CESifo
AREA CONFERENCES 2020

Energy & Climate Economics

Munich, 1–2 October 2020

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

Alice Ciccone and Emilia Soldani

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September 28, 2020

Abstract

Vehicle registrations have been shown to strongly react to tax reforms aimed at reducing CO2 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 to show that, within car model, new car registrations react to tax cuts and rebates significantly more than to tax increases. The estimated elasticity is -1.99 for VRT decreases and 0.77 for increases.

Keywords: CO2 emissions intensity, New vehicles, Vehicle registration tax, Elasticity, Asymmetric response, Norway

*We gratefully acknowledge the Norwegian Research Council, the Department of Economics, University of Oslo and Institute of Transport Economics (TØI) for financial support when acquiring the data. We wish to thank Lasse Fridstrøm, Simon Heß, Bjørn Gjerde Johansen, Chiara Lacava, Vegard Østli, Patrick Schmidt, Matthias Schündeln, Steinar Strøm, Paal Brevik Wangsness and Alfons Weichenrieder for their valuable comments.

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1 Introduction

In the last decade, many European countries have reformed their taxes on vehicle purchases in order to reduce CO_2 emissions rates. Typically, the reforms consisted in 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 show generally 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 and, as we discuss below, it is not obvious whether the results for non-durables may apply to costly goods like vehicles. In general, providing evidence on durables is complicated because of high product differentiation and data scarcity for actual transaction prices.

In order 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 ranged between 12% and 75% of new car vehicles prices, placing the country among those with the highest vehicle taxation in Europe (Gerlagh et al., 2018; Runkel et al., 2018). Every car model is available in different engine versions and the reforms de facto decreased the tax for versions with low CO_2 emissions and increased it for those with higher potential emissions, within car model. We identify the reform's impact and estimate the elasticities of registrations to tax changes thanks to within-car-model variation, in the spirit of Klier and Linn (2015). The resulting estimated elasticity of new vehicles registrations is -1.99 for VRT decreases and 0.77 for increases. Additional evidence is found by considering the impact of the introduction of partial rebates: since 2009, cars emitting less than $120gCO_2/km$ receive a partial cash back[1]. Our estimates show that sales reactions to tax changes are dis-proportionally stronger when the change involves a partial cash-back. These

[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.

results are particularly relevant for policy design. The baseline model, which does not allow for asymmetric reactions, underestimates the number of vehicle registrations, especially for low emitting vehicles. Hence, for any given targeted shift in the distribution of registrations by emissions, a VRT reform which ignores the asymmetric response of registrations to tax cuts and increases will result in overly-generous tax cuts for low emitting vehicles. The asymmetry also helps explain the striking heterogeneity of effects of the 2007 reform across emissions ranges: within vehicle-model substitution was especially higher among low and medium emission vehicles, which on average experienced a decrease in VRT.

Building on previous empirical and laboratory evidence for durable and non-durable goods, we discuss several mechanisms which might explain the documented asymmetries. Higher elasticity to tax decreases than increases, or vice versa, could arise for a variety of reasons. From the demand side of the market, consumers could exhibit behavioral patterns such as salience. From the supply side, sellers could pass on tax increases more than tax decreases to consumers or, conversely, they may compensate tax increases with promotional sales, or inform consumers of a tax decrease more than a tax increase. The limited available data does not offer particular support to any of these mechanisms, but anecdotal evidence suggests that the asymmetry could be driven by non-price competition among car dealers.

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 (Durrmeyer and Samano, 2018; D'Haultfœuille, Givord and Boutin, 2014; Gerlagh et al., 2018; Rogan et al., 2011; Alberini and Bareit, 2019; Cerruti, Alberini and Linn, 2019; Klier and Linn, 2015). Two other studies have analyzed the ex-post effects of the Norwegian VRT reforms: Ciccone (2018) and Yan and Eskeland (2018)[2]. We complement their findings by empirically documenting the higher elasticity of registrations linked to tax decreases than increases. This contribution is far from

[2]Ciccone (2018) uses a pre-post design to study the short run effect of the 2007 tax reform on CO_2 intensity, documenting a reduction in the market shares of high-emitting vehicles in favor of low-emitting ones and a stark increase of diesel vehicles shares. Yan and Eskeland (2018) use an approach similar to Klier and Linn (2015) and estimate the effect of the reforms on aggregate vehicles' sales. Using the tax as an instrument for prices, they suggest that the average elasticity of CO_2 intensity to CO_2 price in the fleet is negative, confirming that the reforms shifted registrations toward lower-emitting vehicles.

trivial, as it speaks to the risks of overly generous incentives and helps explain the heterogeneous effects across emission ranges.

Our findings also add to the empirical literature on asymmetric reactions to price and/or tax changes, which highlights important asymmetries for everyday goods (Bidwell, Wang and Zona, 1995; Dargay, 1991; Gately, 1992; Dargay and Gately, 1997; Gurumurthy and Little, 1989; Kalwani et al., 1990; Bonnet and Villas-Boas, 2016) [3]. The literature also suggests that the (a)symmetry of elasticity might depend on the price levels. In the soda drinks market, for example, 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. The only existing evidence for vehicles is based on comparisons across Swiss cantons. For the annual circulation tax, some cantons use a bonus policy and others a malus policy: Exploiting variation in circulation taxes over time and across car models and administrative cantons, Alberini and Bareit (2019) conclude that the evidence of asymmetries in this context is very limited. In comparing our results to this evidence, it should be noted that we focus on a very large tax which in Norway is paid up-front, unlike circulation taxes which in Switzerland are paid annually.

This paper is structured as follows. We first describe the reforms (Section 2) and our data (Section 3) and methodology used (Section 4). We then present our main results on asymmetric reactions to tax changes with additional empirical evidence in their support (Section 5) and discuss possible mechanisms which might explain such asymmetries (Section 6). Before concluding, we discuss two important caveats (Section 6.1). First, we document large anticipatory responses to the announcement of the reform, leading to a +27% increase in emissions with respect to our counterfactual simulation. Second, because of the gaps between lab-based and

[3] Specifically, Bidwell, Wang and Zona (1995); Dargay (1991); Gately (1992); Dargay and Gately (1997); 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); 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.

consumers-reported emissions, the overall reduction in emission attributable to the reform might be overestimated by up to 30%[4].

