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Charging Drivers by the Pound: How Does the UK Vehicle Tax System Affect CO_2 Emissions?

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Abstract

Policymakers have been considering vehicle and fuel taxes to reduce transportation greenhouse gas emissions, but there is little evidence on the relative efficacy of these approaches. We examine an annual vehicle registration tax, the vehicle excise duty (VED), which is based on carbon emissions rates. The UK first adopted the system in 2001 and made substantial changes to it in the following years. Using a highly disaggregated dataset at the trim-variant level of UK registrations and characteristics of new cars, we estimate the effect of the VED on new vehicle registrations and their carbon emissions. The VED increased the adoption of low-emissions vehicles and discouraged the purchase of very polluting vehicles, but it had a small effect on aggregate emissions. Using the empirical estimates, we compare the VED with two hypothetical taxes: a tax proportional to carbon emissions per kilometer, and a carbon tax. The VED reduces total emissions from new cars twice as much as the emissions rate tax but by half as much as the emissions tax. Much of the advantage of the emissions tax arises from adjustments in miles driven, rather than the composition of the new car sales.

Keywords CO_2 emissions · Vehicle registration fees · Carbon taxes · Vehicle excise duty · UK

JEL Classification H23 · Q48 · Q54 · R48

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1 Introduction

Transportation accounts for about 14% of global greenhouse gas emissions and 23% of carbon dioxide (CO_2) emissions (IPCC 2014). To reduce these emissions, many countries have adopted tighter fuel economy and CO_2 emissions rate standards for passenger vehicles, as well as other policies such as plug-in vehicle subsidies.[1] Countries adopting such policies account for about three-quarters of global passenger vehicle fuel consumption and include developed and developing countries.

Many countries are redesigning their vehicle tax systems to complement fuel economy standards. This approach is particularly common in Europe, where vehicles are often subject to a sales tax at the time of purchase, as well as annual registration (circulation) fees. For example, France offers subsidies for purchasing vehicles with low CO_2 emissions rates and imposes substantial taxes on purchasing vehicles with high emissions rates. In Germany, a vehicle's circulation tax increases linearly with its emissions rate, whereas in the UK, it is a step function of the emissions rate.

The literature has typically estimated the average effect of CO_2 taxes on new vehicle registrations, finding that the taxes reduce average new vehicle emissions rates (e.g., Adamou et al. 2012; Ciccone 2014; D'Haultfœuille et al. 2014; Konishi and Meng 2014; Klier and Linn 2015; Alberini and Bareit 2016; Yan and Eskeland 2016). A common approach to measure consumer responses to vehicle taxes is to estimate a price coefficient in a vehicle demand model and use the coefficient to simulate the effect of a vehicle tax, assuming that consumers respond to the vehicle tax the same way they respond to the vehicle price. This assumption has been adopted by Adamou et al. (2014), D'Haultfœuille et al. (2014), and Grigolon et al. (2015), among others. However, Brockwell (2013), Li et al. (2014), Rivers and Schaufele (2015), and D'Haultfœuille et al. (2016) provide evidence contradicting this assumption.[2] Moreover, some studies assume that consumers respond similarly to purchase taxes as they do to discounted annual registration taxes. However, consumers could respond differently to these taxes for a variety of reasons, such as uncertainty or salience (Chetty et al. 2009). This has potentially important implications in terms of tax design.

Many countries have also considered carbon taxes.[3] One simple way to implement a carbon tax is through a fuel excise tax proportional to the carbon content of the fuel. Fuel excise taxes are present virtually everywhere. Although some studies conclude that carbon taxes are more efficient than vehicle standards at reducing carbon emissions (Jacobsen 2013), others find that consumers undervalue the vehicle's fuel economy (Grigolon et al. 2015; Allcott and Wozny 2014). If that is the case, instruments such as vehicle taxes, subsidies, or feebates could be more efficient than carbon taxes (Allcott et al. 2014).

In sum, policymakers aiming to reduce carbon emissions can tax vehicles or fuels, and if they tax vehicles, they must decide how to structure the system. Much of the literature

[1] A vehicle's CO_2 emissions rate is inversely proportional to its fuel economy.

[2] In their study on feebates in France, D'Haultfœuille et al. (2016) show that 40% of the effect on emissions is due to a change in preferences, above and beyond the increase in vehicle costs. This may be because of a higher salience of taxes than prices (perhaps as a result of heavy media coverage), the perception that tax changes are more persistent than price changes, and the fact that the tax itself might convey additional information on the environmental impact of the good.

[3] Because there is a fixed, proportional relationship between CO_2 emissions rate and fuel economy within fuel type, for the purposes of this paper a carbon tax can be considered equivalent to a fuel tax, the only possible difference being the point of collection (at the pump or as a yearly amount like the current registration tax).

has imposed strong assumptions on consumer behavior in comparing these tax approaches, and these two sets of alternatives are rarely compared explicitly with one another.

In this paper, we analyze an annual vehicle registration tax, the vehicle excise duty (VED), which the UK adopted in 2001. Before adoption of the VED, annual vehicle registration taxes depended on engine size, but since 2001, taxes have depended on CO_2 emissions rates. The taxes are imposed each year the vehicle is owned and driven. There is considerable variation in VED rates over time and over different emissions levels. For instance, in April 2005, taxes ranged from £65 for vehicles with emissions rates below 100 grams of CO_2/kilometer (g/km) to £165 for vehicles with emissions rates above 185 g/km. In May 2009, taxes ranged from £0 for vehicles with emissions rates below 100 g/km to £405 for vehicles with emissions rates above 255 g/km.[4] The UK registration tax system thus penalizes vehicles with high emissions rates and provides discounts to vehicles with low emissions rates. The tax advantage for low-emissions vehicles has increased over time.

Because its tax rate is based on group bands, one would expect the VED to induce substitution between cars belonging to different bands, but not within bands. On the one hand, the VED system is very simple and understandable to consumers. On the other hand, a registration tax with a rate strictly proportional to emissions rates per km can push more consumers to switch to clean cars, and a carbon tax can also reduce miles driven.

Focusing on the VED tax changes allows us to relax assumptions on consumer responses to vehicle taxes and fuel prices. Using a highly disaggregated dataset at the trim-variant level of UK new car registrations and characteristics, we estimate the effects of the taxes on new car registrations. As in Marion and Muehlegger (2008) and Li et al. (2014), we test the assumption made by the previous literature that consumers respond equally to a change in vehicle tax and a change in vehicle price. We reject this hypothesis, which is consistent with our reduced-form approach that omits vehicle price as an independent variable and estimates the effect of taxes on equilibrium registrations, instead of using either the discounted sum of vehicle taxes and vehicle price or just vehicle price. The tax effect is identified by variation in tax rates across vehicles and over time. This approach does not impose the assumption that consumers respond similarly to vehicle prices as to taxes, or that they respond similarly to annual registration as to purchase taxes. It is thus in sharp contrast with much previous literature, where the dependent variable is log sales or log market shares, and vehicle price (plus tax) is entered linearly in the right-hand side of the regression equation and must be instrumented for, since it is endogenous with sales or shares.[5]

We use the results to compare the effects on new registrations, tax revenue, and carbon emissions of several policies against the pre-VED tax system: (i) the 2005 VED rates, (ii) the actual VED rates imposed between 2005 and 2010, (iii) a tax proportional to carbon emissions *rates*, and (iv) a carbon tax (depending on both vehicle emissions rates and miles driven). We find that the actual VED has reduced emissions rates from newly registered

[4] The CO_2 emissions rate is inversely related to the fuel economy of the car. For a gasoline-powered car, 100 g CO_2/km are equivalent to a fuel economy of about 56 miles per gallon (mpg), while 185 g CO_2/km are equivalent to a fuel economy of 30 mpg and 255 g CO_2/km imply 22 mpg.

[5] When we describe our model as reduced-form, we simply mean that all of the variables in the right-hand side are exogenous. We do not use models of shares (Berry 1994) as our starting point, and for this reason our "reduced-form" approach is different from the reduced form that would be obtained if price were considered endogenous. The reduced form of a log share model would include vehicle attributes, the VED and the usual Berry et al. (1995) instruments. The latter have no role, and are therefore not included, in our specification.

vehicles by almost 2% compared with the preexisting engine tax. Moreover, a carbon tax that achieves the same revenue as the VED would have reduced emissions by about twice as much, whereas the proportional tax would have reduced emissions by about half as much.

The structure of the VED explains these results. The VED severely penalizes the most polluting vehicles and greatly favors the cleanest ones, which explains why the VED causes greater emissions reductions than the proportional tax. However, the VED provides small incentives for consumers to switch among moderately polluting vehicles—and it is the latter that account for most new car registrations. A carbon tax has a similarly small effect on new vehicle choices but attains greater emissions reductions because it encourages people to reduce miles driven.

The reminder of the paper is organized as follows. Section 2 provides a background of the UK vehicle registration tax scheme. Section 3 describes the vehicle registration data. Section 4 shows the estimation model and the identification strategy. Section 5 presents the results, and Sect. 6 concludes.

2 Background

Before March 1, 2001, the VED depended on the size of the engine. Owners of cars with larger engine capacity paid a higher registration fee. Since that date, a vehicle is placed in a CO_2 emissions “band” that determines its tax. The higher the emissions rate, in g/km, the greater the VED amount, and the tax varies discretely across bands. Cars first registered before March 2001 continued to pay a registration tax based on engine size.

Initially, there were four bands. Band A included cars with emissions rates up to 150 g/km; band B, those with rates between 151 and 165 g/km; band C, those with rates between 166 and 185 g/km; and band D, those with rates of 186 g/km or more.[6] In March 2002, band A was broken into bands AA (less than 120 g/km) and A (121–150 g/km), while all other bands remained unchanged. In March 2003, vehicles that emitted 100 g/km or less were placed in band AAA, those between 101 and 120 g/km remained in band AA, and those between 121 and 150 g/km continued to be in band A (see Tables 1, 2).

In April 2005, the bands were renamed, with no changes to the emissions range for each band (see Tables 3, 4). In March 2006, band F was split to form a new band F (186–225 g/km) and band G, which includes vehicles with emissions rates 226 g/km and higher. Major revisions to the system occurred in May 2009, when the existing bands were redefined using 10 g/km intervals for the first nine bands, and new bands were added. As shown in Tables 3 and 4, the highest band is M, with emissions rates of 256 g/km or more.[7] During this period, vehicles registered for the first time before 2001 continued to pay a tax based on their engine size, but those rates changed as well (Table 5).

