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An Assessment of the Social Costs and Benefits of Vehicle Tax Reform in Ireland
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Building on COM/ENV/EPOC/CTPA/CFA/RD(2018)1, this document presents a social cost-benefit analysis of reforms in the motor vehicle taxes in Ireland since 2008.

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Note from the Secretariat

Building on COM/ENV/EPOC/CTPA/CFA/RD(2018)1, this document presents a social cost-benefit analysis of reforms in the motor vehicle taxes in Ireland since 2008. It has been written by Lisa Ryan[1], Andrew Kelly[2], Ivan Petrov[3], Yulu Guo[4] and Sarah La Monaca[5].

ACTION REQUIRED: For discussion.

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An Assessment of the Social Costs and Benefits of Vehicle Tax Reform in Ireland

1. Introduction

1. OECD's *Joint Meetings of Tax and Environment Experts* has started a project that will assess *ex post* the social costs and benefits of selected environmentally related taxes and tax provisions, cf. COM/ENV/EPOC/CTPA/CFA(2016)1. This project was in part motivated by a finding that there are very few fully-fledged cost-benefit analyses of such policy instruments available in the literature.[6] The aim of this project is to enrich this sparse literature and to provide illustrations of how both public authorities, academics and other interested stakeholders could carry out more such studies, in OECD countries and in any other country.

2. The term *environmentally related taxes* refers to any compulsory payment to general government levied on a tax-base of a particular environmental relevance, for which the tax payer does not obtain a benefit in return that is more or less in proportion to the amount paid in taxes. This includes e.g. any taxes levied on energy products, on motor vehicles, on measured or estimated emissions to air or water, as well as taxes on the landfilling or incineration of waste, taxes on packaging, taxes on hazardous chemicals, etc.

3. The term *environmentally related tax provisions* refers here, i.a., to a broad spectrum of *tax reductions* introduced primarily with an environmental motivation, such as reduced rates for a tax on mineral oils for fuels with a lower sulphur content; reduced rates in taxes on motor vehicles for electrical vehicles; as well as income tax reductions for certain behaviours judged to be environmentally benign (the use of public transport, investments in renewable energy generation, etc.). The term also refers to *other tax provisions* with unintended negative environmental impacts, such as e.g. increased air pollution and congestion due to favourable income tax treatment of the benefits employees might receive if they are allowed to use a company-owned car also for private purposes, commuting, etc.

4. This report follows the recommended approach for *ex post* cost-benefit analysis of environmentally related taxes and tax provisions to assess the vehicle tax reform in Ireland that occurred in 2008 and subsequent policy interventions in that same vein.

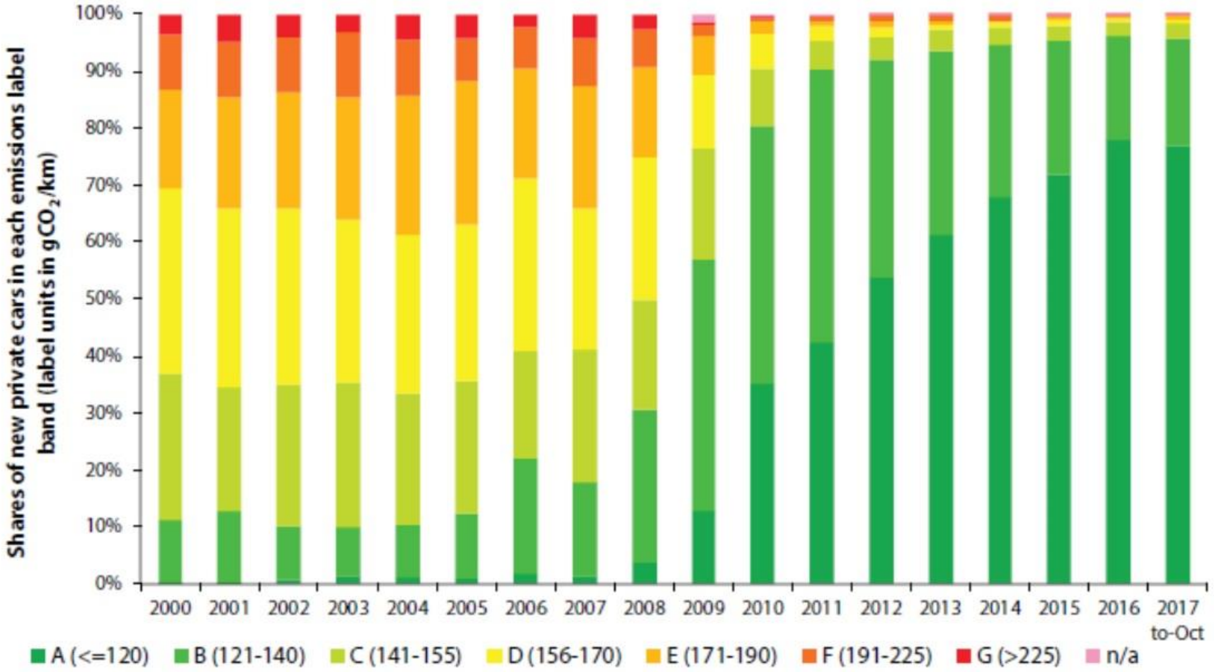
[6] Chen et al. (2017) is a rare *related* example, analysing impacts of a Chinese cash subsidy scheme for energy-efficient vehicles.

5. Over the past decade, EU Member States have introduced policies designed to reduce the CO_2 emissions intensity of the passenger car fleet. EU-wide policies, such as the CO_2 vehicles regulation, along with the economic recession in 2008, have influenced national passenger car CO_2 emissions rates. Detailed analysis has shown that countries with CO_2-differentiated vehicle taxes are observed to have been more likely to have achieved greater reductions in CO_2 emissions (Dineen et al., 2018; Gerlagh et al., 2016; Ryan et al., 2009).

6. This study focuses on the case of Ireland where until 2008, vehicle taxes were levied based on engine size. In July 2008, both the annual motor tax and the vehicle registration tax (purchase tax) were converted to a system based on the CO_2 emission rating of the vehicle, with lower taxes levied on lower-emitting vehicles. Figure 1 shows the emissions profile of Irish new car sales 2000-2017 in terms of their rated grams of CO_2 emitted per kilometre. A dramatic change in new car sales is apparent since 2008, with the rated CO_2 per kilometre of new vehicles having decreased significantly. This change is reflective of a variety of factors, including a shift in the CO_2 rating performance of vehicles being offered for sale and the purchasing behaviour of car purchasers.

Figure 1. Shares of new private cars in each CO_2 emission band

2000 – 2016 (+2017 to October)



Source: SEAI (2017), Energy in Ireland 1990-2016, Dublin.

7. Broadly, the share of diesel cars, which generally offer a more favourable CO2 rating per kilometre, increased with consequences for levels of harmful air pollutant emissions. At the time of the tax change, Ireland was also at the outset of a severe recession, which introduced considerable market volatility. Tax revenue from cars fell and purchasing patterns changed, inter alia as a result of both the tax change and the recession.

8. This study attempts to disentangle the impacts of these policy intervention changes from recessionary and other effects, and carries out a full social cost-benefit analysis of the vehicle tax switch

2. Description of policy measures

9. In 2008, the Irish Government changed the basis for vehicle taxation from vehicle engine capacity to a carbon dioxide (CO2) emissions rating per kilometre. The policy shift was announced in the budget for 2008 as part of a broader package of environmental measures which included stricter standards for the energy efficiency of lightbulbs and proposals for carbon taxation (O'Halloran, 2007). The introduction of the new vehicle registration tax (VRT) and motor tax regimes came at a time when the private vehicle fleet was responsible for a rising share of CO2 emissions in Ireland, accounting for 12% of total emissions in 2006 (Duffy et al., 2018; O'Gallachoir et al., 2009).

10. Vehicle taxation in Ireland is implemented through two mechanisms. One measure is a vehicle registration tax (VRT), which is calculated as a percentage of the Open Market Selling Price (OMSP) and collected as a one-time tax when the car is purchased. For new vehicles purchased within Ireland, this tax is effectively hidden in the car price. The second is an annual motor tax (AMT), collected as a yearly flat tax. The transition to CO2 emissions-based vehicle taxation in Ireland involved a combination of changes to these two schemes, with the fundamental shift occurring in 2008, followed by subsequent incremental changes. Before 2008, vehicle taxes were levied on the basis of engine capacity (Table 1). This paper examines the effects and outcomes of each phased change, as described in Table 2. This provides a comparative basis for quantifying the impact of individual policy adjustments, in addition to the overall change from engine size to emissions rating.

