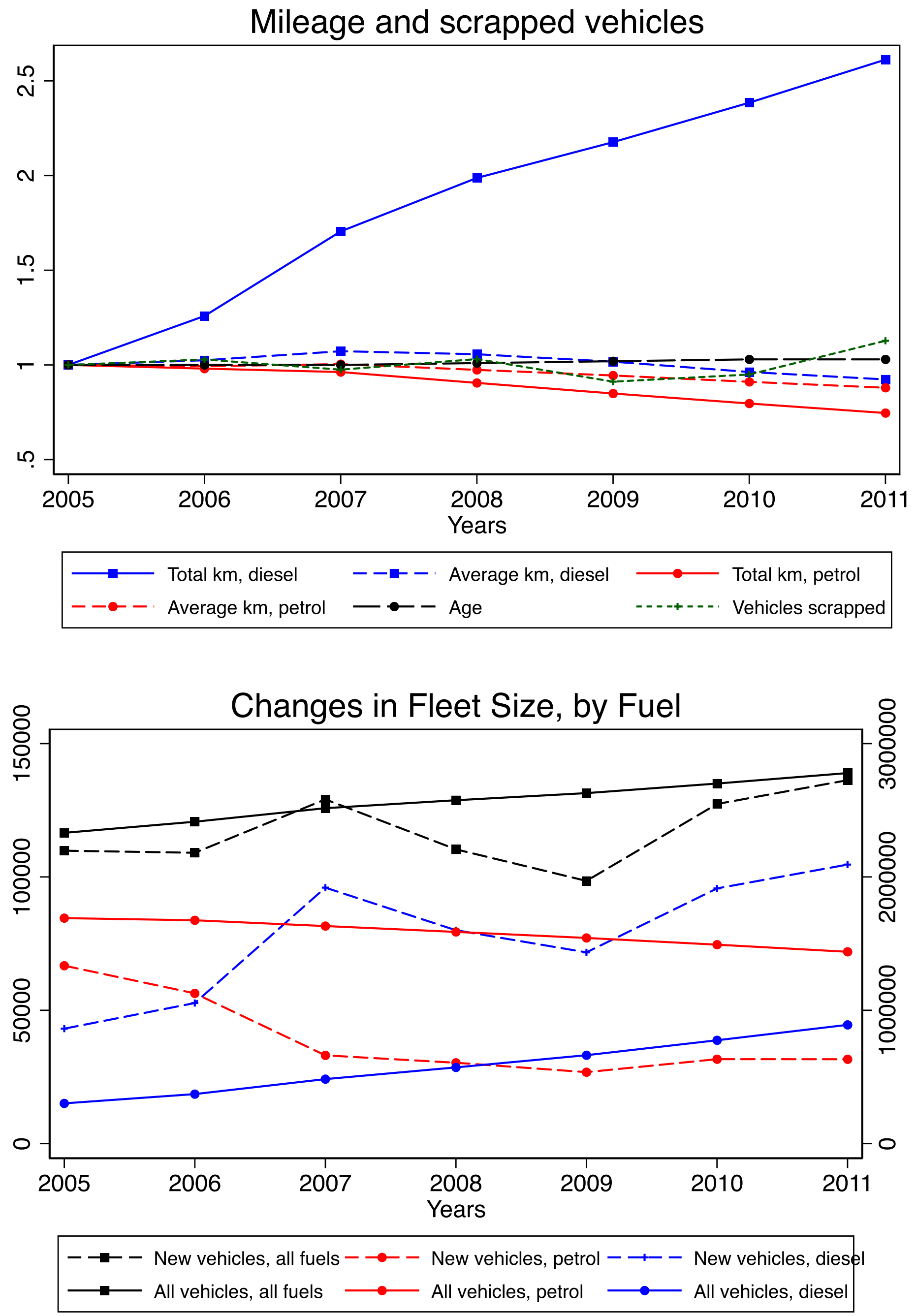

Fig. 10 Other characteristics of the passenger vehicles fleet. *Note*: All time series in the top panel are normalized to one in 2005. In the bottom panel, the number of new vehicles is shown on the left axis, the total number of vehicles (including old ones) on the right axis. Data sources: SSB, *Table 04759: Stock of vehicles and population, by contents, and year.*, *Table 12577: Road traffic volumes, by vehicle type, type of fuel, contents, and year* and *Table 05522: Vehicles scrapped for refund, by region, contents, and year*