[6] It is unclear how the government selected the band thresholds. A 1998 consultation document by the UK treasury on possible changes to the registration tax mentions that “the majority of current new vehicles produce 150–250 g of CO_2 per km; the average is about 185 g/km,” and that “The current EU aim is to reduce average fleet emissions rate to 120 g/km by 2010 […] Manufacturers envisage an interim target of 165–170 g/km by 2003.” The initial bands may have been based on these numbers.

[7] Starting in 2006, cars that were first registered after 2001 but before the current fiscal year may be given a slightly different tax schedule than the one shown in Table 4, which refers to new cars.

In sum, over the years, the number of bands increased, the thresholds between bands changed, and the registration fees were changed. The dominant trend was to increase the tax differences between low- and high-emissions vehicles. These tax changes yielded two sources of tax variation. First, in the cross section, taxes vary across cars because of differences in emissions rates. Second, the tax applied to a car with a specific emissions rate may change over time because of changes in the definitions of the bands and in the tax rates. Until 2006, diesel fuel cars paid a slightly higher VED (between £5 and £15 more) than gasoline vehicles that had the same emissions rate.

3 Data

Our main data source is a large dataset compiled by R. L. Polk & Company, where the unit of observation is a make-model-trim variant (throughout the paper, make is the same as brand).[8] For each such unit, we observe the number of new registrations in the UK each month from January 2005 to October 2010.

In this paper, attention is restricted to gasoline or diesel passenger cars, and we exclude vans and commercial or other large vehicles because of incomplete coverage. The excluded vehicles account for only 1.30% of the original sample. We are also forced to drop from the analysis variants with no price information (0.27% of the sample).

Although the original data are at the monthly level, we use the policy period as the time interval for our analysis to reduce measurement error arising from monthly fluctuations in vehicle registrations not related to the VED. The policy period is essentially the fiscal year and includes a unique set of VED bands and rates. The six policy periods are described in Table 6. The table shows that the policy periods exclude months in which the VED bands or rates changed during the month rather than at the beginning of the month.

We tally the number of new registrations for each make-model-trim variant over each policy period, thus forming a panel dataset where the cross-sectional unit is the make-model-trim variant. The make-model-trim variant is a highly disaggregated unit of observation; the data include 55 makes, 507 make-models, 3130 make-model-trims, and 36,110 make-model-trim variants. The maximum panel length is six, and the panel is unbalanced because some cross-sectional units enter or exit the market during our study period.

Toward the end of our study period, new vehicle registrations declined sharply, especially after 2007 (Fig. 1). This is likely due to the major recession that started in 2008, which reduced new car registrations across Europe. In our sample, a make-model has an average of about 21,245 new registrations, while a single variant has an average of about 299. About 13% of the variants had no new registrations during a given policy period. On average, each make has 205 different variants per period and includes vehicles with 5 different nominal VED rates per period. As we explain below, the effect of taxes on new registrations is identified by within-make and period tax variation.

On average, vehicles became cleaner over time. Figure 2 shows unweighted average CO_2 emissions rates by variant and by make-model. In less than 6 years, average emissions rates by variant declined by about 30 g/km, from about 190 g/km to 160 g/km. We observe a similar trend when looking at average emissions rates by make-model—from about 217 g/

[8] A unique variant is an observation with a given make-model-trim, number of doors, market segment, body type, two- or four-wheel drive, transmission type and number of gears, fuel type, engine size, weight, length, height, number of cylinders, horsepower, fuel consumption rate, market segment, and price.

Table 1 VED bands classification for new cars between 2001 and 2003

CO_2 emissions rate (g/km)	Mar-01	Mar-02	Mar-03
100 or less	A	AA	AAA
101–120	A	AA	AA
121–150	A	A	A
151–165	B	B	B
166–185	C	C	C
186 and higher	D	D	D

Table 2 VED rates for new cars between 2001 and 2003

CO_2 emissions rate (g/km)	Mar-01	May-02	May-03
100 or less	£100	£70	£65
101–110	£100	£70	£75
111–120	£100	£70	£75
121–130	£100	£100	£105
131–140	£100	£100	£105
141–150	£100	£100	£105
151–165	£120	£120	£125
166–175	£140	£140	£145
176–185	£140	£140	£145
186–200	£155	£155	£160
201–225	£155	£155	£160
226–255	£155	£155	£160
256 and above	£155	£155	£160

Table 3 VED bands classification for new cars after April 2005

CO_2 emissions rate (g/km)	Apr-05	Mar-06	May-09
100 or less	A	A	A
101–110	B	B	B
111–120	B	B	C
121–130	C	C	D
131–140	C	C	E
141–150	C	C	F
151–165	D	D	G
166–175	E	E	H
176–185	E	E	I
186–200	F	F	J
201–225	F	F	K
226–255	F	G	L
256 and higher	F	G	M

Table 4 VED rates for new cars after April 2005

	CO_2 emissions (g/km)	Apr-05	Mar-06	Mar-07	Mar-08	May-09	Apr-10
A	100 or less	£65 (£75)	£0	£0	£0	£0	£0 [£0]
B	101–110	£75 (£85)	£40 (£50)	£35	£35	£35	£0 [£20]
C	111–120	£75 (£85)	£40 (£50)	£35	£35	£35	£0 [£30]
D	121–130	£105 (£115)	£100 (£110)	£115	£120	£120	£0 [£90]
E	131–140	£105 (£115)	£100 (£110)	£115	£120	£120	£110 [£110]
F	141–150	£105 (£115)	£100 (£110)	£115	£120	£125	£125 [£125]
G	151–165	£125 (£135)	£125 (£135)	£140	£145	£150	£155 [£155]
H	166–175	£150 (£160)	£150 (£160)	£165	£170	£175	£250 [£180]
I	176–185	£150 (£160)	£150 (£160)	£165	£170	£175	£300 [£200]
J	186–200	£165 (£170)	£190 (£195)	£205	£210	£215	£425 [£235]
K	201–225	£165 (£170)	£190 (£195)	£205	£210	£215	£550 [£245]
L	226–255	£165 (£170)	£210 (£215)	£300	£400	£405	£750 [£425]
M	256 and higher	£165 (£170)	£210 (£215)	£300	£400	£405	£950 [£435]

VED rates for gasoline vehicles. If rates are different for diesel vehicles, they are reported in parentheses. Rates in April 2010 are different for the first year and the following years. Rates for the years after the first are reported in square parenthesis

Table 5 VED rates for cars registered before 2001 (engine-based tax)

Engine size	Apr-05	Mar-06	Mar-07	Mar-08	May-09	Apr-10
Up to 1549 cc	£110	£110	£115	£120	£125	£125
Over 1549 cc	£170	£175	£180	£185	£190	£205

Table 6 Policy periods used in this analysis

Policy period	Beginning	End	Duration in months (30 days)
1	Apr-05	Feb-06	9.2
2	Apr-06	Feb-07	10.2
3	Apr-07	Feb-08	10.2
4	Apr-08	Apr-09	12.2
5	May-09	Mar-10	10.1
6	Apr-10	Oct-10	6.1

km to 195 g/km. Because the average is not weighted by registrations, the change reflects the evolution of vehicles offered in the market.[9]

[9] The reduction in average emissions rates comes from improvements in vehicle technology, as well as entry and exit of variants. It is unlikely that such improvement, entry, or exit is caused by manufacturers' direct response to changes in the VED for two reasons. First, the UK accounts for just 10% of the EU car market, and other European countries have different tax schemes. Second, manufacturers require time to design their vehicles, and it is difficult to predict the VED changes. Third, the small changes in VED would only affect exit for the likely small number of variants that would have been barely profitable without the VED change.

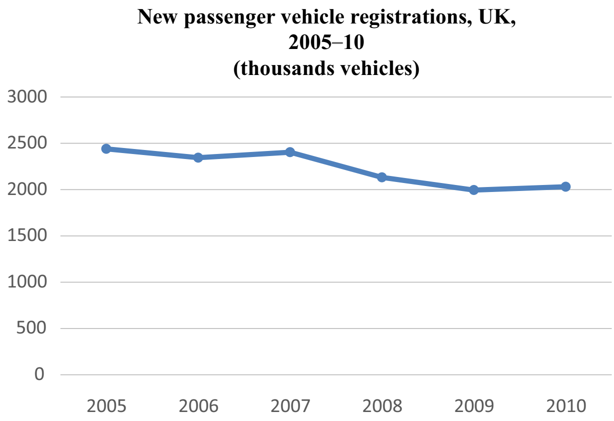

Fig. 1 New passenger vehicle registrations in the UK between 2005 and 2010. *Source*: European Automobile Manufacturers Associations (ACEA)

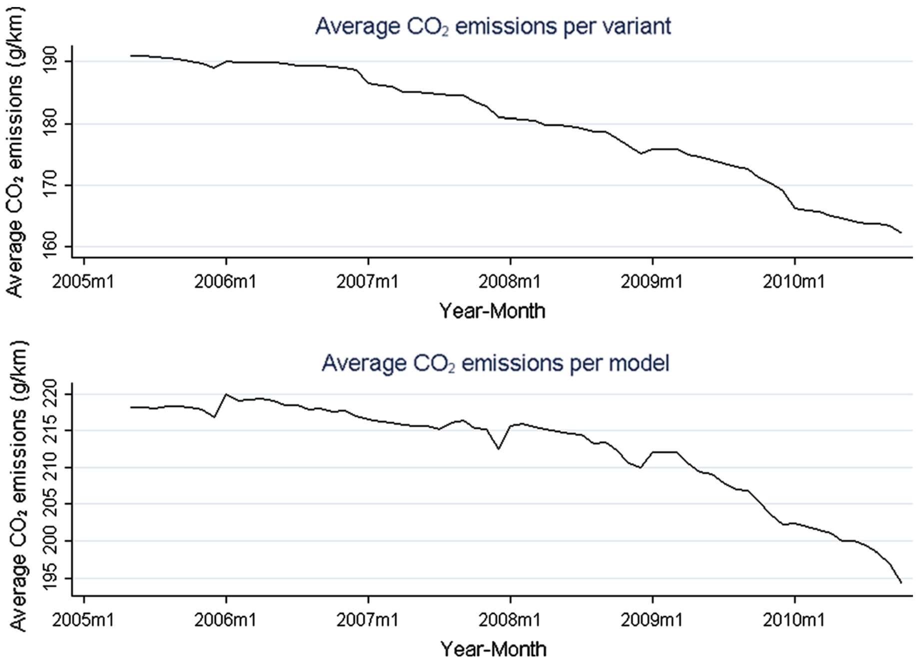

Fig. 2 Average CO_2 emissions per variant and model (not registrations-weighted)

Table 7 shows registrations-weighted summary statistics of the vehicles in our sample. Although the average annual VED is quite small compared with the average price of a vehicle, because it is paid during the entire lifetime of the vehicle, its discounted sum can be fairly large.[10] This table reports the real VED amount for the first year of registration of a vehicle and the total amount for an estimated vehicle lifetime of 14 years (SMMT 2016). In calculating the estimated vehicle lifetime VED, we assume consumers expected nominal VED rates not to change over time. In most cases, the nominal VED amount paid in the first year of registration is the same for all subsequent years the vehicle is registered, which is consistent with our assumption on consumer expectations. The one exception is that in the last period of our sample (April–October 2010), the VED had different rates for the first year of registration and for the following years.