Table 1. Nominal vehicle taxes up to July 2008

Engine capacity cm^3	Annual motor tax €	VRT (% OMSP)
Not over 1 000	165	22.5%
1 001 to 1 100	249	
1 101 to 1 200	275	
1 201 to 1 300	298	
1 301 to 1 400	320	
1 401 to 1 500	343	25.0%
1 501 to 1 600	428	
1 601 to 1 700	453	
1 701 to 1 800	530	
1 801 to 1 900	560	
1 901 to 2 000	590	30.0%
2 001 to 2 100	754	
2 101 to 2 200	791	
2 201 to 2 300	827	
2 301 to 2 400	861	
2 401 to 2 500	899	
2 501 to 2 600	1 067	
2 601 to 2 700	1 109	
2 701 to 2 800	1 147	
2 801 to 2 900	1 189	
2 901 to 3 000	1 231	
3 001 or more	1 491	
Electrical	146	

Source: ACEA, 2018.

11. The first iteration of emissions-based vehicle taxation established seven rated bands or categories, according to an upper and lower limit for grams of CO_2 emitted per kilometre driven (CO_2 g/km). The emissions rating bands that went into effect on 1 July 2008, and the associated VRT and AMT rates, are shown in Table 3.

Table 2. Policy implementation for emissions-based vehicle taxation

Policy phase	Effective date	Summary change
Initial policy implementation	01-Jul-08	Transitioned from engine capacity to CO_2 emissions taxation basis; introduced initial A-G emissions ratings for VRT and AMT
Interim policy change A	01-Jan-09	Slight increases (4-5%) in Annual Motor Tax (AMT) amounts; no change to Vehicle Registration Tax (VRT)
Scrappage scheme	1 January 2010 – 30 June 2011	VRT relief of up to €1 500 for cars aged 10 years or older when traded in for an A- or B-rated vehicle
Interim policy change B	01-Jan-12	Substantial increases (up to 54%) in AMT amounts; no change to VRT
Final policy change	01-Jan-13	Introduction of graduated A- and B- ratings (A0, A1, A2, A3, A4, B1, B2); introduction of lower AMT rate for electric vehicles

Table 3. Initial policy implementation

Emissions rating bands with Annual Motor Tax (AMT) and Vehicle Registration Tax (VRT) rate, effective 1 July 2008.

Rating	CO_2 g/km		Annual Motor Tax (AMT)	Vehicle Registration Tax (VRT) as % of selling price
	Lower Limit (>)	Upper Limit (<=)		
A	0	120	€100	14%
B	120	140	€150	16%
C	140	155	€290	20%
D	155	170	€430	24%
E	170	190	€600	28%
F	190	225	€1 000	32%
G	225	225+	€2 000	36%

12. Following the initial transition to CO_2 ratings, the Irish government made several adjustments to its vehicle taxation schemes, including slight increases of 4-5% in AMT rates in 2009. However, by 2011, the share of A- and B-rated cars had grown from just 17% in 2007 to approximately 90% of new cars sold in 2011, and VRT and AMT revenues had fallen by 71% and 2.4%, respectively (Department of Finance, 2012). While the 2008 economic crisis surely played a role in depressing total car purchases (new car sales had dropped by more than half from 2007 to 2010), the Government noted that the high share of lower-emitting vehicles had contributed considerably to the fall in revenues. As a result, the Department of Finance announced substantial AMT rate increases, as part of the 2012 national budget, with a rise of 54% and 44% in tax for A- and B-rated cars, respectively, and smaller increases (7-8%) for vehicles in higher bands. See Table in 0.

13. In 2013, the Government updated the emission bands more dramatically, creating several subcategories to capture the evolving variation in performance of low-emitting cars. The 2013 changes included a more granular scale for A- and B-rated cars, and reduced AMT for electric vehicles (EVs) (See Table in 0). Whilst the 2012 changes to AMT and VRT rates were simple rate increases, the introduction of new vehicle ratings (A0, A1, A2, etc.) represented a more visible signal to consumers.

14. Concurrent with the period during which the Irish Government made adjustments to the rated emissions bands under the VRT and AMT schemes, officials also introduced a scrappage scheme intended to stimulate the purchase of new vehicles in Ireland in the wake of the 2008 economic recession. The conditions of the scheme were such that cars aged 10 years or older were eligible for VRT relief of up to €1 500 when traded in for a new vehicle, provided that the new vehicle was A- or B-rated (i.e. rated at CO_2 emissions of 140g/km or

less). The scheme was initially slated to run until 31 December 2010, and was subsequently extended until 30 June 2011, albeit at a reduced rate of €1 250 from 1 January 2011.[7]

15. In terms of policy interactions, CO_2 emissions-based vehicle taxation is one of several policy measures currently in place in Ireland to encourage the uptake of low-emission vehicles, some of which could also contribute toward the uptake of A-rated vehicles, particularly electric cars. VRT tax relief for electric vehicles provides a tax benefit of up to €5 000 for fully electric vehicles and €2 500 for plug-in hybrid cars. In 2017, government also introduced a 0% benefit-in-kind rate for electric company cars.[8] Other EV incentives include a grant for installation of home EV charging, worth up to €600, which was introduced in January of 2018.

16. By transitioning to vehicle taxation on the basis of average CO_2 emissions, the new tax regime placed an indirect cost on the carbon emitted from personal cars (a direct incidence of tax would be linked to usage, i.e. fuel cost). The explicit intent of Ireland's vehicle taxation regime was, of course, to encourage drivers to purchase more fuel-efficient vehicles, or low-carbon vehicles, and to consequently reduce harmful emissions from the transport sector. However, as noted by Hennessey and Tol (2011), and explored further in this paper, an outcome of CO_2-based car taxes, in the absence of electric or other ultra-low emissions vehicles, was a rise in the share of diesel cars.

3. Analysis of the behavioural impacts triggered by the policy measure

17. This section analyses how the policy changes described in Section 2 have impacted the vehicle purchasing patterns of Irish consumers. It begins by providing some context to the Irish passenger car stock, in terms new registrations vs. used imports (**Error! eference source not found.**).

18. Figure 2 presents the total number of passenger cars registered for the first time in Ireland, disaggregated as new domestic registrations and used imports. While new registrations have declined since 2008, there has been a steady rise in the total number of used imports as a share of first registrations. Used imports in this context are second-hand passenger cars registered for the first time in the Republic of Ireland. The majority of these come from the United Kingdom (UK), which is Ireland's largest trading partner, and sells right-hand drive vehicles.[9]

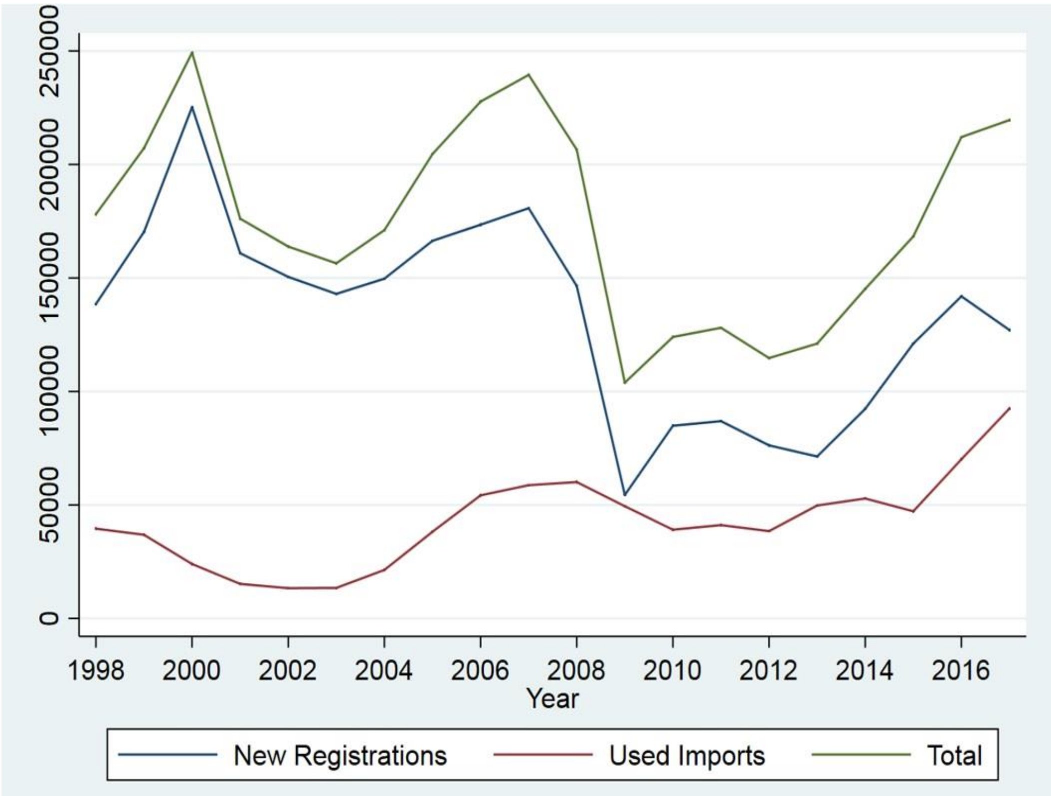
[7] Source: www.citizensinformation.ie/en/money_and_tax/budgets/budget_2011.html.