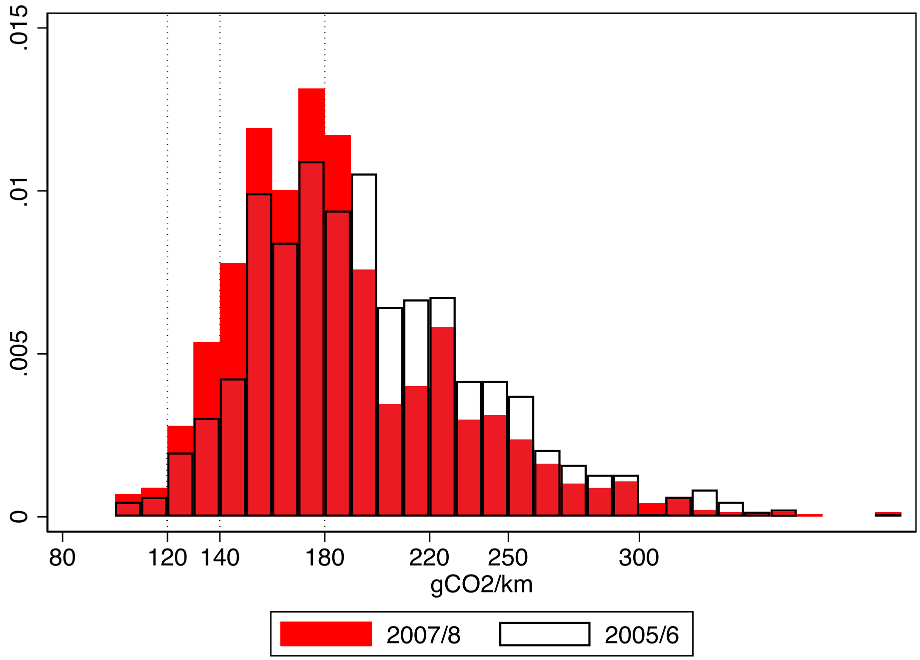

Fig. 11 Unweighted distribution of new cars sold, by CO_2 Emissions. *Note*: distribution of CO_2 emissions for passenger cars sold in Norway before and after the 2007 VRT reform, not weighted by the number of cars sold. Data for the main six brands in Norway: Volkswagen, Mercedes Benz, Audi, BMW, Opel, and Toyota

Table 7 Distribution of relevant characteristics

	Min	25th percentile	Median	75th percentile	Max
Total tax in thousand NOK	9.79	72.72	107.09	159.79	1529.32
CO_2 intensity (gCO_2/km)	59.00	132.00	154.00	177.00	448.00
Weight	510.00	1250.00	1407.00	1538.00	6420.00
Power (KW)	30.00	74.00	84.00	103.00	601.00
Cilinder volume (cm^3)	659.00	1560.00	1798.00	1995.00	8128.00

Unweighted characteristics for 2005–2011

Table 8 Summary statistics

	Average	SD	Min	Max	Median
Total tax in thousand NOK	124.59	77.84	9.79	1529.32	107.09
CO_2 intensity (gCO_2/km)	156.47	33.06	59.00	448.00	154.00
Weight	1396.61	236.87	510.00	5980.00	1407.00
Power (KW)	88.08	24.04	30.00	593.00	84.00
Cilinder volume (ccm)	1780.19	373.02	698.00	7011.00	1798.00

Sample size 935,586 new passenger cars sold between 2005 and 2011 (petrol and diesel only)

Table 9 Ceteris paribus differences in emissions by fuel

	(1) CO_2 Emissions	(2) NOx Emissions
Diesel	− 38.997***	0.194***
	(0.078)	(0.000)
Power (KW)	0.117***	− 0.001***
	(0.003)	(0.000)
Vehicle weight	0.095***	0.000***
	(0.000)	(0.000)
Cylinder volume	0.023***	0.000***
	(0.000)	(0.000)
Constant	12.420***	− 0.113***
	(0.204)	(0.001)
Brand FE	✓	✓
Year FE	✓	✓
No. observations	233961	203839
R^2	0.844	0.803