The main statistical analysis relies primarily on the data just described, and the policy simulations incorporate data on miles traveled as well. We obtain information about annual UK vehicle miles driven, vehicle characteristics, and driving costs from the UK National Travel Survey (NTS). The UK NTS is conducted each year and collects information from households about individual trips taken during a specified period, car ownership and characteristics (including miles driven each year and odometer reading), and household sociodemographics. We use six waves of the UK NTS, from 2005 to 2010, which matches the vehicle registrations dataset. The NTS sample contains 81,855 households.[11] We consider only gasoline and diesel cars owned by households, and for estimating the relationship between miles driven and vehicle characteristics, we also use only observations with information on carbon emissions (49% of all vehicles and 31% of all households covered by the survey). The vast majority of these vehicles with no CO_2 emissions rates were bought before 2001, when reporting emissions rates was voluntary. Because our focus is on new vehicles bought between 2005 and 2010, dropping the older vehicles does not affect our analysis.

The NTS dataset reports the exact CO_2 emissions rate of each vehicle, as specified by the automaker, when available, but does not contain information on fuel economy. We construct the vehicle's fuel economy using data from the UK Driver and Vehicle Licensing Agency on passenger car emissions and fuel economy, taking advantage of the fact that the emissions are proportional to the vehicle's fuel consumption rate (in liters per 100 km) and that the proportionality factor is different for diesel and gasoline (see "Appendix A").

4 Empirical Model

The analysis is conducted in two steps. First, we estimate the relationships among fuel prices, vehicle taxes, and new registrations. Second, we use the estimated relationships to simulate the effects of various tax systems. This section explains the methodology for the first stage.

The goal of the first stage is to understand the short-run effects of hypothetical changes in vehicle or fuel taxes on the registrations-weighted average CO_2 emissions rate of new cars registered in the UK. The short run refers to a period of time in which the attributes of cars in the market are fixed, or roughly 1 year (Klier and Linn 2015). The short-run effects of vehicle and tax changes therefore depend on the resulting changes in equilibrium registrations of each car sold in the market.

[10] With the assumptions made in our main analysis—a vehicle lifetime of 14 years and a discount rate of 6%—the discounted sum of the VED is on average about 10% of the average price of a vehicle.

[11] We form multiyear cross sections, as the households interviewed as part of the UK NTS are different every year.

Table 7 Summary statistics, April 2005–October 2010 (registrations-weighted)

Variable	Mean	Median	SD
CO_2 emissions (g/km)	159	153	36
Real price (2005 GBP)	11,636	10,438	6162
Real VED tax first year (2005 GBP)	128	122	63
Real VED tax total vehicle lifetime (2005 GBP)	1517	1453	628
Engine size (cc)	1731	1598	529
Fuel consumption (L/100 km)	6.41	6.10	1.48
Vehicle weight (kg)	1829	1810	357
Variable	**Share**		
Diesel vehicles	41.46%		

Vehicle and fuel taxes affect equilibrium registrations because they are components of the lifetime costs of owning the vehicle. For example, increasing the tax on one particular car type raises the future cost of owning the car, relative to other cars sold in the market. The tax change induces consumers to substitute away from that car toward other new cars (or to used cars), reducing the equilibrium registrations of that car. More broadly, increasing the tax of vehicles with high CO_2 emissions rates shifts consumer demand to low-CO_2-emitting cars, and reducing the equilibrium registrations-weighted average CO_2 emissions rate. The tax increase may also reduce total UK new car registrations if it causes consumers to purchase a used car or forgo a purchase altogether. Regardless of the magnitude of this effect, increasing the tax on cars with high emissions rates reduces the registrations-weighted average emissions rate of new cars.

The empirical estimation strategy follows a reduced-form approach similar to that taken by Klier and Linn (2015) and Alberini and Bareit (2016) for other European countries. In our regressions, the dependent variable is the log registrations by model-trim variant i, make m, and period t, normalized by the number of months in the policy period[12]:

$$\ln(REG)_{imt} = \beta \ln(VED)_{imt} + \delta \ln(FUELCOST)_{imt} + \mathbf{x}_{im}\boldsymbol{\theta} + \alpha_{mt} + \varepsilon_{imt} \quad (1)$$

where VED is the discounted flow of the annual registration tax in 2005 GBP.[13] The variable $FUELCOST$ is the fuel cost per 100 km, which depends on the price of fuel (gasoline or diesel, in 2005 GBP) and the fuel consumption rate of the car. The fuel costs are proportional to the discounted flow of fuel costs over the lifetime of the vehicle under

[12] If a make-model-trim variant is introduced after the beginning of the policy period or is withdrawn from the market during that policy period, we normalize the registrations by the number of months that the make-model-trim variant is offered within that policy period. In some cases, the VED changes occurred in the middle of a month. We remove from the original dataset the months in which this occurs, as we cannot assign the registration to a specific tax rate, and adjust the normalization of the registrations accordingly. The months removed are March 2006, March 2007, and March 2008.

[13] Calculating this variable requires assumptions on vehicle lifetime, discount rates, and expectations of future VED rates. We assume a vehicle lifetime of 14 years, which is consistent with the average scrappage age estimated by the Society of Motor Manufacturers and Traders (SMMT 2016). As in Allcott and Wozny (2014) and Grigolon et al. (2015), we use a discount rate of 6%. Finally, in our framework, consumers expect VED rates not to change over the years. This is reasonable because in practice, the VED rates for vehicles have changed little after those vehicles were purchased (see "Appendix C"). The only exception to this assumption is the period at the end of our sample, from April 2010 to October 2010, when the government made changes to the rate for the first year of registration but kept the rates in later years unchanged.

the assumption that fuel prices follow a random walk (Grigolon et al. 2015). The vector **x** contains vehicle attributes such as engine size, horsepower, weight, length and height, and fixed effects for body type, number of doors, type of transmission, number of gears, gasoline or diesel fuel, number of cylinders, and whether two- or four-wheel drive. We also include a dummy for vehicles emitting 100 g/km or less.[14] The vehicle attributes control for supply-side changes during this period, such as manufacturer responses to the EU-wide CO_2 emissions standards and technological progress.[15] The make-period fixed effects control for unobserved and potentially time-varying characteristics at the make level, such as consumer perceptions of make quality. Because the CO_2 standards apply at the manufacturer level, the make-period fixed effects also help control for the effects of the CO_2 standards on vehicle attributes and prices.

We estimate Eq. (1) by ordinary least squares, and the VED and fuel cost coefficients are the coefficients of interest. Because an increase in tax or fuel costs reduces demand for that car, we expect the coefficients to be negative. The VED coefficient is identified by cross-sectional and time-series variation in CO_2 emissions rates interacted with time-series variation in tax rates. Likewise, the fuel cost coefficient is identified by cross-sectional and time-series variation in fuel consumption rates, interacted with time-series variation in tax-inclusive fuel prices.

Including make-period interactions and vehicle attributes controls for other demand shifters that might be correlated with the VED and fuel costs. It is straightforward to show that the make-period effects imply that the coefficient on the VED is identified as long as there is substitution between different models within the same make. That is, the coefficients are identified while imposing few assumptions on substitution patterns. The estimation results show that there is sufficient VED variation within make and period to identify the VED coefficient.

As noted above, Eq. (1) describes the reduced-form relationship between vehicle taxes and registrations. This is distinct from a demand model, which would include the price on the right hand side. Holding all else constant, an increase in the tax on one vehicle causes the demand curve for that vehicle to shift to the origin. The manufacturer may respond to the demand shift by reducing the vehicle price. The tax coefficient identifies the net effect of the tax on equilibrium registrations, after accounting for any vehicle price changes that are caused by the tax changes. The tax coefficient would only be biased if unobserved demand or supply shocks are correlated with the taxes, after controlling for make-period fixed effects and other vehicle attributes. In the robustness analysis we report results that support the exogeneity of the taxes to unobserved shocks.

One concern whenever one exploits tax variation is whether the public anticipates the tax changes. For example, anticipating a future tax for high-CO_2-emitting vehicles, consumers could decide to purchase such vehicles before the tax increase. This behavior would bias estimates of the effects of taxes on registrations, similarly to the bias introduced by

[14] In the first year of the sample, there were no cars in the market emitting 100 g/km or less, and the share of these vehicles in total registrations never rises above 1%. Because the VED for these cars equals zero, we add 1 to the discounted VED flow. The dummy variable for these vehicles captures the entrance of these new cars into the market.

[15] In 1998, the European Commission and the European Automobile Manufacturers Association (ACEA) signed a voluntary agreement for the reduction of carbon emissions rates of passenger vehicles. The original goal was to reach an average emissions rate for new cars of 140 g/km by 2008 and 120 g/km in 2010. Due to the failure in reaching such goal, the European Commission announced in 2007, and approved in 2009, mandatory emissions performance standards to begin in 2012.

anticipated fuel tax changes (Coglianese et al. 2017). Based on our reading of Her Majesty's Treasury documentation of each year's budget and on examining news coverage about the budget and VED debate prior to the final budget approval, we believe that anticipation effects are unlikely to be important in this setting (see "Appendix C").