[8] Company cars are not eligible for VRT relief (Office of the Revenue Commissioners, 2017).

[9] For example, in 2016, 69 042 of the used vehicles imported into Ireland were from the UK, while just 3 111 of the remaining imports were from anywhere else. Source: https://stats.beepbeep.ie/.

Figure 2. Passenger cars registered for the first time in Ireland

Annual new registrations and used imports



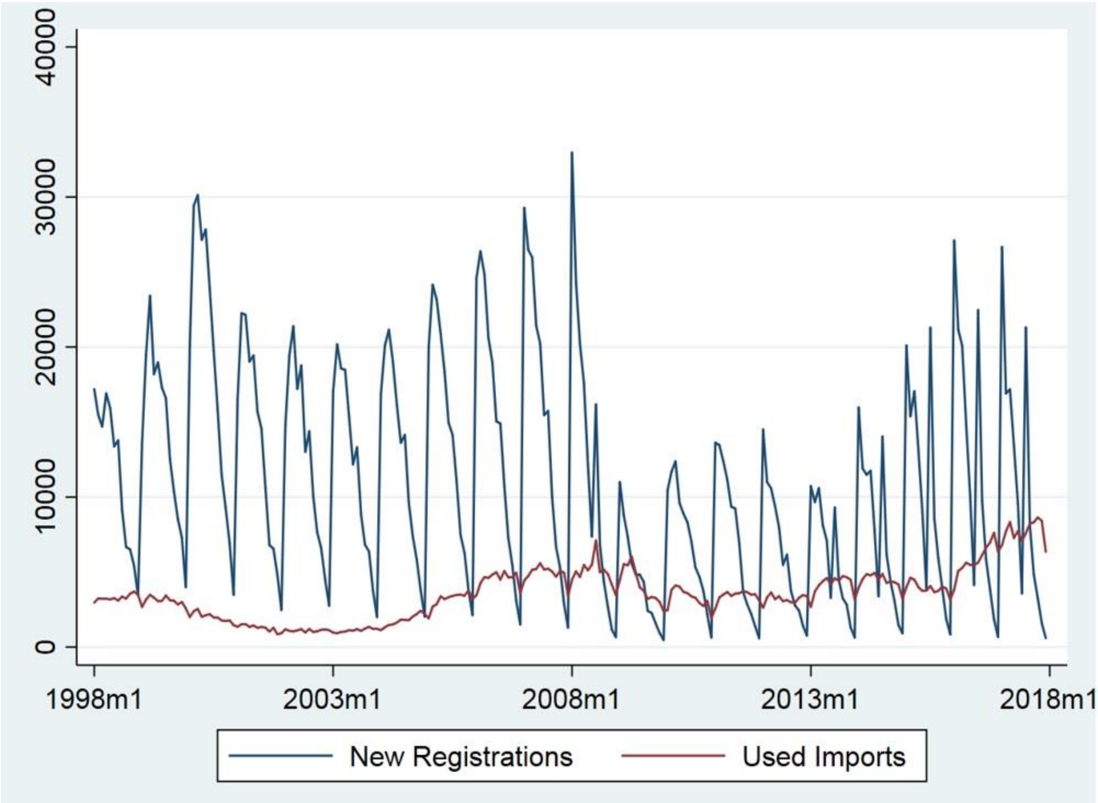
Source: Central Statistics Office (CSO) 2018.

19. It is clear from Figure 3 that the 2008 economic crisis appears to have had a considerable impact on the total number of vehicle registrations in Ireland. This impact appears to have been driven by a decline in new registrations, while used imports appear to have been largely unaffected. Around 2008, the exchange rate between the euro and sterling reached close to parity for a time, which would certainly have offered added incentive for consumers to purchase vehicles from the UK. This may explain why used imports remained relatively stable while new registrations declined sharply.

20. In addition to **Error! Reference source not found.**, which presents annual totals f new registrations and used imports, it is useful to examine the monthly variation in passenger car registrations, which is presented in Figure 3.

Figure 3. Passenger cars registered for the first time in Ireland, by month

Monthly new registrations and used imports



Source: Central Statistics Office (CSO) 2018.

21. New domestic registrations experience a high degree of volatility, while used imports exhibit a much more stable pattern. In particular, new domestic registrations peak every year in January, and subsequently decline throughout the year. This trend is likely attributable to a behavioural response to the system for license plate registrations in Ireland., by which registration year is presented as the first three digits (formerly two) on the licence plate of newly registered passenger cars. Individuals who wish to purchase a new car typically wait to register the vehicle until January of the following year, as this improves the vehicle's resale value. In 2013, in an effort to stimulate new car purchases mid-year, the government introduced a bi-annual vehicle licencing system, whereby cars registered in the first half of the year would have licence plates beginning with "131" while cars registered in the second half of the year would have licence plates beginning with "132".[10] This appears to have had a dramatic effect on the timing of new vehicle

[10] In part, this measure was also introduced due to fear that new car sales may be reduced in 2013 due to superstition regarding the number "13" as the first two digits of the registration number. Source: https://www.independent.ie/irish-news/2013-number-plates-to-be-changed-to-avoid-unlucky-13-26890349.html

registrations, as exemplified by the double peaks in new domestic registrations following 2013.[11]

22. The following analysis focuses on the impact of the tax change on the average CO_2 emissions ratings and the diesel share of first-registered private cars. Since the tax change applies to first registered after July 2008 only, the focus is specifically on the change in new registrations in the following section.

3.1. Rated CO_2 Emissions

23. In order to assess the impact of the change in the registration and circulation vehicle tax regime on CO_2 emissions of passenger cars, this analysis focuses specifically on domestic registrations of new vehicles in Ireland. Although used imports constitute a significant proportion of Irish vehicle registrations, reliable CO_2 ratings data for used imports prior to 2008 are not available, and hence the change in import CO_2 ratings attributable to the 2008 tax regime change cannot be observed. Figure 4 presents the average CO_2 rating of new passenger cars registered in Ireland and in the United Kingdom over the period from January 2003 to June 2018.

Figure 4. Average CO_2 rating of first registration of new passenger cars

Source: Society of the Irish Motor Industry 2018 and UK Department of Transport - Vehicle Licensing Statistics 2017

[11] The only other year where one can observe a double peak is in 2008, when the initial policy change took effect on 1 July

24. The dashed lines in Figure 4 represent years in which various changes to the circulation tax regime took effect, as discussed in Section 2. The data demonstrate a significant decline in the average CO_2 emissions rating of new passenger cars in Ireland over the period 2002 to 2018. The average rated CO_2 emissions of new passenger cars in Ireland has declined from approximately 170 gCO_2/km to less than 120 gCO_2/km in the span of 10 years – an improvement of 30%. This decline was particularly pronounced around the time of the first change in the motor tax regime (July 2008), as average CO_2 rating decreased by approximately 35 gCO_2/km over one month. Interestingly, in the month prior to the change in the tax regime, average CO_2 rating of new cars exhibited a sharp increase. This suggests a behavioural response whereby individuals may have hastened the timing of their purchase of high-emitting vehicles in order to avoid being subject to the new tax regime. Indeed, only vehicles register on or after the effective date of the policy change were subject to the new system.

25. In addition to the sharp decline in average CO_2 rating of new passenger cars in 2008, Figure 4 also shows that the average CO_2 ratings declined considerably from 2010 to 2011. This is likely attributable to a government-led scrappage scheme which was proposed in Budget 2010[12] and came into effect on 1 January 2010, as discussed in Section 2 (the scrappage scheme is depicted in the grey box in Figure 4).

26. Volatility in average CO_2 rating at precisely the time of the change in the motor tax regime in 2008, and of the scrappage scheme in 2010, is a strong indication of an immediate response to the policy change. However, the data also demonstrate a downward trend in the CO_2 emissions profile of newly registered vehicles in the years prior to and following the effective date of the policy. This underlying downward tendency suggests that the CO_2 intensity of new passenger cars may have improved over time, even in the absence of changes in the motor tax regime. Indeed, the long-term decrease in the average rating of newly registered passenger cars may have been affected more acutely by supply side effects (i.e. manufacturers producing less CO_2 intensive cars) rather than by a consumer response to the change in vehicle taxation policy. It is therefore useful to construct a counterfactual prediction of what might have occurred without any policy change, in order to measure the relative effect of adjustments to the tax regime.

27. Identifying a reasonable counterfactual for changes in Ireland's average CO_2 emissions ratings in Figure 4 requires using data from a comparable market. To approximate this counterfactual, the emissions profile of corresponding vehicle registrations in the United Kingdom for the same period has been used.