The sample used for estimation is the universe of all new passenger cars sold in Norway between 2004 and 2006, not weighted by sales volumes

Appendix 3: Additional Results

Tables 10, 11, and 12 present several robustness checks on the ancillary difference-in-difference analysis reported in Sect. 5. In Table 10 we re-estimate the difference-in-difference Eq. 4 on a wider range of emissions around each cutoff (± 7 g, rather than our preferred range ± 5g). In Table 11 we re-estimate the same equation in logarithmic form, rather than in levels (on our preferred range $\pm 5g$ around each emission threshold). In Table 12 we include segment-quarter fixed effects, instead of the model-quarter fixed effects used in our preferred specification in Table 4. This specification allows us to capture substitutions within the car segment, rather than only within the car model. All in all, the robustness checks do not contradict our finding that the substitutions, which we interpret as attributable to the 2007 VRT reform, are larger for low and mid CO_2 emission ranges. In addition, Fig. 12 highlights the significant shift towards lower emissions for vehicles of each fuel type.

Table 10 Difference in difference around the tax thresholds, range ± 7*g*

Equation (4): $Sales = \alpha AboveC + \gamma \cdot After2007 + \delta \cdot (AboveC \cdot After2007) + \delta \cdot X + \mu$

	Subsample: 120 *g* ± 7		Subsample: 140*g* ± 7		Subsample: 180 *g* ± 7	
	(1)	(2)	(3)	(4)	(5)	(6)
δ	− 0.29*	− 0.30**	− 0.30***	− 0.14*	− 0.04	0.08
	(0.12)	(0.11)	(0.08)	(0.06)	(0.07)	(0.09)
α	− 0.00	− 0.13	0.26**	0.10	0.02	− 0.06
	(0.08)	(0.09)	(0.08)	(0.08)	(0.07)	(0.09)
γ	0.35*	0.36*	0.03	0.01	− 0.63	− − 0.59
	(0.15)	(0.15)	(0.19)	(0.19)	(0.45)	(0.43)
Constant	1.22***	5.07***	1.27***	3.59***	2.38***	− 2.09***
	(0.27)	(1.10)	(0.31)	(0.72)	(0.40)	(0.62)
County FE	✓	✓	✓	✓	✓	✓
Month FE	✓	✓	✓	✓	✓	✓
Quarter*Model FE	✓	✓	✓	✓	✓	✓
Segment FE	✓	✓	✓	✓	✓	✓
No. of doors FE		✓		✓		✓
Gear FE		✓		✓		✓
Brand FE		✓		✓		✓
Body FE		✓		✓		✓
Driving axel FE		✓		✓		✓
Weight		✓		✓		✓
Power KW		✓		✓		✓
No. obs.	8668	8668	16,504	16,504	18,757	18,757
R^2	0.10	0.11	0.08	0.09	0.12	0.13

Dependent variable: number of new passenger car registered, by municipality and month, between January 2006 and December 2007. Standard errors, in parentheses, are clustered at the municipality level

*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$

Table 11 Difference in difference around the tax thresholds, logarithmic form

Equation (4): $Sales = \alpha AboveC + \gamma \cdot After2007 + \delta \cdot (AboveC \cdot After2007) + \delta \cdot X + \mu$