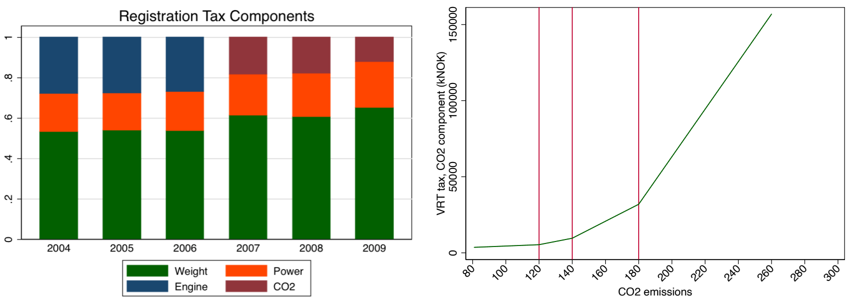
2 Context

Purchase, ownership, and usage taxes are generally used as economic instruments to affect car purchase and usage decisions. Between 2005 and 2011 many European countries focused their attention on vehicle taxes in order to reduce CO_2 emissions from road transport. The most common type of reform implemented in those years was to modify the structure of the VRT linking it directly to the CO_2 potential emission of each car. Taxing CO_2 emissions through the VRT is just one of many possible approaches to provide incentives in favor of less polluting vehicles. One important difference between these approaches is that the VRT is a large upfront payment, while circulation and fuel taxes involve smaller payments deferred in time. 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), policy makers 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). The reform of 2007 replaced the engine displacement component with a CO_2 component

[4]The latter has received growing attention in the literature (Ewing, 2017; Boudette, 2017; Tietge et al., 2017; Fontaras et al., 2017; Fontaras, Zacharof and Ciuffo, 2017).

(measured in gCO_2/km)[5]. This change is shown in the left panel of Figure 1, from Ciccone (2018).



Note: 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: 120g, 140g, and 180g of CO_2/km

Figure 1: Tax composition.

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: 120g, 140g, and 180g of CO_2/km). These thresholds create 4 bands of emissions: in 2007 each gram of CO_2/km up to 120g is taxed approximately 45 NOK, each additional gram up to 140 is taxed 212 NOK, each additional gram till 180 is taxed 558NOK and the reminder is taxed 1562NOK. In addition, each vehicle is also still taxed propotionally to its weight and engine power. In 2009 a new major reform was implemented: a partial rebate of 524NOK was introduced for all vehicles emitting below 120g CO_2/km, and the unitary tax per gram of CO_2/km above 250 grams was increased. Due to data limitations, we do not considered any of the subsequent reforms, which introduced subsidies for electric vehicles. More details about the structure of the VRT and the relative weight of each component can be found in Table A1 in the Appendix.

The last three rows of Table **??** explicitly look at the relative importance of CO_2 in determining a car's VRT: 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

[5]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 Section 6.1.

over 69%. With the introduction of fee-bates, 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 Section 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 Figure B1 in the Appendix reveals no evidence of such effects, in the reminder we focus exclusively on registrations, and turn to fleet composition and polluting emissions in the discussion (Section 6.1).

3 Data

The main data used in this study were provided by the Norwegian Road Federation OFV AS[6]. The original dataset contains information about all new passenger vehicles registered in Norway between 2004 and 2011, by month and municipality.[7] 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)[8], and monthly average fuel prices and fuel taxes, provided by the Institute of Transport Economics (TØI).[9]

Between 2004 to 2011 we observe the sale of a total of 431 different models, 5,412 different vehicles and 4,765 specifications (Table 1). 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.

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

[7]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.

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

[9]More information at `www.toi.no`

Table 1: Sample Composition

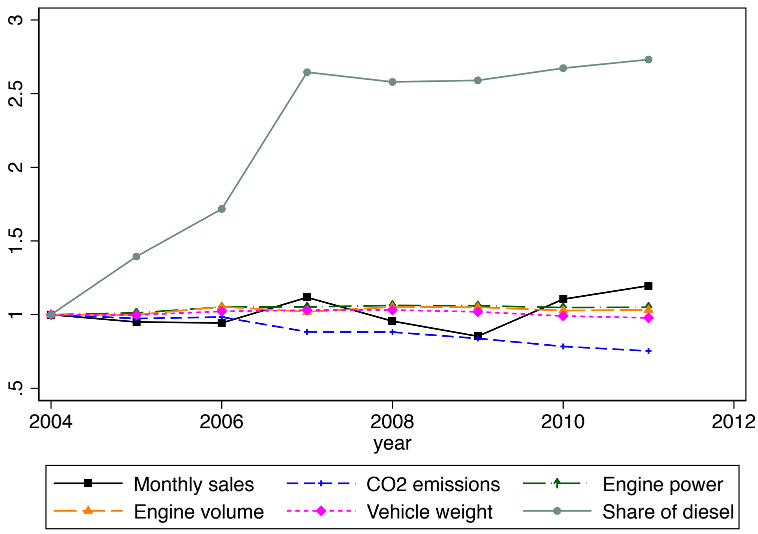
Aggregation level	No. Observations
No. of models	431
No. of models / CO_2 emission level combinations	5,412
No. of specifications	4,765

Data for the period January 2004-December 2011. A *specification* is defined as a unique combination of model, number of doors, cylinder volume, engine power, gear and fuel.

In our estimations, the unit of observation is the model-quarter (15,249 observations from 2005 to 2009) or model-month (8,668 observations from 2006 to 2007)[10]. We aggregate our data at the national level because none of our regressors of interest (tax and fuel prices) varies across municipalities.

Summary statistics for the most relevant vehicle characteristics are shown in Table B2 in the Appendix. Figure (2) shows the evolution over time of average characteristics for new vehicles registered each year, using 2004 as base year. The average number of new cars sold in a month, the corresponding average vehicle weight, engine volume and power are mostly constant over time, suggesting that sales did not significantly shift to “smaller” or bigger vehicles. At the same time the plot also shows a striking increase in the share of diesel vehicles (which in 2007 is about 2.5 times higher than in 2004) and a slow but steady decrease in CO_2 emissions. We discuss these patterns in relation to aggregate emission levels in Section 6.1.

[10]The choice of using quarterly observations in Section 5 is led by the will to facilitate the comparison of our results to previous studies.An additional advantage is that quarterly data smooths away the model-month fluctuations and possible measurement errors, while still preserving most of the tax variation Klier and Linn (2015). In our additional estimates based on double difference, however, we must 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. As using quarterly data would leave us with limited sample size for estimation, we decided to use monthly data.



Note: For every time series, the average value in 2004 is normalized to one.