28. The United Kingdom provides a suitable counterfactual for the Irish market for a number of reasons. First, prior to the tax regime change in Ireland in 2008, the average CO_2 rating for newly registered passenger cars in Ireland and the United Kingdom appear to be on a very similar trajectory, as shown in Figure 4. This relationship meets the parallel trends assumption which is central the application of difference-in-difference analysis applied here (Angrist & Pischke, 2008). Second, there were no substantial changes to the UK motor taxation system over the period from March 2001 to April 2017,[13] other than the

[12] Source: www.citizensinformation.ie/en/money_and_tax/budgets/budget_2010.html.

[13] For more information on the UK circulation tax rates, please refer to: https://www.rac.co.uk/drive/advice/buying-and-selling-guides/car-tax-bands-explained/.

introduction of a small first year ("show-room") tax in April 2010.[14] Since March 2001, the annual motoring tax, Vehicle Excise Duty (VED), in the United Kingdom has been calculated based on CO_2 emissions ratings. As such, the United Kingdom provides an example of policy stability, against which to compare the policy change in Ireland. Third, the United Kingdom and Ireland share similar road infrastructure and driving rules. Both jurisdictions operate under Left-hand Traffic (LHT) (LHT) rules, and nearly all vehicles registered in both countries are Right-hand Drive (RHD).[15] These characteristics, coupled with the close proximity of the two markets, suggest a similar product offering by car manufacturers in both jurisdictions.

29. Using the United Kingdom as a comparison case, this report uses a difference-in-difference econometric methodology to estimate the magnitude of the effect of the 2008 policy change and subsequent adjustments in Ireland on the average CO_2 rating of newly registered passenger cars. In this application, the difference-in-difference approach uses the UK data to estimate the probable trajectory of Irish average CO_2 ratings, if no policy change occurred. It then compares the no-change trajectory to one based upon the observed data for Ireland, incorporating the implemented policy changes. Per Wing, Simon, & Bello-Gomez (2018), the basic form for a difference-in-differences analysis with multiple periods and countries in a regression framework is as follows:

$$\boldsymbol{Y_{st} = \gamma_s + \lambda_t + \delta D_{st} + \epsilon_{st}} \qquad (1)$$

In the above, γ_s is the state (country) fixed effect and λ_t is the time fixed effect. Monthly data are being used. D_{st} is an interaction term of treated units after the treatment date (i.e. $IRL_s \cdot d_t$) The results of the above specification are presented in column (1) of Table 4.[16]

30. As a second specification, the individual effects of each of the interim policy changes which occurred in Ireland between 2008 and 2013 have been estimated (i.e. the increases to AMT which occurred in 2009 and in 2012, and the scrappage scheme which was in effect from 2010-2011). Equation (1) above has been expanded to include interaction terms for each of the interim policy changes.

31. As a third specification, country-specific covariates which vary over time and may influence vehicle purchase decisions have been controlled for. These include household income, as well as the price of diesel and petrol fuels, and are modelled as follows:

$$\boldsymbol{Y_{st} = \gamma_s + \lambda_t + \delta D_{st} + X'_{st}\beta + \epsilon_{st}} \qquad (\mathbf{2})$$

32. The results of the above specification are presented in column (3) of Table 4. Finally, as a robustness check, a country-specific linear trend has also been included as follows (Angrist & Pischke, 2008):

[14] From Figure 4, one can see that this does not appear to have had a substantial impact on the average CO_2 rating of newly registered cars in the United Kingdom.

[15] Source: https://www.worldstandards.eu/cars/driving-on-the-left/.

[16] Since there are only two (aggregate) observations per country in each time-period, this means that the standard errors produced are likely to be understated. However, using a difference-in-differences specification in this manner can nonetheless give us an indication of the magnitude of the effect of the policy.

$$Y_{st} = \gamma_{0s} + \gamma_{1s}t + \lambda_t + \delta D_{st} + X'_{st}\beta + \epsilon_{st} \quad (3)$$

33. The results of the above are presented in column 4 of Table 4.

Table 4. Difference–in-difference results – CO_2 emissions rating

	(1)		(2)		(3)		(4)	
Initial policy (2008)	-8.4341	***	-10.2867	***	-9.1726	***	-11.0948	***
	(0.5305)		(1.2322)		(1.5756)		(1.7125)	
Interim policy change A (2009)			4.4843	***	4.6711	***	4.1186	***
			(1.3622)		(1.5178)		(1.5029)	
Scrappage scheme			-5.8059	***	-6.5564	***	-6.2573	***
			(0.9632		(1.0403)		(1.0262)	
Interim policy change B (2012)			-2.0461	*	-2.4954	**	-3.3853	***
			(1.0769)		(1.1108)		(1.1415)	
Final policy change (2013)			-0.1239		0.1249		-0.9659	
			(0.987)		(1.0086)		(1.0741)	
Household consumption					0.0124	*	-0.0001	
					(0.0064)		(0.0079)	
Price of petrol					-0.0098		-0.005	
					(0.0126)		(0.0125)	
Price of diesel					0.0026		0.0001	
					(0.0133)		(0.0131)	
Adjusted R	0.9867		0.9893		0.9895		0.99	
Country-specific trend	No		No		No		Yes	
N	300		300		300		300	

Note: *** Statistically significant at p<0.01
** Statistically significant at p<0.05
* Statistically significant at p<0.1

34. Testing solely for the effect of the 2008 policy change (column 1), average CO_2 rating of newly registered passenger cars decreased by approximately 8.4 gCO_2/km in each subsequent year, relative to the counterfactual trend of no policy change. Although this is a significant result, it does not disaggregate the effect of subsequent changes to the VRT and AMT following the initial policy change (as discussed in Section 2). As such, the effect of the 2008 change may be under- or overstated in column 1.

35. In order to analyse the effect of each of the policy changes individually, Equation (2) includes interaction terms at each of the policy change dates, with results presented in column 2. Adding the interaction terms for each policy change increases the size of the coefficient associated with the 2008 policy change to approximately 10 gCO_2/km. Interestingly, the first interim policy change, which occurs in 2009, actually reduces the difference in average CO_2 rating by 4.5gCO_2/km. Although this is counterintuitive, as mentioned previously, this effect is a comparison between the difference in the observed and counterfactual emissions rating after the 2009 change, compared with the difference prior to the change. Thus, while the Irish average emission rating is still lower than the no-change trajectory, the difference between the two trajectories has narrowed after the 2009 policy change. Per Figure 4, the period after the 2009 change was defined by falling average CO_2 emissions ratings in the United Kingdom, which is the basis for the Irish no-change counterfactual. During the same period, emission ratings appear to have stagnated in Ireland, resulting in a smaller effect from the 2009 policy change. The stagnation in average

emission ratings in Ireland may also be a correction following a strong response by consumers to the initial policy change in June 2008.

36. Another finding from the second specification of the difference-in-difference model is that the scrappage scheme had a significant impact on the emissions rating of new passenger cars in Ireland, reducing average rated emissions by an additional 6.6 gCO_2/km compared to the previous period. This result is consistent with expectations, as a condition of the scheme was that newly purchased vehicles had to be at least B-rated or better in terms of CO_2 emissions per kilometre. The 2012 interim policy change also had a small but significant effect on average emissions rating, which decreased by an additional 2gCO_2/km. The interim policy change in 2012 increased the circulation tax rate specifically for lower rated vehicles (A and B in particular). An explanation for this effect may be, however, that the policy change may have been a signal as to the significant financial benefits associated with purchasing a lower CO_2 rated vehicle.[17]

37. The third specification of the difference-in-difference model (column 3) includes a number of control variables which may influence vehicle purchasing decisions, and which vary by country and over time. Household consumption per capita exerts only a weakly significant effect on average emission rating, whereby an increase in household consumption increases the average CO_2 rating of newly registered cars by a small amount. This effect may be due to individuals purchasing vehicles with bigger engines (both diesel and petrol) in periods with high per capita consumption.

38. Finally, as a robustness check, the fourth specification of the difference-in differences model includes tests for country-specific trends. Reassuringly, the findings are of a similar effect of the policy changes across all of the coefficients, with the exception of household consumption per capita, whose effect is insignificant.

3.2. Diesel share

39. Section 3.1 demonstrates a significant decrease in the average CO_2 rating of newly registered passenger cars in Ireland as a result of the relevant policy measures. Section 3.2 further explores the underlying reasons for this result in terms of new registration composition by fuel type. Again, the analysis distinguishes between the first registration of a new vehicle (new registrations) and the first registration of used import vehicles (import registrations).