	Subsample: 120 g±5		Subsample: 140 g±5		Subsample: 180 g±5	
	(1)	(2)	(3)	(4)	(5)	(6)
δ	− 0.10*	− 0.10*	− 0.10***	− 0.05**	− 0.04*	0.00
	(0.05)	(0.04)	(0.02)	(0.02)	(0.02)	(0.02)
α	− 0.02	− 0.07*	0.09***	0.05*	0.03	− 0.00
	(0.03)	(0.03)	(0.02)	(0.02)	(0.02)	(0.02)
γ	0.12*	0.12*	0.01	0.01	− 0.24	− 0.23
	(0.05)	(0.06)	(0.07)	(0.07)	(0.15)	(0.14)
Constant	0.15	1.49***	0.07	0.96***	0.49***	− 1.42***
	(0.11)	(0.41)	(0.10)	(0.22)	(0.12)	(0.21)
County FE	✓	✓	✓	✓	✓	✓
Month FE	✓	✓	✓	✓	✓	✓
Quarter*model FE	✓	✓	✓	✓	✓	✓
Segment FE	✓	✓	✓	✓	✓	✓
No. of doors FE		✓		✓		✓
Gear FE		✓		✓		✓
Brand FE		✓		✓		✓
Body FE		✓		✓		✓
Driving axel FE		✓		✓		✓
Weight		✓		✓		✓
Power KW		✓		✓		✓
No. obs.	8668	8668	16,504	16,504	18,757	18,757
R2	0.14	0.15	0.13	0.14	0.17	0.18

Dependent variable: logarithmic transformation of the number of new passenger cars registered, by municipality and month, between January 2006 and December 2007. Standard errors, in parentheses, are clustered at the municipality level

$*p < 0.1$, $**p < 0.05$, $***p < 0.01$

Table 12 Difference in difference around the tax thresholds, segment-quarter fixed effects

Equation (4): $Sales = \alpha AboveC + \gamma \cdot After2007 + \delta \cdot (AboveC \cdot After2007) + \delta \cdot X + \mu$

	Subsample: 120 g±7		Subsample: 140 g±7		Subsample: 180 g±7	
	(1)	(2)	(3)	(4)	(5)	(6)
δ	– 0.03	– 0.00	– 0.30***	– 0.12	– 0.09	0.06
	(0.06)	(0.07)	(0.08)	(0.06)	(0.06)	(0.05)
α	– 0.18**	– 0.12*	0.10*	0.02	– 0.08	– 0.15*
	(0.06)	(0.06)	(0.04)	(0.04)	(0.06)	(0.07)
γ	– 0.18	0.01	0.42***	0.22*	0.11	0.14
	(0.10)	(0.10)	(0.11)	(0.09)	(0.16)	(0.16)
Constant	1.36***	1.27*	1.05**	1.45*	0.50	0.02
	(0.20)	(0.51)	(0.38)	(0.62)	(0.59)	(0.94)
County FE	✓	✓	✓	✓	✓	✓
Month FE	✓	✓	✓	✓	✓	✓
Quarter*model FE	✓	✓	✓	✓	✓	✓
Segment FE	✓	✓	✓	✓	✓	✓
No. of doors FE		✓		✓		✓
Gear FE		✓		✓		✓
Brand FE		✓		✓		✓
Body FE		✓		✓		✓
Driving axel FE		✓		✓		✓
Weight		✓		✓		✓
Power KW		✓		✓		✓
N	8668.00	8668.00	16504.00	16504.00	18757.00	18757.00
R2	0.06	0.08	0.05	0.07	0.08	0.11

Dependent variable: number of new passenger car registered, by municipality and month, between January 2006 and December 2007. Standard errors, in parentheses, are clustered at the municipality leve

$*p < 0.1$, $**p < 0.05$, $***p < 0.01$

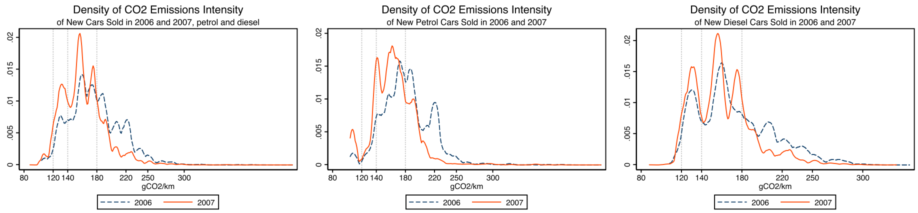

Fig. 12 Shifts in emissions, by fuel. *Note*: data weighted by the number of vehicles sold