We conduct several other robustness checks of the baseline specification. For example, we assess the sensitivity of the estimates to different discount rates used to construct the VED variable. We drop models with the top 1% of new registrations in each period to test whether the estimates are driven by the top-selling models or reflect consumer substitution across a broad range of models. We also drop the month preceding and the month following the time when the new VED becomes effective, and, in alternate runs, the vehicles with CO_2 emission rates within 1 g/km from a VED band cutoff.

Implicit in Eq. (1) is that the baseline specification identifies the tax and fuel cost coefficients from consumer substitution within makes. Given the magnitude of VED variation across cars and over time, it may be unlikely for VED variation to induce substitution between vehicles that are much different from one another. However, a potential concern with the baseline version of Eq. (1) is that it may not control for all unobserved car attributes that are correlated with the VED or fuel costs. To address this concern and take advantage of the fact that consumers may substitute across similar vehicles in response to VED changes, as an alternative to the baseline we generate price categories with £500 intervals and control for category-period fixed effects rather than make-period fixed effects.

Before turning to the empirical estimates, we note that many earlier studies of vehicle taxes and CO_2 emissions have estimated structural demand models. Typically, these studies assume that consumers derive disutility from fuel costs as well as the price of the vehicle, where the price includes all taxes paid at the time of purchase or subsequently. Identification is ensured through variation in vehicle prices or taxes (Adamou et al. 2012, 2014; D'Haultfœuille et al. 2014; Grigolon et al. 2015; Stitzing 2016).

By combining the vehicle taxes and prices into a single variable, these studies assume that consumers respond similarly to vehicle price and tax changes, although salience or other factors may cause consumer responses to differ (Chetty et al. 2009; Marion and Muehlegger 2008). In "Appendix B", we use the methodology of Marion and Muehlegger (2008) and Li et al. (2014) to test the null hypothesis that consumers respond equally to the discounted flow of registration taxes and the vehicle price. We find that consumers respond more to taxes than to equivalent car price changes, invalidating the assumption made in these studies. Our results are consistent with the reduced-form approach taken in this paper, which identifies the tax coefficient entirely from *actual* tax variation, rather than a mixture of tax and car price variation as in the other studies.

5 Results

5.1 Estimation Results

Regression results for Eq. (1) are presented in Table 8a. All standard errors are clustered at the make-policy-period level. The first column shows the key coefficients from our main specification of Eq. (1). In our main specification, the VED elasticity is −0.296. This value

Table 8 (a) Main regression results based on Eq. (1). (b) Additional regression results based on Eq. (1)

Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)
(a)							
ln(FUELCOST)	−1.424*** (0.186)	−1.425*** (0.186)	−1.423*** (0.186)	−1.282*** (0.187)	−1.814*** (0.197)	−1.708*** (0.210)	−1.398*** (0.181)
ln(VEDTAX)	−0.296*** (0.067)	−0.294*** (0.067)	−0.299*** (0.068)	−0.373*** (0.073)	−0.241*** (0.068)	−0.232*** (0.072)	−0.379*** (0.073)
Observations	55,811	55,811	55,811	50,705	53,448	55,811	51,453
(b)							
ln(FUELCOST)	−1.364*** (0.182)	−1.389*** (0.183)	−1.596*** (0.190)	−1.336*** (0.235)	−1.512*** (0.208)	−0.921*** (0.179)	
ln(VEDTAX)	−0.235*** (0.070)	−0.224*** (0.073)	−0.181** (0.077)	−0.286*** (0.102)	−0.268*** (0.076)	−0.189*** (0.067)	
Observations	55,811	55,811	55,811	55,811	55,811	55,811	

(a) Results using model 1. The dependent variable is the log of the normalized number of vehicles registered. Only coefficients for log fuel cost and log VED are reported. Column 1: main specification. Column 2: 10% discount rate. Column 3: 0% discount rate. Column 4: dropping top 1% models sold. Column 5: dropping the month before and after changes in VED. Column 6: using price category (£500 range) by period fixed effect. Column 7: dropping observations within 1 g/km from VED band cutoffs. Robust standard errors in parentheses, clustered by make-by-period. Fixed effects at make-by-period level

***$p<0.01$; **$p<0.05$; *$p<0.1$

(b) Results using model 1. The dependent variable is the log of the normalized number of vehicles registered. Only coefficients for log fuel cost and log VED are reported. Column 1: Controlling for average characteristics of other vehicles in the same market segment and same period. Column 2: Controlling for market segment-by-period fixed effects. Column 3: Interacting vehicle characteristics with policy period dummies. Column 4 and 5: Allowing in the same regression for separate fuel cost and tax coefficients for the first half (Column 4) and second half of our sample period (Column 5). Column 6: Controlling for make-by-model fixed effects

***$p<0.01$; **$p<0.05$; *$p<0.1$

is within the range of the tax elasticities in Klier and Linn (2015) for France, Germany, and Sweden.[16]

Results from various robustness checks are displayed in columns 2–7. Specifically, columns 2 and 3 use discount rates of 10% and 0%, respectively, instead of 6%. In column 4, we drop the vehicle models that rank in the top 1% of new registrations. In column 5, we drop the month before and after any VED changes. In column 6, we use fixed effects at the price-by-period level, using a price range of £500. Finally, in column 7, we drop vehicles within 1 g/km from VED band cutoffs to see if results are driven by marginal adjustments made by manufacturers to let a vehicle qualify for a lower VED band (and rate). The VED coefficient estimate is similar across all columns, ranging from −0.232 to −0.379. All VED coefficients are statistically significant at the 1% level.

Before we turn to our policy simulations, however, we discuss additional robustness checks. A potential threat to identification is the presence of omitted variable bias. For instance, preferences towards smaller and cleaner cars might change over time due to macroeconomic conditions and environmental awareness, and such changes might be correlated with changes in vehicle registration taxes. We seek to control for these changes and other omitted variables by adding fixed effects in the base model (Table 8b). For example, we control for average characteristics of other vehicles in the same market segment sold in the same period. We control for fixed effects at the vehicle segment-by-policy period level. We interact vehicle characteristics with policy period dummies. We allow for two separate tax coefficients for the first and the second half of our sample period. Finally, we add make-model fixed effects.

An important caveat is that adding these fixed effects tends to reduce the variation in tax that we can exploit in the analysis. Nevertheless, the coefficient on the VED is statistically significant at the conventional levels in all of these specifications, and its magnitude is generally similar to those in Table 8a. The policy simulations below are thus based on column 1 of Table 8a.

5.2 Policy Scenarios

We wish to understand the effects of different tax structures on vehicle registrations, tax revenues, and emissions. We adopt as a baseline the engine size-based registration tax, which was the tax system prior to the VED. We use the estimation results to predict vehicle registration shares between March 2005 and October 2010 under four alternatives to the baseline: (i) using the actual VED rates adopted in that period; (ii) keeping the 2005 VED rates throughout the sample; (iii) imposing a registration tax proportional to carbon emissions rates; and (iv) levying a carbon tax.

Comparing (i) and (ii) illustrates the effects of the changes in tax rates that occurred after 2005, and comparing (iii) and (iv) with (ii) illustrates the effects of alternative systems. To enable direct comparisons among the actual VED, the emissions rate tax, and the carbon tax, we calibrate the policies to achieve the same revenue. The proportional tax that satisfies this requirement is £0.825 per g/km, and the carbon tax is £63 per ton of CO_2.[17] We normalize registrations at the make-by-period level, allowing shares to change

[16] These are −0.417, −0.301, and −0.244, respectively.

[17] For comparison, the value of carbon suggested by the UK government at the time was £25 and £76 per ton CO_2 in 2009 for sectors not included in the European Union Emissions Trading System (EU ETS). These figures become £30 and £90 per ton CO_2 in 2020 (in 2009 GBP). The transportation sector is included in this group. Note that these rates are much higher than the EU ETS prices, which ranged between £11 and £26 per ton CO_2 in 2009 and between £14 and £31 per ton CO_2 in 2020 (DECC 2009).

within each make and period, but not across them. This allows us to hold the make-period fixed effects at their estimated values, and is consistent with the assumption implicit in our model (that substitution occurs solely within a make). We assume a vehicle lifetime of 14 years (see "Appendix A"). The calculation of the proportional tax and carbon tax rates is described in "Appendix D".

To calculate total emissions for the baseline and four other scenarios, we assume that all vehicles are driven the average annual miles observed in the UK fleet according to the NTS (see "Appendix A"). Supporting this assumption is the fact that miles driven are weakly correlated with carbon emissions rates: the correlation between the two variables is 0.09 for new cars purchased between 2005 and 2010, and 0.07 for cars of any age still registered during the same period. In addition, Table 9 shows that the distributions of annual miles driven within emissions rate classes are similar.

Figures 3, 4, 5 display summaries of the tax liability by vehicle group under the baseline engine tax, VED, emissions rate tax, and carbon tax in different periods. These totals are expressed in 2005 GBP, but we do not discount the future years' amounts. We weight cars by the number of registrations predicted by Eq. (1). The 45-degree line in Figs. 3, 4, 5 helps identify which vehicles would be taxed more or less under the different schemes. We consider two periods: April 2005–March 2006 and May 2009–March 2010.

Figure 3 compares the VED with the engine size-based tax in these two periods. Within each of the two engine size categories, there is considerable variation in VED rates. The majority of vehicles pay more under an engine size tax; vehicles with large engines and low emissions are taxed less under the VED scheme.

Figure 4 contrasts the VED with the proportional tax. In the earlier period, many vehicles are close to the 45-degree line, and the VED scheme is very close to a proportional tax for many vehicles. The exceptions are very polluting cars, which would generally be taxed less under the VED than under a proportional tax. A group of low-polluting cars is taxed less under the VED as well. Between May 2009 and March 2010, the VED imposed a much higher tax on high-polluting vehicles than the proportional tax and offered generous discounts to low-polluting vehicles. Differences between the VED and the proportional tax are less pronounced for medium-emissions vehicles (121–185 g/km).