3.2.1. Registrations of new private cars

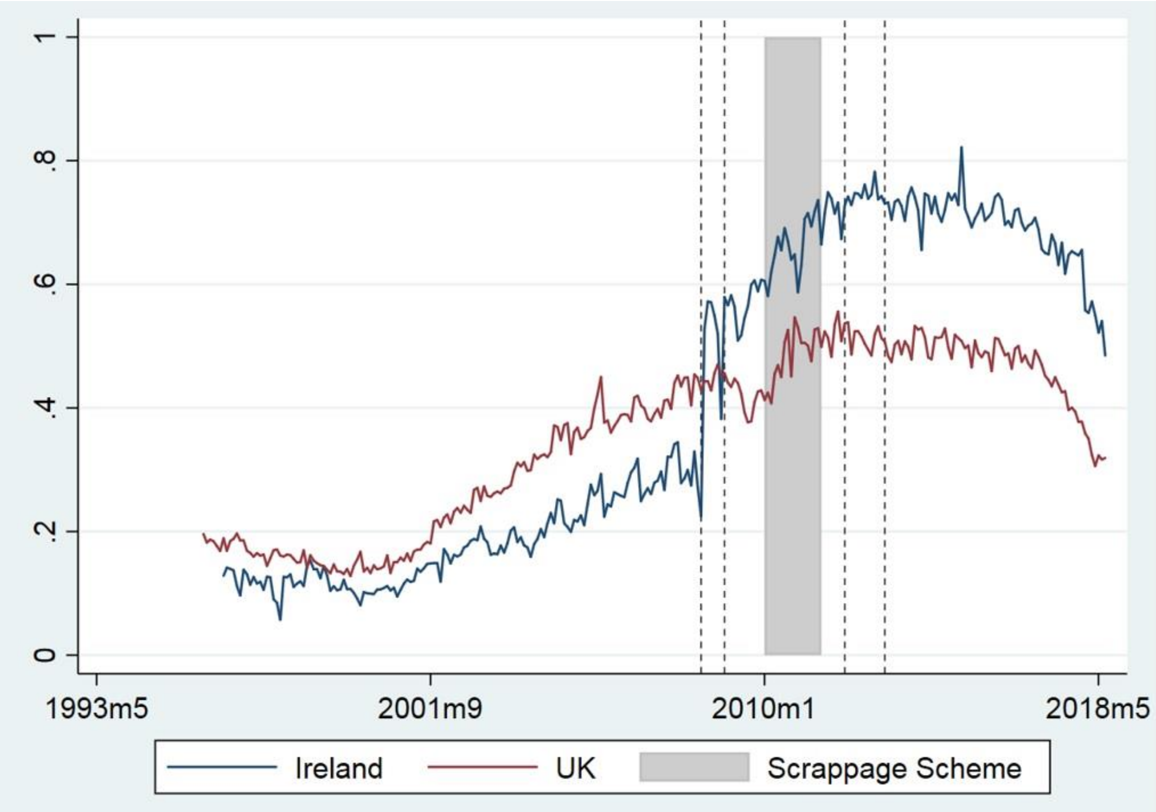
40. Figure 5 presents the diesel share as a proportion of new domestic car registrations in Ireland and the United Kingdom. Prior to 2001, the diesel share trend in the United Kingdom and Ireland appears to be the same, with the United Kingdom consistently experiencing a slightly higher share of new vehicles registered as diesels. After 2001, however, the two trends begin to diverge slightly, which may be attributable at least in part to the United Kingdom's introduction of CO_2 emissions-based taxes in March 2001.[18] From

[17] In other words, it may have confirmed to buyers of new vehicles the significant financial savings associated with purchasing an A or B rated passenger car.

[18] Source: https://www.rac.co.uk/drive/advice/buying-and-selling-guides/car-tax-bands-explained/. It is interesting to note, however, that there does not appear to have been an immediate response in

this point forward, the diesel share of new vehicle registrations in the United Kingdom was consistently higher than in Ireland (by at less than 30%), until June 2008.

Figure 5. Diesel share – New domestic registrations



Source: Central Statistics Office (CSO) - Ireland 2018 and The Society of Motor Manufacturers and Traders (SMMT) – UK 2018.

41. In July 2008, in the month following the introduction of the CO_2 tax regime in Ireland, the proportion of diesel vehicles registered in Ireland shifted dramatically. The diesel share of new registrations in Ireland increased by almost 40% over the course of one month, reaching approximately 80% of new registrations. Furthermore, the shift appears to have been a sustained, as the years following the 2008 tax regime change saw the diesel share of new registrations remain consistently higher than in the United Kingdom. As in Section 3.1, this analysis uses a difference-in-differences quasi-experimental design to quantify the proportion of the shift in diesel share that is attributable to the 2008 policy change. The first iteration of the difference-in-differences specification examines the single policy change in 2008, then adds the remaining changes, controls and country-specific trends to the model in the same manner detailed in Section 3.1. The results are presented in Table 5.

the diesel share of vehicle registration in the United Kingdom immediately following the tax regime change in March 2001.

Table 5. Difference-in-difference results – Diesel share

	(1)		(2)		(3)		(4)	
Initial policy (2008)	0.3244	***	0.1939	***	0.2016	***	0.2071	***
	(0.0071)		(0.0145)		(0.0169)		(0.0174)	
Interim policy change A (2009)			0.0942	***	0.1066	***	0.1075	***
			(0.016)		(0.0175)		(0.0175)	
Scrappage scheme			0.0103		0.0007		-0.0009	
			(0.0113)		(0.0121)		(0.0122)	
Interim policy change B (2012)			0.065	***	0.0647	***	0.0683	***
			(0.0126)		(0.013)		(0.0133)	
Final policy change (2013)			-0.0052		-0.0024		0.0045	
			(0.0106)		(0.0112)		(0.0125)	
Household consumption					0		0.0001	
					(0.0001)		(0.0001)	
Price of petrol					-0.0003	**	-0.0004	**
					(0.0001)		(0.0001)	
Price of diesel					0.0003	**	0.0003	**
					(0.0001)		(0.0001)	
Adjusted R	0.9626		0.9798		0.98		0.9801	
Country-specific trend	No		No		No		Yes	
N	300		300		300		300	

Note: *** Statistically significant at $p<0.01$
** Statistically significant at $p<0.05$
* Statistically significant at $p<0.1$

42. Column 1 in Table 5 shows that including only the 2008 tax regime change in the difference-in-differences estimation produces a positive and significant effect of an increase of approximately 32% on the diesel share of new registrations in Ireland. Including the subsequent policy changes in column 2, however, reduces the size of the effect of the initial policy change to roughly 20%, and this remains consistent throughout the remaining specifications. Column 2 shows that the subsequent policy changes also had a significant impact on the diesel share of new registrations in Ireland. The second biggest impact appears to have been the policy change in January 2009, which increased the diesel share by approximately 9%. As with the finding in Section 3.1, however, this may be attributable to a residual effect from the initial policy change. The scrappage scheme did not have a significant impact on the diesel share across any of the model specifications. This suggests that although the scheme had a significant impact on average CO_2 ratings by incentivising consumers to buy more CO_2 efficient vehicles, it did not have an impact on the type of vehicles consumers chose to purchase in terms of fuel type. Finally, it should be noted that the 2012 interim policy change increased the diesel share in Ireland by approximately 7%. As with the explanation in Section 3.1, this may be attributable to a signalling effect of the policy change, whereby consumers were reassured that buying a lower-emitting vehicle would be beneficial in terms of the associated tax savings.

43. Column 3 in Table 5 shows the results of adding control variables to the difference-in-differences model. Household consumption did not have a significant effect on diesel share. Petrol and diesel price do show a small but significant effects, albeit with counterintuitive signs. The coefficient on petrol price suggests that as petrol price in the current period increases, the diesel share decreases. Intuitively, the opposite should be true: as petrol prices increase, consumers would switch to diesel cars, and vice versa for diesel prices and petrol cars. This result may be explained, however, by the fact that consumers'