Figure 2: Average characteristics of new registrations, by year

4 Methodology

In the existing literature, the impact of tax reforms on car sales and registrations has been estimated either through structural and semi-structural models of consumers' demand (in the spirit of Berry, Levinsohn and Pakes (1995)) or through reduced form models of equilibrium sales or registrations (Klier and Linn, 2015, 2016). Given its parsimonious data requirements and identifying assumptions, and the fact that equilibrium registrations, rather than demand, are the main outcome of interest for policy interventions, the latter approach is more suitable to our goals. It 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[11]. The model, to be estimated on data aggregated at the

[11] *Vehicles* are defined by unique combinations of brand, model and CO_2 emission. Estimating the equation with first differences implies that data for quarters when no change in tax is observed will not be included in the estimation sample.

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 logarithm). It does not separately identify changes in demand and in 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 100km), and the residuals (ϵ_{jt}) are clustered at the segment-quarter level to allow for correlation within quarter and market segment[12]. The tax coefficient (α) if identified off variation in VRT within car models (i) over time (by first differences) and (ii) 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[13]

Section 5 presents estimates of the above equation for our entire sample and for the subsamples of (i) vehicles whose VRT increased and (ii) vehicles whose VRT decreased. To explicitly test whether the tax effect differs across the two subsamples, we then extend the equation as follows[14]:

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

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)[15].

[12] 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).

[13] 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}.

[14] In addition, we also estimated the following version of Equation 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.

[15] 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 a 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

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 120g CO_2 per kilometer. To check this prediction, we further interact the tax and a binary variable for partial rebates:

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

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[16].

For the first time in Norway, the reform of 2007 introduced the use of CO_2 emission thresholds. 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 type i and month t from January 2006 to December 2007 via ordinary least squares on the following Difference-in-Difference equation

$$q_{imt} = \alpha \cdot AboveC_c + \gamma \cdot After2007 + \delta \cdot (AboveC_c \cdot After2007) + \beta X_i + \Theta_{ijt} + \mu_{imt}, \quad (4)$$

To exploit the discontinuity of VRT at the thresholds 120, 140 and 180g CO_2, we estimate the equation separately for vehicles emitting in the ranges 115-125, 135-145 and 175-185gCO_2/km[17]. 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 5g above the cut-off C_c, and zero if it is within 5g 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[18] The inclusion of model-by-

focus on the resulting sales and not on the patterns of substitution within and across car models.

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

[17]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.

[18]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.

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 a 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 which also characterizes the choice across different car models, in Appendix C 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 Equations 1, 2 and 3 on data aggregated at the vehicle-quarter level.

Estimates for Equation 1 on the entire sample, covering registrations in the period January 2005 to January 2011, are reported in Column (1) of Table 2. The estimated tax coefficient is -0.008 and is significant at the 1% level[19]. In absolute values, the corresponding elasticity of car registrations at the sample means is equal to 1.37, implying that on average a 1% difference in VRT corresponds to a 1.37% difference in registrations[20].

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 mentioned in the introduction

[19]Note that our estimate is comparable to those obtained by Yan and Eskeland (2018) on similar data covering registrations in Norway between 2006 and 2014.

[20]The elasticity is computed by multiplying the tax coefficient by the average tax in the estimation sample, and comparable to previous estimates in the literature (Yan and Eskeland, 2018)

Table 2: 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	-	-

Note: Dependent variable: natural logarithm of the number of new passenger car registered, by model, CO_2 emission and quarter. By construction, Columns (2), (3) and (4) only include vehicles observed in two consecutive quarter 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. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

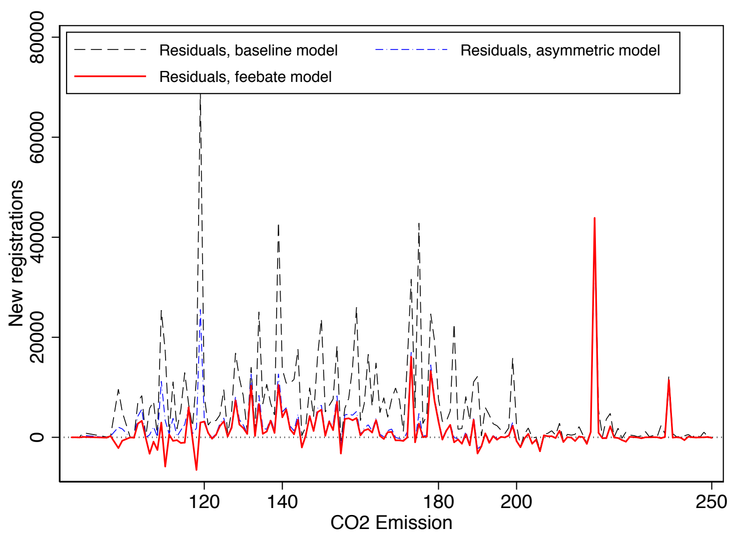
and discuss in more detail in section 6, there are many reasons to expect elasticity to be asymmetric in our context.

Re-estimating Equation (1) on the subsample of vehicles experiencing an increase in VRT yields the estimates in Column (2) of Table 2. 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 Equation (2) and report the results in Column (4) of Table 2: 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 tax decreases -0.014: we interpret this as further (statistically weak) evidence that registrations react more to VRT decreases than to increases.

Given such evidence, we estimate Equation 3 on our sample, to check whether registrations react dis-proportionally strongly to 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. The resulting estimates are shown in Column (5) of Table 2: a tax decrease of 1NOK is associated to a 0.8% increase (captured by coefficient $-\alpha$) in registrations, while a 1NOK rebate is associated to 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 difference from a policy perspective. To answer this question, in Figure 3 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 (Equation 1, estimates shown in Column (1) of Table 2), the asymmetric model for tax cuts (Equation 2, estimates shown in Column (3) of Table 2) and the model with fee-bates (Equation 3, estimates shown in Column (5) of Table 2).