Finally, Fig. 5 displays the VED vis-à-vis the carbon tax. Under the assumption that all vehicles are driven the same miles, the only difference between a proportional tax and a carbon tax is that in the latter case individuals can reduce their miles driven to lower their tax liability. For this reason, the graphs look very similar to Fig. 4 and the same considerations apply.

5.3 Policy Simulations

Table 10 displays the predicted vehicle registration shares by VED band for the different tax schemes over our entire study period. Table 11 reports the percentage changes with respect to the engine size-based tax. The VED, the proportional tax, and the carbon tax all reduce the share of new registrations of high-polluting vehicles and increase the share of low-polluting vehicles.[18] The magnitude of the effect is the largest for the actual VED and is substantial in percentage terms but small in absolute terms. Unlike the other policies, the VED disproportionately penalizes very high-polluting vehicles and favors very

[18] Market shares under the proportional tax and carbon tax are almost the same because of the assumption that all vehicles are driven the same number of miles.

Table 9 Summary statistics of kilometers driven by emissions rates deciles (UK NTS data)

Emissions deciles	CO_2 range (g/km)	25th percentile	Median	75th percentile	Mean
1	0–136	8046.70	12,874.72	19,312.08	14,435.20
2	137–142	8046.70	12,874.72	16,093.40	13,608.88
3	143–149	8046.70	12,874.72	17,702.74	14,132.49
4	150–155	8046.70	12,874.72	19,312.08	15,175.61
5	156–161	8046.70	12,874.72	17,702.74	14,377.19
6	162–169	8046.70	12,874.72	17,702.74	14,331.21
7	170–179	8851.37	12,874.72	19,312.08	14,880.07
8	180–191	8046.70	14,484.06	19,312.08	14,919.59
9	192–216	9656.04	14,484.06	19,312.08	15,840.88
10	217 or more	9656.04	14,484.06	19,312.08	16,299.07

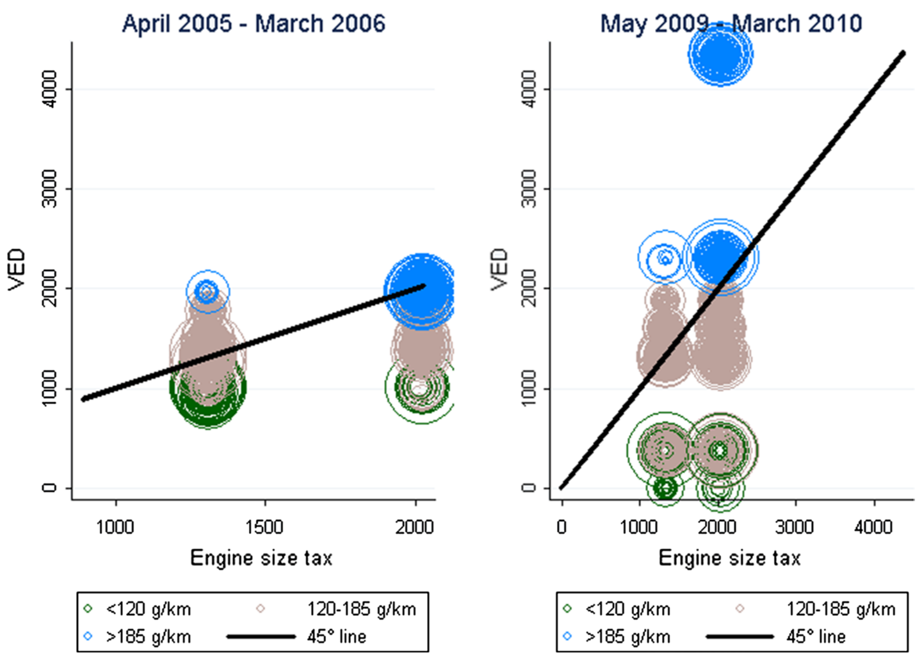

Fig. 3 Total tax payment under VED and engine size-based tax. *Note* Each circle represents a given make-model-trim variant in the same period. The size of the circle represents new registrations

clean vehicles, but because these vehicles account for a small share of new registrations, the overall effect is limited.

Table 12 shows the differences in total tax real revenues between the engine size-based tax, the 2005 VED rates, and the actual VED.[19] Compared with the engine size tax, both

[19] The proportional tax and the carbon tax generate the same revenue as the actual VED, so they are not included in the table.

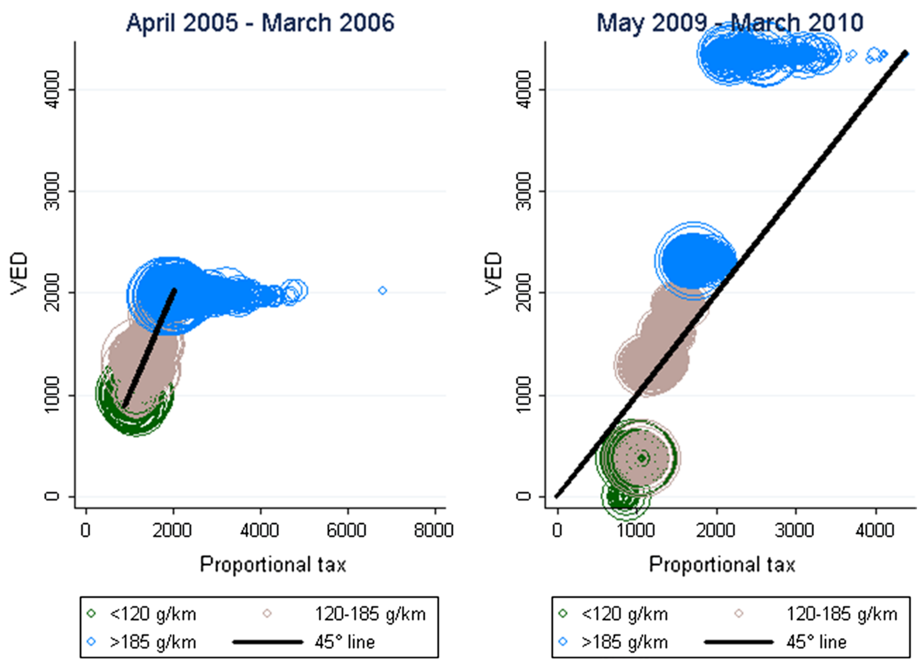

Fig. 4 Total tax payment under VED and proportional tax. *Note* Each circle represents a given make-model-trim variant in the same period. The size of the circle represents new registrations. The proportional tax rate is £0.83 per g/km of CO_2

VED schemes generate less revenue: during its lifetime, each vehicle would pay on average £308 less under the actual VED (−17.19%) and £354 less with the 2005 VED rates (−19.72%).

We then estimate the effects of each tax on CO_2 emissions. Table 13, panel A, shows the effects on total carbon emissions during the lifetime of a vehicle registered between April 2005 and October 2010. Compared with the engine size tax, all other policies reduce carbon emissions. The magnitude of the effect varies: the effect of a proportional tax (−0.56%) and of the 2005 VED (−0.46%) is smaller than the effect of the actual VED (−1.64%). The actual VED had a larger effect on emissions rates than the proportional tax or the 2005 VED. A carbon tax would have reduced emissions by about twice as much as the VED did (−3.72%).

The actual VED has a larger effect on emissions than the emissions rate tax because the VED creates stronger incentives in favor of very clean cars and against very polluting cars. Hence, a proportional tax is less effective than the VED at reducing emissions.[20] Under the carbon tax, consumers can decrease their total tax liability by switching to a different type of car or reducing miles driven. Our calculations, which assume a miles

[20] It is, however, possible to envision cases where the proportional tax is more effective than the VED. Because the proportional tax is continuous but the VED is not, under the former, consumers have the incentive to switch to cleaner vehicles within the same VED band. This would not happen under the VED, as the tax rate is the same within a band. Our result is the combination of this effect and the loss of tax incentives (disincentives) for very clean (very polluting) vehicles.

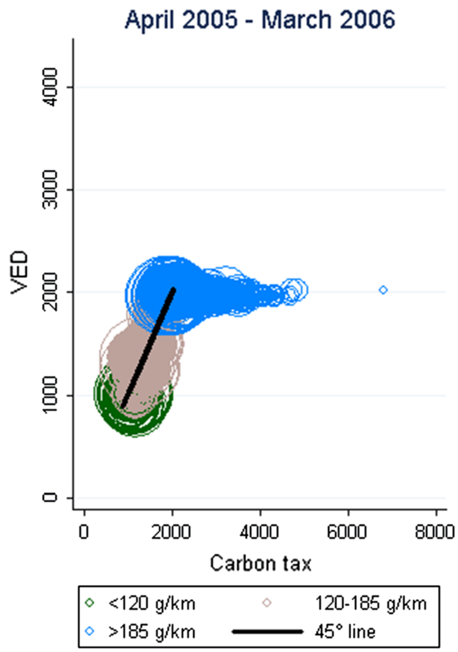

Fig. 5 Total tax payment under VED and carbon tax. *Note* Each circle represents a given make-model-trim variant in the same period. The size of the circle represents new registrations. The carbon tax rate is £63.0 per ton CO_2

Table 10 Predicted new vehicle registration market shares, April 2005–October 2010

VED bands	CO_2 range (g/km)	Shares (engine size tax) (%)	Shares (VED) (%)	Shares (VED 2005) (%)	Shares (proportional tax) (%)	Shares (carbon tax) (%)
A	100 or less	0.05	0.30	0.05	0.05	0.05
B	101–110	2.67	3.42	2.82	2.76	2.76
C	111–120	10.11	12.88	10.78	10.44	10.44
D	121–130	9.11	8.94	9.08	9.36	9.36
E	131–140	11.68	11.41	11.79	11.79	11.79
F	141–150	12.33	12.07	12.47	12.21	12.21
G	151–165	18.78	18.11	18.74	18.85	18.85
H	166–175	7.71	7.26	7.48	7.73	7.73
I	176–185	6.79	6.50	6.64	6.76	6.76
J	186–200	8.82	8.08	8.50	8.69	8.69
K	201–225	6.12	5.77	5.95	5.92	5.92
L	226–255	3.16	2.85	3.09	3.00	3.00
M	256 and higher	2.66	2.42	2.62	2.43	2.43

driven elasticity of −0.1803 based on UK NTS data calculations (see "Appendix A"), suggest that changing miles driven reduces emissions more than changing the composition of new registrations.