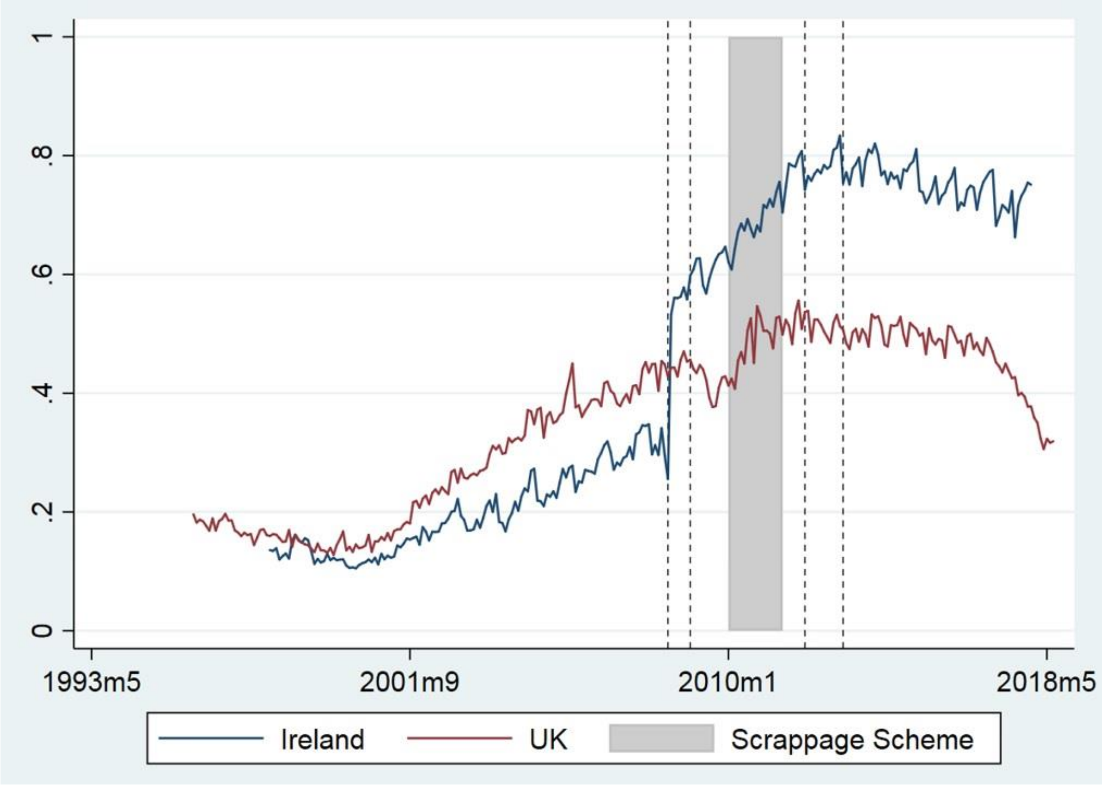
car purchasing behaviour may be more heavily influenced by past fuel prices, rather than current fuel prices, and that a lag effect may be present. Nevertheless, since the coefficient values are close to zero, the effect is negligible. As a robustness check, the model was run controlling for country-specific trends. The size and significance of the coefficients remains largely unaffected, which suggests that the estimated coefficients are robust to the inclusion of a linear country-specific trend.

3.2.2. Diesel share – Including used imports

44. Section 3.2.1 compares the diesel share of Irish registrations of new passenger cars to the diesel share of registrations in the United Kingdom. As noted previously, a sizeable portion of first vehicle registrations per year in the Republic of Ireland, however, are used imports, primarily from the United Kingdom). For example, in 2017, approximately 41% of all private cars registered for the first time in Ireland were used imports. In Figure 6, the diesel share of all vehicle registrations in Ireland per month (including used imports) have been plotted against UK vehicle registrations per month.[19]

Figure 6. Diesel share of total passenger cars registered

Ireland vs the United Kingdom



Source: Central Statistics Office (CSO) - Ireland 2018 and The Society of Motor Manufacturers and Traders (SMMT) - UK 2018.

[19] Note: the UK figures used in this section are the same as those used in Section 3.2.1, and do not include second-hand vehicles imported into the UK. Second-hand imports in the United Kingdom, however, constitute a very small proportion of the vehicle stock. In 2017, only 2.4% of the passenger car stock in the United Kingdom were used imports (Source: Author correspondence with SMMT).

45. Figure 6 shows that the diesel share when including used imports (~80%) is similar to the diesel share of new domestic registrations alone, and appears to have been affected similarly by the 2008 taxation policy change. Mirroring the effect shown solely in new domestic registrations, the diesel share of total passenger car registrations increases considerably precisely in the month following the 2008 tax regime change and appears to have had a persistent effect. To quantify the magnitude of this effect, this analysis employs the same difference-in-differences methodology detailed in prior sections, with the same variations in model specification. The results are presented in Table 6.

Table 6. Difference–in-differences results: Diesel share of total monthly registrations

	(1)		(2)		(3)		(4)	
Initial policy (2008)	0.3538	***	0.2204	***	0.1807	***	0.1865	***
	(0.0073)		(0.0139)		(0.0152)		(0.0157)	
Interim policy change A (2009)			0.1063	***	0.0816	***	0.0826	***
			(0.0154)		(0.0157)		(0.0157)	
Scrappage scheme			-0.0138		-0.021	*	-0.0225	**
			(0.0109)		(0.0109)		(0.0109)	
Interim policy change B (2012)			0.0515	***	0.0391	***	0.0428	***
			(0.0122)		(0.0117)		(0.0119)	
Final policy change (2013)			0.0045		-0.0119		-0.0051	
			(0.0103)		(0.0101)		(0.0112)	
Household consumption					0.0002	***	0.0003	***
					(0.0001)		(0.0001)	
Price of petrol					0		0	
					(0.0001)		(0.0001)	
Price of diesel					0.0001		0.0002	
					(0.0001)		(0.0001)	
Adjusted R	0.9672		0.9841		0.9864		0.9864	
Country-specific trend	No		No		No		Yes	
N	360		360		360		360	

Note: *** Statistically significant at p<0.01
** Statistically significant at p<0.05
* Statistically significant at p<0.1

46. The 2008 policy change, examined on its own (column 1) appears to have had an even larger effect on the diesel share of total registrations than for new cars alone. As before, the size of this effect is smaller when combined with interaction terms for the subsequent policy changes. The 2008 and 2012 policy changes had a significant and positive effect on diesel share, with the change in 2008 appearing to play a more significant role. Adding the covariates of household consumption and fuel price yields only marginal changes the size of the coefficients, shown in column 3, with the exception of the scrappage scheme interaction term, which becomes weakly significant at the 5% level. Among the control variables, only household consumption shows a significant and positive effect on diesel share, which suggests that as household consumption increases, the diesel share of total registrations increases also. Finally, as in Sections 3.1 and 3.2, country-specific trends have been included as a robustness check (shown in column 4) and do not change the size and significance of the estimated coefficients.

3.3. Summary of the estimations of the impacts of the policy changes

47. In summary, the change in the tax regime and subsequent policy changes have had a sizeable impact on the average CO_2 ratings of newly registered passenger cars. Upon closer examination, this effect appears to have been driven by increased purchases of diesel-powered vehicles, which tend to have lower rated CO_2 emissions but higher emissions of other pollutants such as NO_x. This increase in diesel share confirms the prediction made by Hennessy & Tol (2011), and is very close to their estimate of the increase in diesel share attributable to the policy change.[20]

4. Assessments of the impacts of the behavioural changes on environmental pressures

48. In order to examine the impact of the tax changes, this analysis considers two fleet scenarios which simulate the greenhouse gas (GHGs) and air pollution emission outcomes. The first scenario is the policy measure scenario, which captures the actual fleet and emissions outcomes that resulted from the defined policy interventions from 2008. The second scenario is a counterfactual scenario, which draws upon the analysis of new registrations in Section 3 and is designed to represent a situation in which none of the defined policy interventions were introduced between 2008 and 2017.

49. The simulation is supported by an Irish version of SIBYL. SIBYL is a transport fleet model, derived from the COPERT system,[21] that can support the development and analysis of a variety of road transport policies and associated scenarios. The model is calibrated with actual and estimated vehicle stock and activity data, and is utilised as part of the assessment of associated GHGs emissions and air pollution outcomes for a given scenario. The estimated activity data is informed in part by recent analysis of odometer readings from the national car test data in Ireland using an earlier developed method (Kelly et al., 2009).

50. It is important to note that the modelling system allows for evaluations of either "real world" emissions or "type approval" (i.e. rated) emissions. This analysis uses the "real world" option. These deliver higher emission outcomes than the type approval emission factors, which reflect manufacturer or governmental ratings, that may not be as representative of actual on-road emission performance.

[20] Hennessy and Tol (2011) estimated that the overall market share of diesels in Ireland will increase from 25% to 58% as a direct result of the policy shift (an increase of 33%) which is strikingly similar to estimate of the single policy effect (36% - column 1 of Table 6) and the combined effect of the disentangled individual policy measures (29% - column 4 of Table 6).

[21] http://emisia.com/products/copert-4.

51. The policy measure scenario for this modelling was informed by actual historical data of the Irish fleet. Table 7 shows the number of new private vehicle registration and private vehicle stock over the years 2008 to 2017.

52. The total number of private diesel vehicles in the Irish fleet was approximately one third of petrol private vehicles in 2008, but by 2017, they had reached a near-even split in their share of the total market. The data show a clear shift in the purchasing patterns from 2008 onwards, with many years of diesel sales outstripping those of petrol. The proportion of newly registered private vehicles was approximately 8% of total private vehicles in these years.

53. The counterfactual scenario assumes that total new vehicle demand remains the same as in the policy interventions scenario. The policy interventions influence vehicle choice; however, they would not necessarily change the overall level of vehicle demand. The difference between the two fleet simulations in terms of new and newly imported petrol and diesel vehicle purchases are shown in Figure 7.

54. Diesel vehicle purchases are higher under the policy interventions scenario than in the counterfactual scenario. However, in moving from a petrol vehicle purchase in the counterfactual scenario, to a diesel vehicle in the policy scenario, the shift is not necessarily from a small petrol engine to a small diesel engine.[22] Official vehicle sales data (www.simi.ie) suggest that the bulk of new purchases following the policy intervention were medium-sized diesel engines. In the analysis, approximately 90% of the vehicle swaps between the counterfactual and policy intervention scenario over time are consequently defined as small petrol to medium diesel.