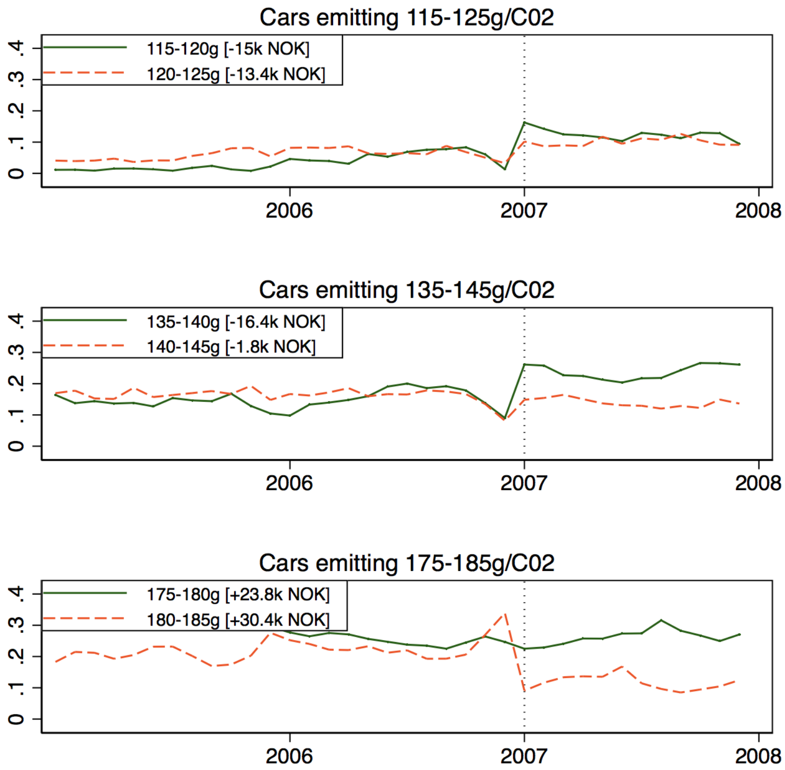
Note: The graph shows the actual and predicted sales of vehicles in the period 2006-2009, by CO_2 emission level. Specifically, *Fitted, baseline model* is the difference between actual registrations and the predicted values from the baseline model without interaction terms, and *Fitted, asymmetric model* is the difference between actual registrations and predicted values from Equation 2.

Figure 3: Goodness of Fit: Actual and Predicted registrations, by CO_2 Emissions

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, which mostly experienced VRT tax cuts and partial rebates, and has important implications for the optimal design of VRT schedules. We can compare alternative VRT reforms schedules based on their effect on tax returns and on pollution. In light of our findings, for any given targeted shift in the distribution of registrations by emissions, a VRT reform which ignores the asymmetric response of registrations to tax cuts and increases will result in overly-generous tax cuts for low emitting vehicles. The resulting tax returns on such vehicles will therefore be too low, with respect to the "ideal" reform which takes into account the asymmetry.

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 4 compares the time series of new registrations for passenger vehicles emitting within a range of $5gCO_2/km$ below and above each of the three thresholds, between January 2006 and December 2007, where each panel corresponds to one threshold.



Note: Categories are defined around the three thresholds used for the registration tax: 120 ± 5, 140 ± 5 and 180 ± 5 g CO_2. The legend in each panel shows the average change in VRT from 2006 to 2007 for cars in the corresponding band, weighted by sales. The average change in VRT, weighted by new registrations, is displayed in brackets in the panel legend.

Figure 4: Share of new vehicles registered by CO_2 intensity category.

Looking at each of the three panels separately and comparing the time series for cars below and above the threshold we notice approximately parallel trends up to 2007 and a divergence afterwards, which might be interpreted as the impact of the reform[21].

Considering the average change in tax between 2006 and 2007, displayed in brackets in the legend of Figure 4, we further notice a tax reduction for cars in the first two panels (larger for cars below the thresholds) and a large increase for cars in the bottom panel (larger for cars above the threshold). Assuming that registrations reacted only to the size of the tax change, regardless of its direction, most of the changes in registrations should therefore appear in the third panel,

[21] Specifically, considering each of the two top panels separately mostly parallel trends with an increase in registrations of cars below the thresholds with respect to those above. The reverse is true in the bottom panel: there the time series of cars below the threshold is approximately flat while the registrations of cars above the threshold sharply decrease in 2007.

where the largest tax change is found. Instead, they seem to be very responsive to the small negative tax changes of the top two panels and less than proportionally responsive to the large positive tax change in the bottom panel. We interpret these patterns as suggestive evidence that the 2007 reform did not have an homogeneous effect, and that impact was dis-proportionally large for low emitting vehicles, whose VRT on average decreased.

To go beyond suggestive evidence, Table 3 presents OLS estimates[22] for Equation 4, which identifies substitutions within car models. De-facto, in each sample we implement a double difference strategy, comparing the pre-post reform change in registrations for vehicles above each threshold to that of vehicles below the same threshold while holding the covariates in Θ and X fixed.

Table 3: 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: $120g \pm 5$		Subsample: $140g \pm 5$		Subsample: $180g \pm 5$	
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.	8,668	8,668	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

Note: 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.

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 (green solid lines in Figure 4), and α the pre-reform differences between

[22] 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 Equation 4 via tobit, getting qualitatively similar results, available on request.

vehicles just below and just above each threshold (gap between the dashed orange and the solid green lines in each panel of Figure 4, before 2007). The coefficient δ captures the double difference: the change from 2006 to 2007 in the difference of registrations of vehicles 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). In each subsample, the double difference can be interpreted as the effect of the reform in 2007, in comparison to 2006. We expect δ to have negative sign if registrations of cars above the thresholds decrease, or registrations below the thresholds increase, or both[23].

We find strong evidence of the effect of the reform for vehicles in the sub-samples 115-125 and 135-145 (first four columns in Table 3), for which the VRT on average decreased in 2007. In these ranges, the registrations of cars just above the thresholds decreased, relative to cars below (this is captured by δ, which is negative and significant even when additional controls are included, in Columns (2) and (4)). In the subsample 175-185g (last two columns in Table 3) the VRT overall increased and, as reported in the legend of Figure 4, vehicles differ in the size of such increase: here we find no statistically significant evidence of an impact of the reform on registrations. In the Appendix, Section C we perform several robustness checks (namely, we use segment-quarter instead of model-quarter fixed effects, we expand the emission ranges from $\pm 5g$ to ± 7 CO_2 around each cutoff and we use the natural logarithm of registrations as dependent variable) and consistently find a sizable impact for cars emitting around 140g CO_2 and a small or null impact for those around 180g CO_2. These results are consistent with our main finding that registrations respond to tax decreases more than to tax increases.

[23]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 obviously 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 175-185g 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 stronger 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 which could explain the asymmetry and which 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 economic and psychology literature suggests 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)[24]. Among the mechanisms compatible with our evidence, the main one is salience: sales might react more to tax decreases because these are more salient to consumers than tax increases[25]. In our setting,

[24]Prospect theory posits that the utility associated to a bundle depends on the consumer's individual reference point and on whether such bundles 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.

[25]The importance of salience in shaping consumers' responsiveness has been underlined in empirical and laboratory evidence on everyday goods (Chetty, Looney and Kroft, 2009; Finkelstein, 2009; Blattberg, Briesch and Fox, 1995) and for private vehicles (Busse et al., 2013). In particular, Chetty, Looney and Kroft (2009) find that consumers' demand under-reacts 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

however, salience probably did not play a decisive role, since total prices shown at purchase include the VRT and, as we detail in Section 6.1, the reforms were widely covered in the media. Therefore, we believe that consumers were well aware of the reforms and their effects on the VRT[26].