Table 11 Change in predicted new vehicle registrations compared with engine size tax

VED bands	CO_2 range (g/km)	VED (%)	VED 2005 (%)	Proportional tax (%)	Carbon tax (%)
A	100 or less	550.38	8.87	8.43	8.46
B	101–110	28.08	5.53	3.44	3.44
C	111–120	27.40	6.57	3.25	3.27
D	121–130	−1.81	−0.37	2.77	2.79
E	131–140	−2.32	0.87	0.91	0.91
F	141–150	−2.16	1.13	−0.98	−0.98
G	151–165	−3.57	−0.19	0.40	0.39
H	166–175	−5.84	−2.94	0.24	0.23
I	176–185	−4.25	−2.13	−0.48	−0.48
J	186–200	−8.42	−3.73	−1.48	−1.49
K	201–225	−5.78	−2.83	−3.27	−3.28
L	226–255	−9.94	−2.26	−5.18	−5.19
M	256 and higher	−9.29	−1.64	−8.60	−8.61

Table 12 Changes in revenue associated with different tax schemes

	Total lifetime fleet revenue (billion 2005 GBP)	Percentage change compared with baseline (%)	Average change in tax revenue per vehicle (2005 GBP)
Engine size-based tax (baseline)	17.09		
VED	14.16	−17.19	−308
VED, 2005 rates	13.72	−19.72	−354

Note that in our policy simulations we consider only small changes in the registration taxes, as is consistent with the relatively modest variation in the actual taxes during our study period.

In Table 13, panel B reports the results of sensitivity analyses for the carbon tax, where we change some of the parameter assumptions (see "Appendix D"). Reducing miles driven plays a more important role than changes in vehicle shares toward reducing total emissions from new vehicles. Assuming different lifetime miles driven affects our results, but the carbon tax always attains larger emissions reductions than the other policies. In our main simulations we assume that the tax changes do not cause substitution across makes. This assumption is consistent with the tax variation that identifies the estimated VED coefficient, but it may yield conservative estimates of the effects of the counterfactual taxes. We can replace this assumption with a milder assumption that a given tax change induces the same substitution within a make as across makes. Panel C reports another sensitivity analysis allowing changes in market shares between makes within each policy periods. Although we find larger changes in carbon emissions between the engine size-based tax and the other policies, the carbon tax still brings the largest reductions in emissions.

Finally, the main results are based on the reduced-form Eq. (1). As an alternative, in "Appendix B" we explicitly model the demand and supply responses to the taxes. To accomplish this, we add to Eq. (1) vehicle prices, for which we instrument using the standard Berry et al. (1995) instruments. We simulate the effect of the VED on

Table 13 CO_2 emissions changes associated with different tax schemes

	Total lifetime fleet emissions (million tons CO_2)	Change in CO_2 emissions (%)	Average change in CO_2 emissions per vehicle (tons CO_2)
Panel A: Base case, emissions			
Engine size-based tax (baseline)	287.13		
VED	282.44	− 1.64	− 0.49
VED, 2005 rates	285.81	− 0.46	− 0.14
Proportional tax, same revenue as VED (£0.825 per g CO_2/km)	285.54	− 0.56	− 0.17
Carbon tax, same revenue as VED (£63.0 per ton CO_2)	276.46	− 3.72	− 1.12
	Carbon tax rate (GBP per ton)	Lifetime miles driven (km)	Change in CO_2 emissions (%)
Panel B: Sensitivity of CO_2 emissions changes to assumptions under a carbon tax			
Preferred specification	63.0	187,557	− 3.72
New registrations inelastic	62.6	187,557	− 3.15
Miles driven inelastic	61.0	187,557	− 0.56
Carbon tax treated as additional fuel cost (i.e., prediction is based on coefficient on fuel costs)	62.3	187,557	− 2.64
Miles driven elasticity = − 0.3	64.5	187,557	− 5.94
Miles driven = 1st quartile	107.3	112,653	− 5.94
Miles driven = median	70.1	168,980	− 4.08
Miles driven = 3rd quartile	52.1	225,307	− 3.17
Miles driven = 90th percentile	34.3	337,961	− 2.28
	Carbon tax rate (GBP per ton)	Lifetime miles driven (km)	Change in CO_2 emissions (%)
Panel C: Base case, only total number of registration per period fixed			
Engine size-based tax	290.92	187,557	
VED	284.24	187,557	− 1.66
Proportional tax	288.45	187,557	− 0.68
Carbon tax	279.30	187,557	− 3.83

See "Appendix D" for a detailed explanation of the different assumptions equilibrium prices and registrations, and we find only small differences with our main simulation results that do not affect our conclusions.

6 Conclusions

This paper compares several hypothetical tax systems for reducing new car CO_2 emissions in the United Kingdom with the actual taxation scheme. To conduct this analysis, we first estimate the effects of vehicle taxes and fuel prices on new car registrations using data covering the UK new car market between 2005 and 2010. The tax variation arises from the VED, a scheme introduced in 2001 that links a car's annual registration tax to its CO_2 emissions rate. The scheme has been revised multiple times since its inception. Using a reduced-form approach, we estimate an elasticity of new car registrations to taxes of -0.296. This coefficient is statistically significant and robust to a series of specification checks.

We use these empirical estimates to assess the effectiveness of the VED at reducing emissions by comparing fleet composition and emissions between 2005 and 2010, during which time the scheme was tightened. We also compare the current scheme with the previous engine size-based registration tax and with hypothetical systems that tax vehicles directly in proportion to their emissions rate or their *total* CO_2 emissions.

We find that the VED causes substantial changes in registrations of the least- and most-polluting vehicles. However, these changes in registrations do not cause a large change in the average emissions rate across new cars, because the least- and most-polluting cars represent a small share of the overall market. The VED provides comparatively little incentive for consumers to switch among vehicles with moderate emissions rates.

We also use our estimates to predict the effects of either a tax that is strictly proportional to emissions *rates* or a tax on total emissions—that is, a carbon tax. We set the tax rates of the proportional and the carbon tax to yield the same revenue as the VED and show that all three policies would reduce aggregate tax liability, compared with the pre-VED engine size-based system. The VED reduces total emissions by 1.64%, whereas a proportional tax would decrease emissions by about one-third as much, 0.56%. A carbon tax would reduce emissions by about twice as much as the VED, 3.72%. The effect of the carbon tax on emissions is almost entirely due to a decline in miles driven. Switching to a carbon tax imposed on drivers would thus provide, at the same or lower aggregate cost for the taxpayer, a stronger reduction in total carbon emissions than the other policies we consider. The size of this reduction depends on the miles driven elasticity to the tax and total miles driven, but the carbon tax causes larger emissions reductions than the other taxes under a wide range of parameter assumptions.

With our reduced-form approach, we are not able to compare the welfare effects of the VED and other taxes. Because the VED provides no incentives to switch to cleaner cars within the same band, we hypothesize that the VED would fare worse than a proportional tax in welfare terms. Similarly, a proportional tax should fare worse than a carbon tax that offers incentives to reduce miles driven as well. A full welfare analysis would include the effects of the taxes on local air pollutants as well as CO_2. Distributional effects are another important aspect to consider.

We conclude by noting several limitations of our study. We do not have registration data and information on emissions before 2001 (the year the VED was introduced), so our identification relies on the variations in the registration tax over time and across vehicles, and on the reclassification of vehicles into different VED bands. We can make predictions about the effect of *small* changes in the tax rates on vehicle shares and emissions but do not consider drastic modifications of the policy. The simulations are designed to be consistent with the variation in taxes and fuel prices used to identify the empirical model.

Another caveat is that in our main analysis we do not consider explicitly the hypothesis of a supply response to the VED—manufacturers changing vehicle characteristics to fit them into a particular VED band. We deem such behavior to be unlikely: manufacturers operate in the European market as a whole and do not change vehicles characteristics for relatively small policy changes in one country, especially when such small changes take place almost every year. Also, recall that our estimates represent the short-run effects of taxes on equilibrium vehicle registrations, which includes the results of any tax-induced vehicle price changes. We do not believe that the relatively small changes in VED payment from one band to the next would justify large decreases in transaction prices in response to higher taxes for more polluting vehicles. However, the long-run demand and price responses may differ from the short-run effects that we estimate.

Finally, we assume that changes in the shares of registrations due to taxes occur only within a given make-model. This is a conservative assumption but relaxing it partly does not affect the main conclusions.

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Appendix A: Fuel Economy and Miles Estimates

The NTS used for the estimation of the miles equation does not have information on fuel economy, only on CO_2 emissions rates. We use instead data from the UK Driver and Vehicle Licensing Agency (UK DVLA), which contains information on passenger cars from 2000 to 2010 to estimate the relationship between fuel economy and emissions rates.

In the New European Driving Cycle (NEDC), the fuel economy of a vehicle is computed from the vehicle's tailpipe CO_2 emissions. The fuel consumption rate is proportional to the CO_2 emissions rate, with the proportionality constant different for different fuels. We regress fuel economy on CO_2 emissions rates separately for diesel and gasoline vehicles, without constant terms. Table 14 shows the virtually perfect correlation between fuel economy and emissions rate. We use the regression coefficients to predict the fuel economy for each vehicle in the NTS dataset.

Next, we use the appropriate 12-month moving average of fuel costs (based on the date of the survey and the geographic location) to calculate the fuel cost in British pounds per 100 km.[21]

We then use the NTS data to regress the log yearly driving (in km) over vehicle age in years, fuel cost in real 2005 British pounds per 100 km, engine size in cubic centimeters (cc), and fuel type.

$$\text{Log(miles)} = \alpha + \beta\,\text{Age} + \gamma\,\text{Fuel Cost} + \delta\,\text{Engine Size} + \theta\,\text{Fuel Type} + \varepsilon \qquad \text{(A1)}$$

[21] The geographic subdivisions used are the Government Official Regions: normally, North East, North West and Merseyside, Yorkshire and Humberside, East Midlands, West Midlands, Eastern, Greater London, South East, South West, Wales, and Scotland. Northern Ireland is not included in the database.