Table 13 Pass-through of VRT variations to listing prices

	Full sample	Tax up	Tax down	Interaction
	(1)	(2)	(3)	(4)
VRT	0.803***	1.072***	0.749***	0.934***
	(0.117)	(0.202)	(0.274)	(0.149)
Fuel costs	− 0.060	− 0.116	0.271	0.109
	(0.259)	(0.653)	(0.432)	(0.293)
Additional effect when VRT decreases				− 0.307
				(0.245)
Constant	1.696***	− 2.289	4.437***	1.700**
	(0.139)	(1.671)	(1.643)	(0.697)
No. observations	3957	992	1318	4316
R^2	0.524	0.525	0.614	0.486

Dependent variable: price reported in official listings, by car model ad quarter, between January 2006 and December 2009. Standard errors, in parentheses, are clustered at the vehicle segment-quarter level. Additional regressors: model-quarter indicators and fuel costs, in first differences

$^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$

Table 14 Supply response to the VRT reform

Below= post 2007 + X + e,	
Post 2007	0.08
	(0.04)
Constant	0.69***
	(0.02)
Car model FE	✓
Linear trend × market segment FE	✓
Linear trend × cutoff FE	✓
Observations	3152

Dependent variable: number of car specifications below one of the three VRT thresholds introduced in 2007. Standard errors in parentheses

$^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$

Tables 13 (pass-through model) and 14 (changes in vehicle availability) report the estimates for the ancillary models to which we refer in Sect. 6.1.

Appendix 4: Polluting Emissions: Lab- and Road-Based Estimates

Average and total polluting emissions from passenger vehicles can be estimated using lab-based or road-based measurements. The latter utilize users' reports of fuel consumption. Figure 13 shows estimates of average CO_2 emissions per km based on these two methods and the difference between them. We compute road-based estimates as the average of the brand's specific coefficients reported by Tietge et al. (2017), weighted by each brand's market share in Norway in the relevant year. The difference sharply increases from 2005 (19.7 g per km) to 2011 (34.7 g per km).

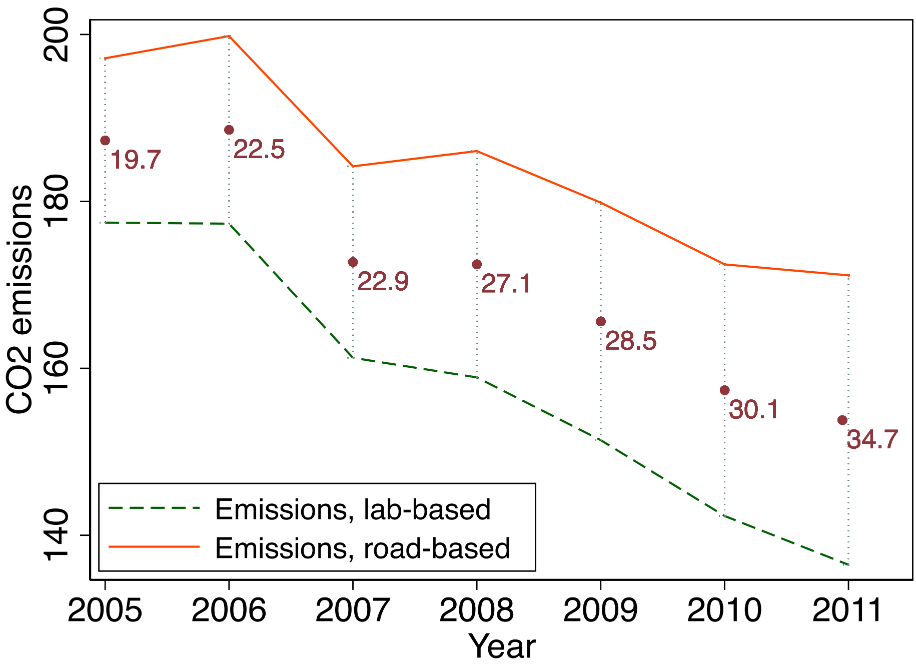

Fig. 13 The gap between lab-based and road-based estimates of CO_2 emissions. *Note*: The graph shows lab-based (dashed line) and road-based (solid line) estimates for new vehicles' CO_2 emissions per km driven, and the difference between the two values in each year (numbers reported in between the two time series)