Car producers: The reaction to tax decreases might be amplified by producers' response, if these start offering more car versions which qualify for tax cuts (Klier and Linn, 2015), thus offering more options to satisfy consumers' non-pecuniary taste. While this mechanism may play a role in countries with local car manufacturers, Norway is a small market with no domestic producer. It is therefore unlikely that the availability of car versions shifted in response to the reform, especially in the short-medium run. Indeed, graphical (Figure B4) and econometric (Table C5) analysis of the distribution of available vehicles over time offer no evidence that suppliers reacted to the VRT reform by offering a higher variety or number of qualifying vehicle versions[27].

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. The resulting asymmetry would however be the opposite of what we observe, with stronger reactions of sales to tax increase. Analogous asymmetries have been documented in the pass-through of discounts for the car market and of changes in taxes and production costs for non-durable everyday goods[28]. To empirically test whether the pass

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.

[26]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.

[27]Figure B4 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. A 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 C5). In summary, we find no evidence of a supply response.

[28]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, Silva-Risso and Zettelmeyer, 2006). In the context of everyday goods, Benzarti et al. (2017) identifies asymmetric pass-through of changes in taxes in wholesale markets

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[29]. 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 C4 in the Appendix).

Price is however only one of the marketing tools that car dealers can utilize. We speculate that, faced with a 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

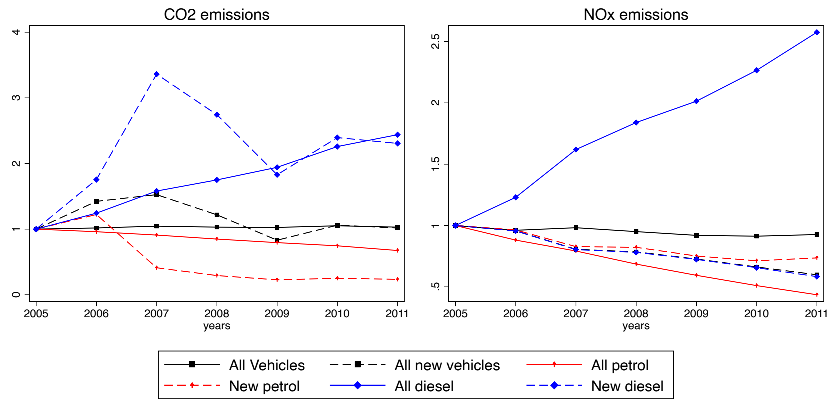
Our main analysis focuses on asymmetric reactions to tax decreases and increases, but the overall aim of the reforms of 2007 and 2009 was to reduce the emissions of CO_2 from passenger vehicles. What was their impact on the size and composition of the passenger vehicles fleet? Did polluting emissions decrease? To answer these questions, we combine our micro-data on registrations with aggregate statistics from Statistic Norway (SSB). In addition, we explicitly consider two main limitations of the reforms: first, the 2007 reform was announced a few months before its actual introduction, resulting in a spike of registrations of highly polluting vehicles in the last trimester of 2006. Second, both reforms are necessarily based on official "in-the-lab" emissions, which may be far from real "on-the-road" emissions.

Figure 5 shows total emissions of CO_2 (left panel) and NOx (right panel) from

and Peltzman (2000) and Blattberg, Briesch and Fox (1995) present evidence of asymmetric reactions to changes in production costs and to marketing promotions in retail markets.

[29] A similar approach has been followed for example in Busse, Silva-Risso and Zettelmeyer (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.

new vehicles[30] and from all vehicles[31], by fuel and year. From 2005 to 2011, total emissions from all passenger cars increased by 2% (from 5100 to 5200 thousand tonnes) for CO_2, and decreased by about 8% (from 16.2 to 14.9 thousand tonnes) for NOx.



Source: Emissions from new vehicles are computed by the authors. Emissions from the entire fleet: SSB estimates, *Table 08940 Greenhouses gases, by source (activity, pollutant, contents and years). Data also shown in Table B1 in the Appendix.*

Figure 5: Changes in CO_2 and NOX emissions from passenger cars, by fuel

To better quantify the importance of this reductions for public health, we use the estimated damage cost of NOx from Samstad et al. (2010) and, social cost of CO_2 from the EU Emission Trading System (ETS) quota price from Duong (2009)[32]. The ETS price of CO_2 fluctuated between €10 and €30 per tonne between 2005 and 2007, while the price for NOx ranged between €20 per kg (for highly populated areas) and €5 per kg (for sparsely populated areas). The total decrease in CO_2 and NOx emissions from new vehicles 2005 to 2011 would then be worth around €5.5 millions if the lower prices for both pollutants are used, and around €23 millions if the higher values are used.

Looking at CO_2 and NOx emission trends, we notice a divergence of time trends between diesel and petrol cars. The emissions derived by petrol cars are decreasing

[30]Total CO_2 emissions for new vehicles are computed based on our registrations 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. We are not aware of any data on mileage by age, so we 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.*

[31]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.*

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

for CO_2 and NOx, for both all cars and new cars. In contrast, those derived by diesel cars are increasing for both all cars and new cars when it comes to CO_2, but only for all cars for NOx[33]. A possible interpretation is that this divergence in emissions from petrol and diesel vehicles is a consequence of the stark increase of diesel shares documented in Figure B1 in Appendix and associated with the 2007 reform. The fact that we do not see an increase of NOx emissions for new diesel cars might be explained with improvements in diesel engine technology.

An additional interesting pattern in Figure 5 is the general increase in CO_2 emissions from any type of new vehicles between 2005 and 2006: to investigate this further we consider the anticipation effect of the 2007 reform.

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 number of articles about the vehicle registration tax ("*engangsavgift*" in Norwegian) in the national newspaper (*Aftenposten*) abruptly increased in 2006 (Figure A1 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 the reduction in CO_2 emissions might have been even larger in the absence of an early announcement.

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 (Figure 6). 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 Figure 6[34].

[33] In 2005, 80% of CO_2 passenger car emissions were due to petrol cars, while in 2011 only 52%, for NOx they went from 76% to 33%. Actual figures in Table B1.