Table 14 Results from emissions rates regression

	Gasoline (g CO_2/km)	Diesel (g CO_2/km)
Consumption rate (l/100 km)	23.77*** (0.0300)	26.49*** (0.0075)
R-squared	0.9995	0.9986
Observations	29,080	17,364

Table 15 Results from miles driven regression

	Log km/year
Age	− 0.0230*** (0.0017)
Fuel cost (pence/100 km)	− 0.0003*** (0.0000)
Engine size (cc)	0.0003*** (0.0000)
Diesel	0.2277*** (0.0120)
Constant	9.1483*** (0.0184)
Observations	29,526

Results based on Eq. (A1). Dependent variable is the log of km driven in a year for a given vehicle in the UK NTS dataset

Because the NTS is a multiyear cross section, we exploit the variation in age and miles driven of the different vehicles surveyed. The results of the miles driven regression are shown in Table 15. As expected, miles driven decrease with fuel cost and vehicle age, but it increases with engine size. Using the sample mean of the fuel cost, we estimate a miles driven elasticity of − 0.1803 with respect to fuel cost.

Finally, we calculate total miles driven during the lifetime of a vehicle. According to the Society of Motor Manufacturers and Traders, the average scrappage age in the UK in a given year is between 13 and 14.5 years.[22] We do not have disaggregated information by vehicle characteristics, so we assume that all vehicles in our dataset have a lifetime of 14 years.

To calculate the lifetime average miles driven used in our main calculations, we simply multiply the average yearly miles driven of our sample in the NTS by 14 (presumed lifetime of the vehicle). We use the age coefficient from our miles driven model to calculate the miles driven for each single year of life of a vehicle. We find out that the average car is driven about 187,557 km during its lifetime. To calculate the miles driven for each year in the vehicle lifetime, we use the age coefficient from Table 15. When estimating the discounted flow of the revenue equivalent carbon tax, we assume people are perfectly aware how much they will be driving in the future (i.e., they will be driving less and less when their car gets old).[23]

An alternative way to calculate total miles driven is to sum together the average yearly miles driven of our sample for each vehicle age (up to the 14th year). The resulting lifetime miles driven are very similar (189,700 km). Nevertheless, we use it as part of the sensitivity analysis.

[22] http://www.smmt.co.uk/2014-sustainability/environmental-performance/end-life-vehicles/.

[23] When we assume that consumers use the mileage of the first year to predict mileage in the future years (i.e., they overestimate it), all the results for the carbon tax look very similar.

Appendix B: Comparing Response to Registration Taxes and Vehicle Price

To test the null hypothesis that the coefficient on price is different from that on the (discounted flow) of registration tax payments over the course of a car's lifetime, we implement a simple modification to Eq. (1) based on Marion and Muehlegger (2008), decomposing the ownership cost of a vehicle in the actual price and the registration tax. We specify the regression equation

$$\ln\left(REG_{imt}\right) = \alpha_{mt} + \beta \ln\left(1 + \frac{VEDTAX_{imt}}{P_{imt}}\right) + \gamma \ln\left(P_{imt}\right) + \delta \ln\left(FUELCOST_{imt}\right) + \mathbf{\theta}\mathbf{x}_{im} + \varepsilon_{imt} \tag{B1}$$

where as in our main specification, i denotes the make-model-trim variant, m the make, t the policy period, and REG the number of new units registered normalized by the number of months in the policy period. On the right-hand side of Eq. (B1), $VEDTAX$ is the discounted flow of the annual registration tax (in 2005 GBP), P is the manufacturer-suggested retail price of the vehicle, and $FUELCOST$ is the fuel cost per 100 km. Vector $\mathbf{x}$ contains vehicle attributes, and we also add a dummy for vehicles emitting less than 100 g/km. It is straightforward to show that if $\beta=\gamma$, then consumers respond equally to a change in price and a change in the discounted flow of the registration tax, and all future VED payments can be added to the price tag of the vehicle (Marion and Muehlegger 2008; Li et al. 2014).

We estimate regression Eq. (B1) using ordinary least squares (OLS) and, since the Berry model regards price as endogenous and vehicle attributes as exogenous, also by instrumenting price with the usual BLP instruments.[24] Because the price appears in two of the variables on the right-hand side, we also add the set of our BLP instruments interacted with the natural log of $VEDTAX$. Then we use an F test or Wald test to check whether $\beta=\gamma$.

The estimation results and the outcomes of the F and Wald tests from models where the shares are allowed to depend on price, fuel cost, and VED separately are displayed in Table 16. We change both the discount rate (6%, 10%, or 0%) and the types of instruments we use: in column 1, we use no instruments; column 2 is an instrumental variable specification using BLP instruments based on engine size, gross vehicle weight, and length; in column 3, instruments are based also on height, engine horsepower, transmission type, and fuel type; and in column 4, we construct our instrument using all the available vehicle characteristics. Clearly, whether or not we allow price to be endogenous and regardless of the discount rate used, in the majority of our specifications the null hypothesis is soundly rejected at the 1% level or better, implying that the effects of VED changes should not be predicted on the basis of the coefficient from the total of all costs. The magnitude of the difference between the two coefficients is also in line with Rivers and Schaufele (2015), who find that consumer response to the British Columbia carbon tax was 4.1 times stronger than the market price of gasoline.

[24] See Berry (1994), Berry et al. (1995), Vance and Mehlin (2009), Adamou et al. (2012, 2014), Huse and Lucinda (2014), Konishi and Meng (2014), Grigolon et al. (2015) and Alberini and Bareit (2016). To construct the BLP instruments, we use the average of the natural log of the characteristics of vehicles, once for vehicles within the same make and period and once for vehicles in a different make or period. For categorical variables such as fuel type, we use the average share of vehicles. Results are very similar when we use the average of the characteristics without taking the natural log.

Table 16 Instrumental variable results: test on equality of LOG PRICE and LOG 1 + (VED/P) coefficients

Variables	(1)	(2)	(3)	(4)
Panel A: Discount rate 0%				
LOG PRICE	−0.957*** (0.156)	−1.100** (0.457)	−0.999** (0.412)	−0.221 (0.368)
LOG 1 + (VED/P)	−2.519*** (0.540)	−2.840*** (0.794)	−2.947*** (0.664)	−2.588*** (0.609)
LOG FUEL COST	−1.137*** (0.168)	−1.096*** (0.178)	−1.077*** (0.172)	−1.097*** (0.181)
TEST STAT	10.25	3.57	7.03	12.38
P value	0.0015	0.0587	0.0080	0.0004
Panel B: Discount rate 6%				
LOG PRICE	−0.959*** (0.156)	−1.090** (0.457)	−0.991** (0.412)	−0.215 (0.368)
LOG 1 + (VED/P)	−3.414*** (0.725)	−3.780*** (1.066)	−3.945*** (0.896)	−3.443*** (0.822)
LOG FUEL COST	−1.136*** (0.168)	−1.102*** (0.178)	−1.082*** (0.172)	−1.103*** (0.182)
TEST STAT	13.54	5.36	9.99	14.12
P value	0.0003	0.0205	0.0016	0.0002
Panel C: Discount rate 10%				
LOG PRICE	−0.959*** (0.156)	−1.084** (0.457)	−0.986** (0.412)	−0.211 (0.369)
LOG 1 + (VED/P)	−4.063*** (0.858)	−4.447*** (1.259)	−4.656*** (1.063)	−4.052*** (0.974)
LOG FUEL COST	−1.136*** (0.168)	−1.106*** (0.178)	−1.085*** (0.173)	−1.106*** (0.182)
TEST STAT	15.13	6.30	11.44	14.77
P value	0.0001	0.0120	0.0007	0.0001
Observations	55,782	55,782	55,782	55,782

Results using model B1 and test of equality of coefficients between LOG PRICE and LOG 1 + (VED/P). The dependent variable is the log of the normalized number of units sold. Column 1: OLS. Column 2: BLP instruments using engine size, gross vehicle weight, and length. Column 3: BLP instruments using also height, engine horsepower, transmission type, and fuel type. Column 4: BLP instruments using all vehicle characteristics. Robust standard errors in parentheses, clustered by make-by-period. Fixed effects at make-by-period level

***$p < 0.01$; **$p < 0.05$; *$p < 0.1$

Because we soundly reject the null hypothesis, we cannot combine price and present and future registration tax payments and use the coefficient on price to estimate the effect of changing the registration tax system or amounts. Another implication of this result and of the variation in the VED across types of cars and over time is that we can estimate a reduced-form equation, where log sales are regressed on the VED and other car characteristics regarded as exogenous, thus omitting car price.

Finally, we use our reduced-form specification to test whether people respond equally to a change in lifetime fuel costs or lifetime VED payment. To calculate the discounted sum of fuel costs during a vehicle's lifetime, we use the default assumptions explained in "Appendix A": a vehicle lifetime of 14 years and a total miles driven of 187,557 km. We use the age coefficient in Table 15 to calculate the km driven each year, assuming that consumers have perfect knowledge of their future miles driven. We calculate the discounted fuel costs using the usual rates of 6%, 10%, and 0%.

In practice, we use a slight modification to Eq. (1), where we have the discounted sum of fuel costs instead of fuel costs per 100 km. Results in Table 17 strongly reject the null hypothesis of equality of coefficients between discounted sum of fuel costs and discounted sum of VED costs.