55. Fuel efficiency generally improves for those users moving from a petrol car to a diesel one. The difference is modest for the main group, who swap between a small petrol and a medium diesel vehicle. Nevertheless, given that the fuel cost per kilometre driven is lower for diesel cars, one would expect to find a rebound effect due to consumers driving more, as is well documented in fuel economy studies (see Dimitropolous et al., 2018, for a recent meta-analysis). Here, the rebound effect is assumed to be 20%, reflecting the latest findings in the United Kingdom (Stapeleton et al., 2016) and the French bonus-malus scheme (D'Haultfoeille et al., 2014) on direct rebound effect. The policy intervention scenario therefore assigns a higher mileage for those new diesel vehicles in the fleet than for the corresponding petrol vehicles in the counterfactual.

[22] In this analysis, vehicles are separated into small (<1.4 litre engine), medium (1.4 to 2 litre engines) and large (>2 litre engine) categories.

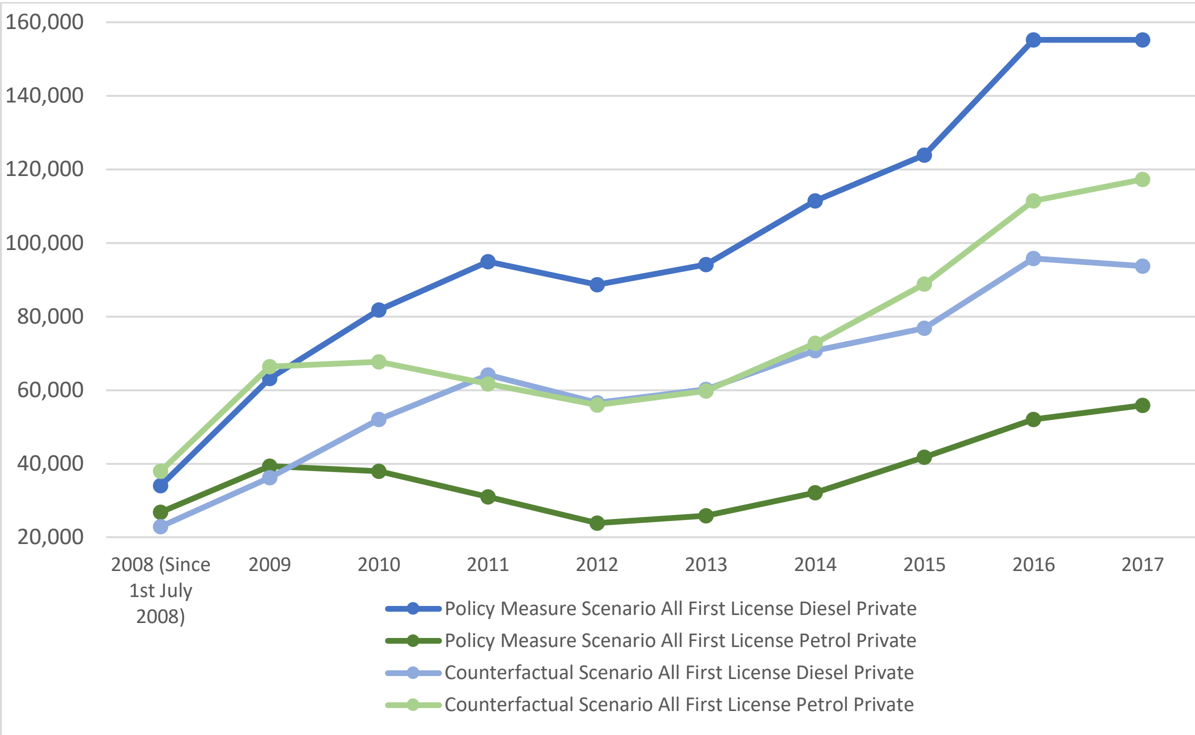
Table 7. New registration of passenger cars and total vehicle stock

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
All new diesel private	77 949	63 223	81 787	94 918	88 668	94 176	111 462	123 949	155 206	155 212
New registration diesel private	50 283	30 645	53 998	61 730	56 520	51 772	67 740	86 103	99 306	82 492
Imported diesel private	27 666	32 578	27 789	33 188	32 148	42 404	43 722	37 846	55 900	72 720
All new petrol private	124 535	39 361	37 934	31 002	23 888	25 849	32 098	41 759	52 087	55 855
New registration petrol private	92 298	22 802	27 124	23 246	17 788	18 964	23 417	32 963	39 472	39 391
Imported petrol private	32 237	16 559	10 810	7 756	6 100	6 885	8 681	8 796	12 615	16 464
Diesel private	383 421	424 478	480 485	559 195	621 105	693 663	776 440	864 925	969 228	1 070 518
Petrol private	1 533 806	1 469 704	1 379 889	1 314 367	1 245 203	1 199 451	1 148 911	1 099 453	1 032 806	962 775
Total vehicle	2 497 568	2 467 660	2 416 387	2 425 156	2 403 223	2 482 557	2 515 322	2 570 294	2 624 958	2 675 879

Source: CSO, DTTaS.

Figure 7: Fleet Simulation of the policy measure and counterfactual scenarios

2008-2017 (numbers of vehicles)



Sources: CSO, DTTaS, own modelling

56. The difference in emission outcomes across the pollutants between the policy interventions and counterfactual scenario are presented in Table 10. The substantive emission changes relate to NO_X, $PM_{2.5}$, NMVOC and CO_2. The increasing rate of diesel vehicles under the policy interventions scenario contribute to a steady increase in both NO_X and $PM_{2.5}$ as those vehicles penetrate the market at an accelerated rate, and thereafter continue to operate within the fleet over time. The rate of increase in those emissions slows in later years as the estimated real-world emission performance sees a continuing convergence between petrol and diesel vehicles in terms of their NO_X and $PM_{2.5}$ emission factors. This convergence is most apparent from 2015 onwards, and it is likely that the improved testing of Euro 6c and Euro 6d temp[23] will offer further confidence in the abatement technology performance. Notably, the "Dieselgate" emissions scandal of 2015 served as an important trigger for change in regard to narrowing the gap between tested and real-world emission performance.

[23] Euro 6c and 6d temp changed the testing, not the standard, for Euro 6. In 6c, vehicles are tested on the worldwide harmonised light vehicle test procedure (WLTP) which offered an improved emission estimate to testing based on the older "New" European Driving Cycle (NEDC). These are both lab tests. Euro 6d temp introduces the real driving emissions (RDE) test which assessed vehicles' on-road performance. It is therefore expected that the gap between tested emissions and actual emissions will close now into the future, as new vehicles adhere to the Euro 6 standard, which see very little difference between petrol and diesel vehicles in terms of their emission performance for NO_X and PM.

57. The growing number of diesel vehicles in the fleet in place of petrol vehicles also delivers a benefit in terms of reduced NMVOC emissions.

58. In terms of CO_2, the analysis suggests that the policy has indeed contributed to a steady and growing reduction of CO_2 as a result of the shift towards more fuel-efficient vehicles. The impact builds from a saving of just under 7kt in 2008 to approximately 166kt in 2017. As indicated, these values allow for a modest rebound effect in regard to the difference in fuel efficiency between the petrol and diesel vehicle choices.

59. It is noteworthy that from 2017 onwards, the difference between petrol and diesel vehicles in terms of air pollutant emissions is likely to have narrowed to the extent that from this point onwards, there would be a limited penalty in terms of additional air pollution irrespective of petrol or diesel vehicle choices. This assumes that Euro6d temp stimulates the desired changes in real world on-road emissions. This work also adds further weight to the argument that in regard to operational emissions, shifting from one internal combustion engine (ICE) vehicle to another offers only modest changes. The greater impacts would be realised where the ICE vehicle use is reduced, or indeed substituted for an electrified alternative that offers a more substantial change in efficiency and exhaust emissions.

Table 8. Annual emission variation between policy and counterfactual scenario

Tonnes

Tonnes	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
NO_X	110	365	673	946	1 218	1 494	1 825	1 879	1 966	2 000
SO_2	1	2	3	4	6	7	8	10	12	14
NMVOC	-57	-188	-328	-451	-575	-700	-850	-982	-1 154	-1 326
$PM_{2.5}$	12	41	48	54	60	66	73	81	92	103
NH_3	-5	-17	-22	-27	-31	-36	-41	-44	-48	-52
CO_2	-6 744	-22 381	-39 892	-55 153	-70 145	-85 013	-102 530	-121 861	-144 821	-166 033

5. Assessments of the impacts of the behavioural changes on environmental states

60. The previous section has provided an estimation of the changes in air pollutant emissions and CO_2 that are attributable to the policy interventions studied here. The change in tonnes of CO_2 emissions is a more broadly understood metric in terms of scale and relevance to climate change policy goals. The changes in air pollution emissions are also easily interpreted in the context of certain environmental directives (e.g. European National Emissions Ceiling Directive), in which their scale gives an indication of relevance to meeting national limits on emissions. However, air pollutants are more challenging to evaluate with respect to their monetised health and environmental impact values. This is due to the more complex interactions between air pollutants and their environment in terms of chemistry, dispersion, concentration in the atmosphere, and the exposure levels of sensitive environments and humans.