[34] 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

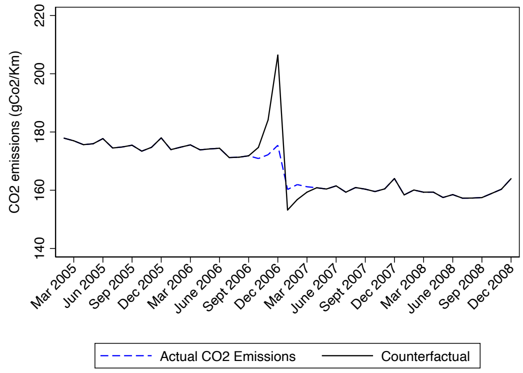


Figure 6: Monthly average CO_2 intensity of new vehicles

This comparison suggests that the announcement of the reform was accompanied by an increase in emissions. Based on the trends we observed in Figure 4, we attribute the increase in emissions to the sharp increase of registrations for high CO_2 emitting vehicles (bottom Panel in Figure 4) and to the decrease in registrations for middle and low emitting vehicles (top and mid Panels in Figure 4). With respect to the comparison benchmark in Figure 6, average emissions were 47g per km higher in the last trimester of 2006, and 14 lower in the first trimester of 2007. To put these numbers in perspective, 47g of CO_2 amount to 27% of the average emission intensity of the last trimester of 2005, and 14g of CO_2 correspond to 9% of the average emission intensity of the first trimester of 2008. Given the average total mileage in this period (32,206 million km per year), the extra 47g of CO_2 per km translate to approximately 1503 tonnes per year. Based on the ETS-provided social costs per ton of CO_2, the monetary value of the additional pollution would range between €15000 and 45000 per year.

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

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

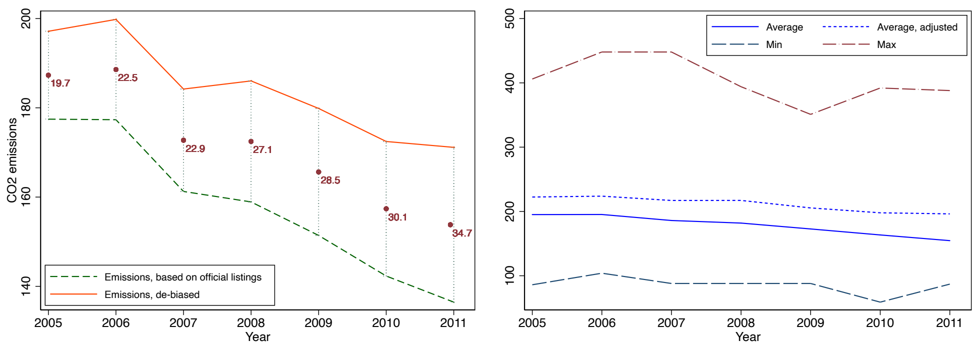
$$\theta = \Delta Emissions_{(QI2007,QI2008)} - \Delta Emissions_{((QII,III,IV2007),(QII,III,IV2008))}$$

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

buyers increase (delay) gasoline purchases before fuel tax increases (decreases).

Real and official emission intensity

Recent scandals point the finger to the gap between the official emission level reported by manufacturers and "real" (road-based) emissions levels. "Real" measures are typically based on users' reports of fuel consumption per kilometer, combined with lab measures of emissions per liter of fuel to obtain the estimated total emissions per kilometer. The left panel of Figure 7 shows the evolution of the gap between the average official and "real" emissions, from 2005 to 2011[35]. First of all, we notice a decline in both official and "de-biased" average emissions, which might be driven by several factors including technological progress, consumers shifting towards greener vehicles, and the producers' reaction to increasingly strict regulations or quotas introduced in other markets, such as the European Union[36].



Note: Emissions based on official listings are yearly averages of CO_2 intensities, weighted by number of new registration. The de-biased emissions in the left panel and the adjusted average emissions in the right panel are obtained by multiplying such averages by the brand-specific coefficients obtained in Tietge et al. (2017). The labels in the left panel show the corresponding gap between official and "real" emissions.

Figure 7: Officially reported and de-biased CO_2 emission rates

The second striking pattern is that the decrease is stronger for official emissions than for de-biased ones, leading to a widening of the gap between the two from 20% to 35% between 2005 and 2011. Measurement errors in the lab or in drivers' reports might explain part of the gap, but probably not its widening over time. In

[35]We are grateful to Uwe Tietge for kindly sharing with us the real world emission data from Tietge et al. (2017).

[36]The decrease in average official emissions is not peculiar to Norway: Figure B2 shows that several other European countries experienced a similar trend.

addition, the gap increases over time for all nine car maker groups for which "de-biased" emissions data are available (Figure B3 in the Appendix), suggesting that the widening of the gap is not due to composition effects.

The right panel of Figure 7 shows that the minimum emission level among all new cars registered is approximately the same every year between 2005 and 2011, with the exception of a temporary drop in 2010. The average and the maximum level, however, steadily declined throughout the period, and the average gets increasingly closer to the minimum. This suggests that consumers are shifting towards (officially) greener cars, possibly in response to incentives such as those put in place by the VRT reforms, by retailers or indirectly by technological progress making greener vehicles progressively cheaper or more reliable or otherwise attractive over time.[37]

As seen above, between 2005 and 2011 total CO_2 emissions from new passenger vehicles, based on official emissions levels per vehicles, decreased by 80 thousand tonnes (going from 349 to 269 thousand tonnes) for CO_2 and by 1.3 thousand tonnes for NOx. Correcting the data for CO_2 using the brand-specific coefficients in Tietge et al. (2017), the total decrease in emissions would be only about 56 thousand tonnes (from 419 to 363). In other words, ignoring the increasing of the gap leads to an overestimate of around 30% in the reduction of CO_2 emissions from new passenger 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 passengers vehicle taxes linking them to the content of 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 an overall success of such reforms and the increase in market shares for

[37] Average emissions are weighted by the number of vehicles sold and are characterized by a sharp and relatively smooth decline. Similar data for NOx emissions are unfortunately not available. As mentioned above, the decline in maximum emissions might reflect the introduction of producer quotas in other countries.

low emission vehicles, mostly driven by the increase of diesel market shares. 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)[38].

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. We follow the standard empirical methodology in this literature, but we allow the tax elasticity of new cars registrations to depend on the direction of the tax change. The resulting estimates suggest that new registrations react to tax decreases and partial rebates significantly (in economic and statistical terms) more than to tax increases. This can have important policy implications for the design of optimal taxation. We find that for any given targeted shift in the distribution of registrations by emissions, a VRT reform that ignores asymmetric responses will result in overly-generous tax cuts for low emitting vehicles. The resulting tax returns on such vehicles will therefore be too low, with respect to the "ideal" reform which takes into account the asymmetry. In our context, it also implies that most of the reduction in emissions, which has been attributed to the reform, is driven by changes in the registrations of vehicles emitting in the lower and middle CO_2 ranges. In addition, the asymmetry we document might explain why in other countries the sales of relatively "green" vehicles have been shown to react so strongly to tax cuts (Alberini and Bareit, 2019; D'Haultfœuille, Givord and Boutin, 2014).