Table 15 reports the average CO_2 and NOx emission intensities in 2005 and 2011, by fuel. According to lab-based estimates, the average CO_2 intensity for new passenger vehicles decreased by 40 g/km (23%) between 2005 and 2011 (going from 176 to 136 g/km). Using road-based estimates, instead, the decrease was only 27 g/km (15%) in the same period. In other words, because the gap between lab- and road- based estimates grew larger

Table 15 Average polluting emission intensity per km driven

	CO_2, lab-based			CO_2, road-based			NOx		
	Petrol	Diesel	All	Petrol	Diesel	All	Petrol	Diesel	All
2005	180	169	176	199	185	194	0.028	0.255	0.117
2011	132	137	136	159	169	167	0.021	0.149	0.119
Change	− 48	− 32	− 40	− 40	− 16	− 27	− 0.007	− 0.106	+ 0.002

All data in grams per kilometer driven

over time, using lab-based estimates leads to overestimating the decrease in average emissions by 33% (i.e., 40 g instead of 27 g).

The increase in the gap between lab- and road-based estimates can also be seen in the corresponding total emissions, in Fig. 14 and Table 16 (which factor in the number of new cars sold and the number of km driven for each car). From 2005 to 2011 total CO_2 emissions from new passenger cars increased by 6 thousand tonnes according to lab-based estimates, and by 42 according to road estimates. The fact that total emissions increased even though average emissions decreased is due to the fact that, as a result of the increase in sales of new diesel vehicles, both the total number of vehicles and the average mileage increased.

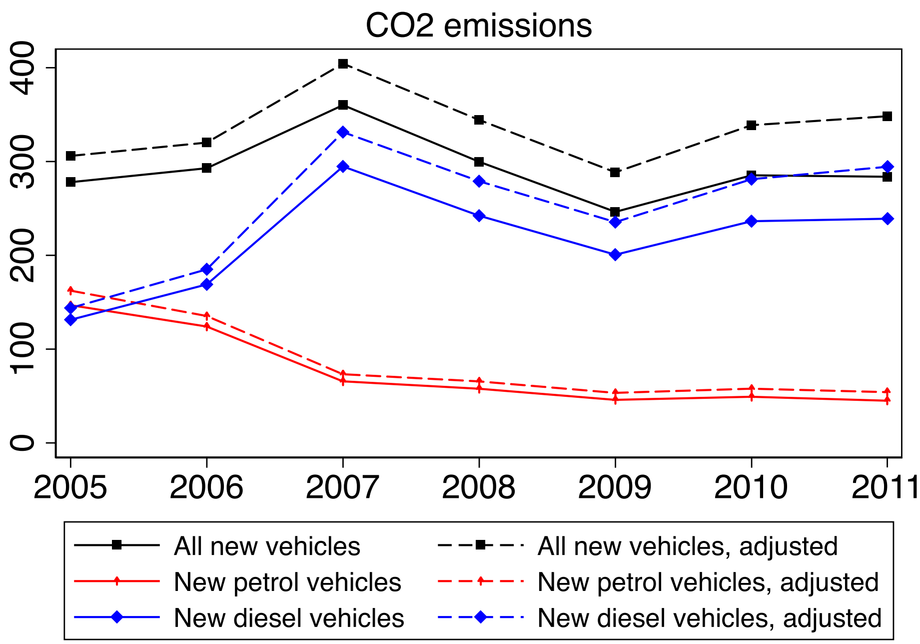

Fig. 14 Total CO_2 emissions from new passenger vehicles, by fuel

Table 16 Total CO_2 emissions, by fuel and year

	New vehicles, lab-estimates			New, road-estimates			All passenger vehicles		
	Petrol	Diesel	All	Petrol	Diesel	All	Petrol	Diesel	All
2005	147	131	278	162	144	306	4061	1027	5088
2011	45	239	284	54	294	348	2737	2505	5242
Change	− 102	+ 108	+ 6	− 108	+ 150	+ 42	− 1324	+ 1478	+ 154

All data in thousand tonnes

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