Table 17 Results of test of equality of coefficients: discounted sum of lifetime vehicle fuel costs and discounted sum of VED costs

Variables	(1)	(2)	(3)
ln(SUM FUELCOST)	− 1.424*** (0.186)	− 1.425*** (0.186)	− 1.423*** (0.186)
ln(VEDTAX)	− 0.296*** (0.067)	− 0.294*** (0.067)	− 0.299*** (0.068)
Observations	55,811	55,811	55,811
Test statistics	30.85	31.04	30.61
P value	0.000	0.000	0.000

Results using model (1), using the discounted sum of fuel costs instead of fuel cost per 100 km. The dependent variable is the log of the normalized number of units sold. Column 1: 6% discount rate. Column 2: 10% discount rate. Column 3: 0% discount rate. Robust standard errors in parentheses, clustered by make-by-period. Fixed effects at make-by-period level

***$p < 0.01$; **$p < 0.05$; *$p < 0.1$

Table 18 CO_2 emissions changes associated with different tax schemes, sensitivity analysis using instrumental variable results

	(1)	(2)	(3)	(4)
Panel A: Total lifetime fleet emissions (million tons CO_2)				
Engine size-based tax (baseline)	287.13	286.81	286.98	286.47
VED	282.44	282.05	282.01	282.14
Proportional tax, same revenue as VED	285.54	284.87	284.95	284.70
Carbon tax, same revenue as VED	276.46	275.84	275.91	275.65
Panel B: Change in CO_2 emissions compared to baseline				
VED	− 1.64%	− 1.66%	− 1.73%	− 1.51%
Proportional tax, same revenue as VED	− 0.56%	− 0.68%	− 0.71%	− 0.62%
Carbon tax, same revenue as VED	− 3.72%	− 3.83%	− 3.86%	− 3.78%
Panel C: Tax rate used				
Proportional tax (GBP g CO_2/km)	0.825	0.826	0.825	0.827
Carbon tax (GBP/ton CO_2)	63.0	63.0	63.0	63.1

Simulation results based on regression models with and without instrumental variables. Column 1: OLS. Column 2: BLP instruments using engine size, gross vehicle weight, and length. Column 3: BLP instruments using also height, engine horsepower, transmission type, and fuel type. Column 4: BLP instruments using all vehicle characteristics

In our simulation exercise, we do not explicitly isolate the demand response from the supply response, presuming that the latter is small enough that our results would not be affected. To test this assumption, we can use model (B1) with instrumented vehicle prices as the basis of the simulation and check how this affects the results in terms of CO_2 emissions (Table 13).

Table 18 compares the simulation results using model (1) with the results using model (B1) with three different sets of instruments. Total CO_2 emissions and changes in emissions compared to the engine size based registration tax are similar to the base results.

Appendix C: News Articles and Web Searches on the Vehicle Excise Duty

Changes in VED occurred regularly, at the beginning of each budget period, and from 2008 on, the government disclosed future changes in the VED in its budget documents. If people are informed in advance about potential changes, they can react accordingly. For instance, they can buy a high-polluting vehicle before the new rates are introduced.

We relied on two measures to assess how aware of changes in the VED the general public is. The first is the number of newspaper articles about the VED, and the second is an index of interest over time through Google searches. We wanted to see if peaks of articles and search interest occurred before the changes were implemented. That would strongly suggest that the general public is aware that changes in the VED are due shortly.

The data on newspaper articles come from LexisNexis and include 156 publications in the UK. Among those outlets, we searched for articles including "VED" or "vehicle excise duty." We considered articles from 2006 to 2010, as before that period, the exact dates of articles are not always specified.

Figure 6 shows the distribution of the news articles over time. Peaks in VED newspaper coverage generally occurred right after the VED changes—in March 2006, March 2007, March 2008, and April 2010. In May 2009, when the changes were modest, we do not observe peaks. Neither do we observe peaks in the month before a change in rates took place.

The peaks in news coverage between May 2008 and July 2008 were caused by protests against scheduled increases in the VED that hit existing vehicle owners instead of just new vehicles. Eventually, these planned increases were scrapped in November 2008, which generated another news peak.

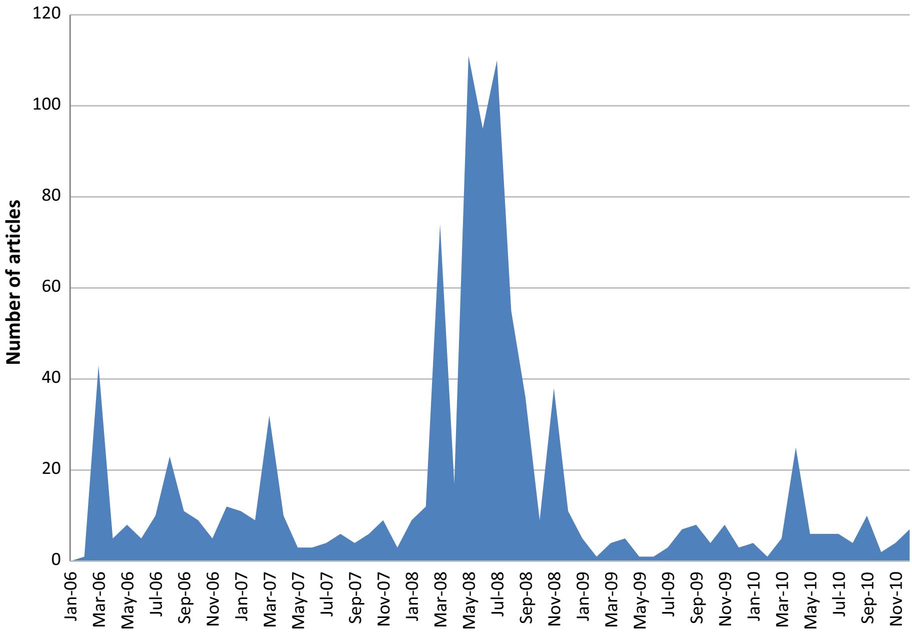

Fig. 6 Newspaper articles on VED per month. *Source*: LexisNexis

Fig. 7 Interest over time for the VED in Google searches. *Source*: Google Trends

Importantly, we do not observe in the headlines or in the article contents information or speculation about future rates, with the partial exception of 2008. Similarly, we do not observe articles warning the readers about imminent changes in the VED. The majority of the articles in our dataset inform the general public about current rates.

We then look at the Google Trends index for web searches about the VED. Google provides an index for all searches related to the VED ("topic"), regardless of the exact words searched. Figure 7 shows a measure of relative interest in the VED between 2005 and 2010. Earlier data, especially for 2005, are less reliable, but we include these data for completeness.

The graph shows that changes in interest occurred the months in which changes in VED rates (2006 and 2007) occurred and in summer 2008, as seen for newspaper coverage. In general, the measure of interest is flat over time.

Appendix D: Calculation of the Proportional Tax and Carbon Tax Rates

The nominal rates for the tax proportional to the carbon emissions rates and for the carbon tax are calculated so that the total real revenue from the vehicles sold and registered between April 2005 and October 2010 is equal to that from the VED.

The revenue takes into account the whole vehicle lifetime, assumed to be 14 years (SMMT data), so the VED revenue from a single model-trim variant *i* during its lifetime is given by

$$\text{Revenue}_i = \sum_{t=0}^{13} \frac{\text{VED}_i}{\frac{HICP_i}{100}\left[1 + (2.8t/100)\right]}$$

where VED_0 is the nominal VED rate for that vehicle at the time of purchase, $\frac{HICP_0}{100}$ is the Harmonised Index of Consumer Prices at the time of purchase, and t is the age of the vehicle.

We make some assumptions on the VED rates and consumer price index following the first registration year: (i) each year the HICP increases by 2.8 points, which is the average yearly increase between 2005 and 2015; and (ii) the VED rates do not change over time, with the exception of the period April–October 2010, where at the moment of the registration, the second-year rate was set to be different from that of the first year.

The total revenue from the VED is simply the sum of the revenues from the predicted number of new registrations. The total revenue from proportional tax is given by

$$\text{REVENUE} = \sum_{i}^{N} \tau_P \delta_i CO2_i REG_i$$

where

$$\delta_i = \sum_{t=0}^{13} \frac{1}{\frac{HICP_{i0}}{100}\left[1 + (2.8t/100)\right]}$$

where τ_P is the proportional nominal tax rate in pounds per grams of CO_2/km, $CO2_i$ is the carbon emissions rate in grams per km, and REG_i is the number of predicted registrations from model-trim variant i.

In a similar fashion, the total revenue from the carbon tax is given by

$$\text{REVENUE} = \sum_{i}^{N} \sum_{t=0}^{13} \frac{\tau_C \delta_{it} CO2_i M_{it} REG_i}{1{,}000{,}000}$$

where τ_C is the nominal carbon tax rate in pounds per ton CO_2, and M_{it} is the driving in km for model-trim variant i at vehicle age t. The miles driven for each year of the vehicle's life are calculated with the methodology explained in "Appendix A".

To calculate the tax rate to use for the proportional tax and the carbon tax, we use a simple algorithm with the following steps: (i) select a tax rate from a range of possible rates for the proportional or the carbon tax, (ii) predict registrations for each model-trim variant and each period (normalized by make-period) under the VED or one of the alternative policies using the main model, (iii) calculate the total revenue from the VED and from the proportional or the carbon tax, and (iv) keep the tax rate only if the absolute value of the difference between the two revenues is within the 0.1% of the revenue from the VED.

We normalize registration within make-period because the estimated tax coefficient relies only on the VED variation within makes in the same policy period, due to the inclusion of make-period fixed effects. Because of those restrictions in substitution patterns, we simulate the effect of the VED using the same tax coefficient, but normalizing registrations of each make and period in each counterfactual to match the observed levels.

However, this assumption might be too conservative if most of the change occurred between different makes. Thus, as a robustness check we also run policy simulations only imposing that the total amount of registrations each period remain fixed.

The revenue from the VED is estimated to be roughly £14.2 billion. In the main specification, we are assuming all vehicles are driven the average lifetime miles driven, derived from the NTS data. For the carbon tax, we are using a miles driven elasticity with respect to fuel cost of −0.1803 from our miles driven model (see "Appendix A"). To predict new vehicle registrations, we are using the VED coefficient (i.e., converting the carbon tax to an amount to pay per year), and we are assuming that people anticipate their reduction in miles driven due to the introduction of a carbon tax when choosing a new vehicle. We assume no rebound effect on km driven from switching to a more efficient vehicle.

When calculating the effect of the carbon tax, we are also performing various sensitivity analyses by modifying some parameters or assumptions of the main specification: (i) using a slightly different way to calculate the average lifetime miles driven (see "Appendix A"), (ii) assuming that new vehicle registrations are inelastic, (iii) assuming that miles driven are inelastic, (iv) using the fuel cost coefficient (based on cost per 100 km) instead of the VED coefficient (based on cost during the first year) to predict new registrations, (v) using a miles driven elasticity to fuel cost of −0.3, and (vi) using various percentiles of lifetime miles driven from the NTS data (1st quartile, median, 3rd quartile, 90th percentile).[25]

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