To further demonstrate such heterogeneous effects by emission ranges, we adopt a difference-in-difference approach and 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 for vehicles emitting around 120 and around 140 grams of CO_2 per km, but no detectable effect for those emitting around 180 grams. 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.

Our main contribution to the literature is the empirical evidence of stark differ-

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

ences in equilibrium responses to tax changes, depending on the direction of changes. Our results (i) are confirmed by several variations of our main estimating equation, (ii) help improve the fit (in-sample) of the model, (iii) could explain the stark heterogeneity in effects for the 2007 VRT reform across emission ranges, and (iv) are in line with empirical findings in other contexts, such as fuel taxes and non-durable goods.

In addition, we discuss and present empirical evidence of two important shortcomings of the first reform, which may also apply to similar reforms introduced in other countries. The first problem is due to the fact that the reform was hardly unexpected: consumers had months to best respond, resulting in a large spike in emissions right before the reform implementation. Back of the envelope calculations using official quotes for the social costs of CO_2 emissions suggest a loss of between 15 and 45 thousand Euros per year associated to this anticipation effect.

The second problem is the fact that this policy instrument is based on official laboratory measurements of emissions, which are increasingly far from on-road values. Based on brand-specific data reported by Tietge et al. (2017), we estimate that the increasing gap between on-road and labor emissions could absorb around 30% of the estimated total reduction in official CO_2 emissions from new petrol and diesel vehicles between 2005 and 2011.

To complete our discussion of the VRT reforms' effects, we complement our data with official aggregate statistics from SSB and show that total CO_2 emissions from new petrol and diesel 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 new diesel vehicles also sharply increase. Total emissions, from both new and older passenger vehicles, slightly increased for CO_2 and decreased for NOx between 2006 and 2011. This change is clearly not purely due to the reform, but also to other changes, including technological progress. Based on literature reports of estimated social costs per unit of polluting emissions, the resulting social benefit could range between 5 and 23 million Euros.

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Appendix

A Details of the Reform

Table A1 shows the unitary tax per kg of car weight, per kW of engine power , per ccm of engine volume (only untile 2007) and per gram of CO_2 (only from 2007), in the time period which is relevant for the study.

Table A1: **Bands for 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)

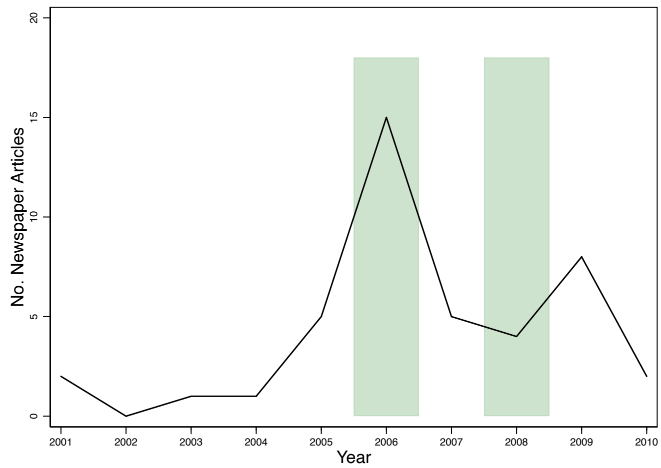
Table A2 shows the average change in registration tax between 2006 and 2007 for vehicle emitting just below or above each of the CO_2 emission thresholds 120, 140 and 180. In general, the VRT decreased for low emitting vehicles, and more so for those emitting just below 120 and 140 grams. While the VRT increased for vehicles emitting below and above the 180 threshold, the increase was larger above the threshold.

Table A2: 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

[1] Thousand NOK (2012 currency). Statistics weighted by total number of cars sold in the period 2006-2007.

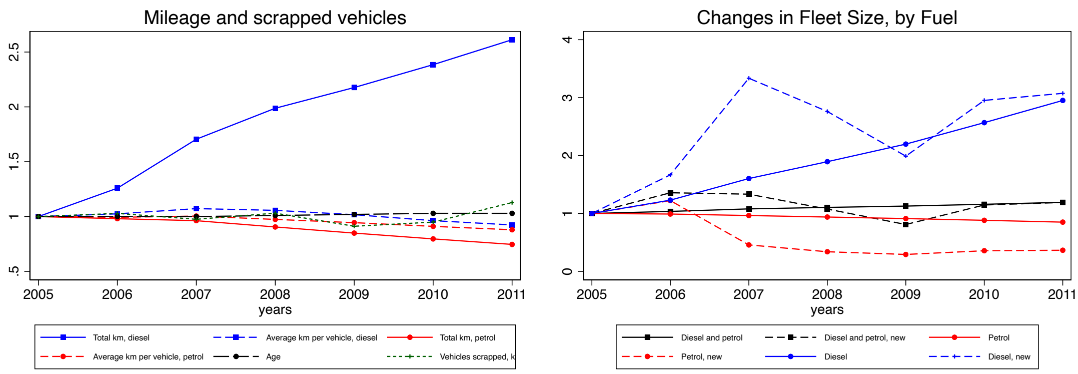
A.1 Evidence of media coverage before the introduction of the reform



Source: Aftenpost website, word search. The calendar years when a new reform is introduced are highlighted in the graph with a green bar.

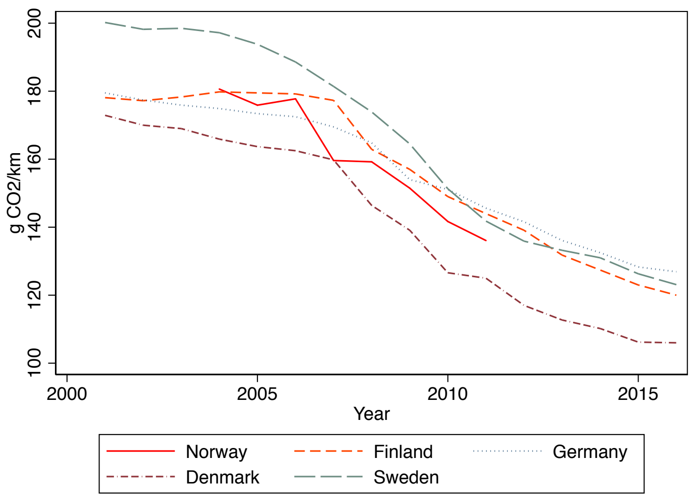
Figure A1: Number of newspaper articles about the VRT

B Fleet Characteristics



Note: In the left panel, all time series are normalized to one in 2005. 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.*

Figure B1: Other characteristics of the passenger vehicles fleet



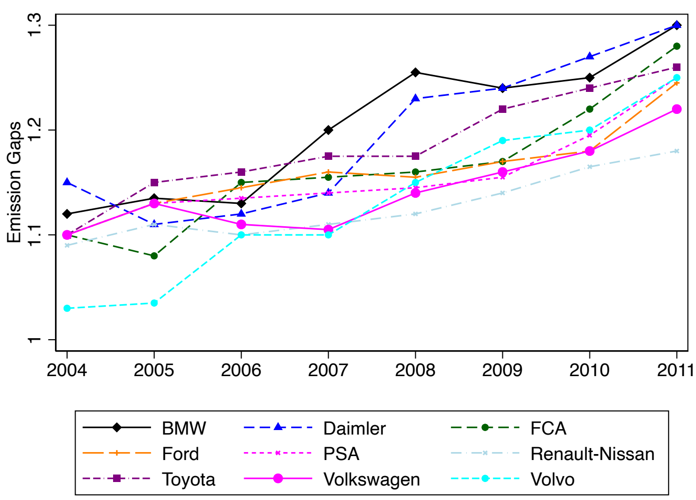
Data source: Table A1.3 in European Environment Agency (2017).

Figure B2: Comparing average fleet's emissions of Norway and other countries

Table B1: Polluting Emissions

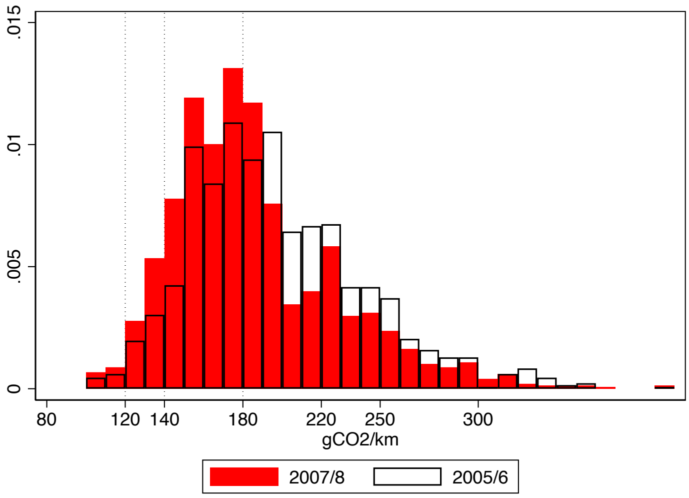
	CO_2		NOx	
	2005	2011	2005	2011
New passenger vehicles				
Petrol	180	137	0.03	0.02
Diesel	169	752	0.25	0.15
Total, new passenger vehicles	349	889	0.28	0.17
All passenger vehicles				
Petrol	4061	2737	12	5
Diesel	1027	2505	3.713	10
Total, all passenger vehicles	5088	5242	16	15

Note: All data in thousand tonnes. Data for new vehicles: authors' computation, obtained as sum of emissions from all new registered vehicles (based on official emissions listed on registration records) times average yearly mileage. Aggregate data by fuel: SSB estimates, *Table 08940 Greenhouses gases, by source (activity, pollutant, contents and years).*



Note: Gaps by brand and year obtained in Tietge et al. (2017).

Figure B3: Gaps between official and "de-biased" CO_2 emission rates, by brand



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

Figure B4: Cars available for Purchase

B.1 Summary Statistics for the Estimation Sample (2004-2011)

Table B2: Summary Statistics

	Mean	Std Dev.	Min	Max	Median
Total tax in Thousand NOK	125.02	76.12	9.79	1529.32	108.31
CO2 intensity (gCO2/km)	159.45	33.68	59.00	448.00	157.00
Weight	1388.72	235.61	510.00	5980.00	1395.00
Power [KW]	87.73	23.84	30.00	593.00	83.00
Cilinder volume [ccm]	1778.28	370.20	698.00	7011.00	1798.00
Diesel	0.62	0.49	0.00	1.00	1.00

Note: sample size 935,586 new passenger cars sold between 2004 and 2011 (petrol and diesel only).

C Additional Results

Table C1: Difference in Difference Around the Tax Thresholds, Range $\pm 7g$

Eq. (4): $Sales = \alpha AboveC + \gamma \cdot After2007 + \delta \cdot (AboveC \cdot After2007) + \delta \cdot X + \mu$						
	Subsample: $120g \pm 7$		Subsample: $140g \pm 7$		Subsample: $180g \pm 7$	
	(1) Number of cars	(2) Number of cars	(3) Number of cars	(4) Number of cars	(5) Number of cars	(6) Number of cars
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.	8668.00	8668.00	16504.00	16504.00	18757.00	18757.00
R^2	0.10	0.11	0.08	0.09	0.12	0.13

Note: 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 C2: Difference in Difference Around the Tax Thresholds, Logarithmic Form

Eq. (4): $Sales = \alpha AboveC + \gamma \cdot After2007 + \delta \cdot (AboveC \cdot After2007) + \delta \cdot X + \mu$						
	Subsample: $120g \pm 5$		Subsample: $140g \pm 5$		Subsample: $180g \pm 5$	
	(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.	8,668	8,668	16,504	16,504	18,757	18,757
R2	0.14	0.15	0.13	0.14	0.17	0.18

Note: 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 C3: Difference in Difference Around the Tax Thresholds, Segment-Quarter Fixed effects

Eq. (4): $Sales = \alpha AboveC + \gamma \cdot After2007 + \delta \cdot (AboveC \cdot After2007) + \delta \cdot X + \mu$						
	Subsample: $120g \pm 7$		Subsample: $140g \pm 7$		Subsample: $180g \pm 7$	
	(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

Note: 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 C4: Pass-through of VRT variations to listing prices

	Entire sample	Subsample: VRT increased	Subsample: VRT decreased	Interaction
	(1)	(2)	(3)	(4)
	b/se	b/se	b/se	b/se
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	3,957	992	1,318	4,316
R^2	0.524	0.525	0.614	0.486

Note: 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 C5: 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	3,152

Dependent variable: Number of car specifications below one of the three VRT thresholds introduced in 2007. Standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.