61. As a part of prior work supported by the Irish Environmental Protection Agency, the EnvEcon team developed a marginal damage valuation (MDV) methodology (EnvEcon, 2015 and 2016) to afford analysts the capacity to apply a monetised weighting to air pollution emission changes in Ireland with relative ease.[24] The applied methodology is summarised with an excerpt from the EnvEcon MDV Guidebook (EnvEcon, 2015) in Annex B. The Guidebook offers damage values for NO_X, SO_2, NMVOC, NH_3 and $PM_{2.5}$ as given in Table 9. For the final calculations in this study these values have been adjusted for inflation to bring them from €2010 values to €2015 values, an increase of less than 5%.

Table 9. Marginal damage values per tonne of air pollutants for Ireland

EUR_{2010} per tonne per annum

	NO_x	NH_3	SO_2	NMVOC	$PM_{2.5}$
	Including secondary PM	Including secondary PM	Including secondary PM	Including secondary PM & O_3	Primary PM only
Ireland all	1 000	825	4 825	875	7 500
Ireland rural	925	650	4 825	850	6 600
Urban, large (Dublin)	9 350	13 175	10 300	2 675	67 650
Urban, medium (Pop. >15 000)	1 550	3 300	4 750	1 550	22 825
Urban, small (Pop. 10 000 – 15 000)	1 375	1 500	5 275	1 350	14 800
Small towns (Pop. < 10 000)	1 150	1 050	4 725	1 025	9 650

Source: EnvEcon, 2015.

62. The emission differentials for the period 2008 to 2017 were presented in Table 8 (prior section) and the cumulative emissions for this ten-year period are presented in Table 10.

Table 10. Cumulative emission differences between the policy and counterfactual scenario

From 2008 to 2017.

Pollutant - Gas	10 Year Total (2008 to 2017)
NO_X	12,476 tonnes
SO_2	66 tonnes
NMVOC	-6,611 tonnes
$PM_{2.5}$	630 tonnes
NH_3	-323 tonnes
CO_2	-814,572 tonnes

63. Table 9 presents the estimated marginal cost of the additional emissions arising from the policy change over the period 2008-2017. As observed in Section 4, the proportional change in emissions is initially modest. This is unsurprising, as the new vehicles purchased following the policy introduction in 2008 remain a minor subset of the overall vehicle fleet in the country at the outset of the intervention. Furthermore, the new

[24] Similar to the environmental appraisal and evaluation guidance offered in the United Kingdom's 'Green Book' that can be accessed here: https://www.gov.uk/government/publications/the-green-book-appraisal-and-evaluation-in-central-governent.

vehicle purchases largely remain as internal combustion engine (ICE) vehicles (albeit more efficient ones), which still combust fossil fuel and generate emissions.

64. Nonetheless, the impact of the policy interventions increase over time as the policy intervention continues to influence purchase decisions, and a greater share of lower CO_2 rated vehicles (principally diesels) gradually penetrate the market over the subsequent years. NO_x and PM emissions grow steadily before slowing as the standards converge in later years, and NMVOC drops notably as fewer petrol vehicles are operating within the system.

65. In the assessments, a value of €30 per tonne has been assigned to CO_2. This value would be at the lower bound of international estimates as a shadow price for carbon.[25]

66. Air pollution impacts are heavily influenced by incidence and exposure, and as a result, where increased emissions occur in highly populated areas (e.g. a major city), the consequent change in local concentrations of air pollutants are likely to have a greater impact on human health. The MDV methodology provides conservative valuations per tonne of emissions in a variety of contexts from large urban areas to less populous rural areas in Ireland. In the case of this particular policy intervention, the changes are from a ground-level mobile emission source (i.e. private passenger cars), and consequently, the precise location where the emissions are generated is unknown, given that users drive their cars in a variety of locations and conditions. This variation in the location of the emission source introduces further uncertainty as to whether the emissions occur in a densely populated urban area, or in a more remote rural area.

67. This analysis considers the variation in tonnes of air pollutant emissions between the policy interventions scenario and the counterfactual scenario over time and assigns a conservative damage valuation to those additional emissions. A range is provided which assumes that all emissions occur either in a large urban area, Dublin (upper range), or are distributed evenly on a national scale (lower range). As an indicative mid-point assumption, 70% of emissions are deemed to occur in Dublin, and 30% are distributed evenly on the national scale. The reason for this allocation is that Dublin (and urban areas more generally) has traditionally had a far higher share of smaller petrol vehicles, and has exhibited the greatest change in shares of diesel vehicle purchases.[26] As a result, it is likely that a high share of these new diesels were operating in Dublin.

68. In summary, the policy intervention scenario benefits from reduced CO_2, NMVOC and NH_3 are outweighed in the upper and central estimate by the consequent rises in NO_X and $PM_{2.5}$ emissions. Where emissions of air pollutants are evenly distributed across the country (in less populous areas), there is an estimated net environmental and human health benefit of approximately €12.5m over the 10-year period under the lower estimate. Under the upper-range valuation, where all additional air pollution occurs in Dublin, there is a net environmental and human health cost of just under €119m over the 10 years. The central estimate indicates net costs of €79.5m for the 10-year period.

[25] https://www.carbonpricingleadership.org/report-of-the-highlevel-commission-on-carbon-prices/.

[26] In 2007, over 75% of new vehicles purchased in Dublin were petrol, by 2012 over 70% of new vehicles purchased in Dublin were diesels. As such it would seem that a large share of the new vehicles shifting towards diesel were purchased in Dublin – See statistics at https://www.simi.ie/en.

Table 11. Impact valuations of emissions changes

In EUR2015

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Upper limit										
NO_x	1 069 800	3 550 900	6 542 000	9 190 800	11 842 600	14 520 900	17 739 500	18 266 100	19 105 200	19 438 700
SO_2	6 400	21 200	35 300	47 800	60 400	73 000	88 300	104 200	124 600	145 100
NMVOC	-157 500	-522 800	-911 200	-1 255 100	-1 598 500	-1 945 200	-2 362 300	-2 730 500	-3 208 800	-3 687 400
$PM_{2.5}$	858 600	2 849 800	3 346 100	3 779 700	4 204 900	4 627 800	5 157 800	5 721 300	6 483 700	7 238 000
NH_3	-71 500	-237 200	-306 500	-367 400	-428 400	-489 500	-564 600	-602 100	-654 600	-707 400
CO_2	-202 300	-671 400	-1 196 800	-1 654 600	-2 104 300	-2 550 400	-3 075 900	-3 655 800	-4 344 600	-4 981 000
Lower limit										
NO_x	114 400	379 700	699 600	982 900	1 266 500	1 552 900	1 897 100	1 953 500	2 043 200	2 078 900
SO_2	3 000	9 900	16 500	22 400	28 300	34 200	41 300	48 800	58 400	67 900
NMVOC	-51 500	-171 000	-298 100	-410 600	-523 000	-636 400	-772 900	-893 400	-1 049 900	-1 206 400
$PM_{2.5}$	95 200	316 100	371 200	419 200	466 400	513 300	572 100	634 600	719 200	802 800
NH_3	-4 500	-14 900	-19 200	-23 100	-26 900	-30 700	-35 500	-37 800	-41 100	-44 400
CO_2	-202 300	-671 400	-1 196 800	-1 654 600	-2 104 300	-2 550 400	-3 075 900	-3 655 800	-4 344 600	-4 981 000
Central estimate										
NO_x	783 200	2 599 600	4 789 300	6 728 500	8 669 700	10 630 500	12 986 800	13 372 300	13 986 600	14 230 700
SO_2	5 400	17 800	29 700	40 200	50 700	61 400	74 200	87 600	104 800	121 900
NMVOC	-125 700	-417 300	-727 300	-1 001 700	-1 275 900	-1 552 500	-1 885 500	-2 179 400	-2 561 100	-2 943 100
$PM_{2.5}$	629 600	2 089 700	2 453 600	2 771 500	3 083 300	3 393 400	3 782 100	4 195 300	4 754 400	5 307 400
NH_3	-51 400	-170 500	-220 300	-264 100	-307 900	-351 900	-405 800	-432 800	-470 500	-508 500
CO_2	-202 300	-671 400	-1 196 800	-1 654 600	-2 104 300	-2 550 400	-3 075 900	-3 655 800	-4 344 600	-4 981 000

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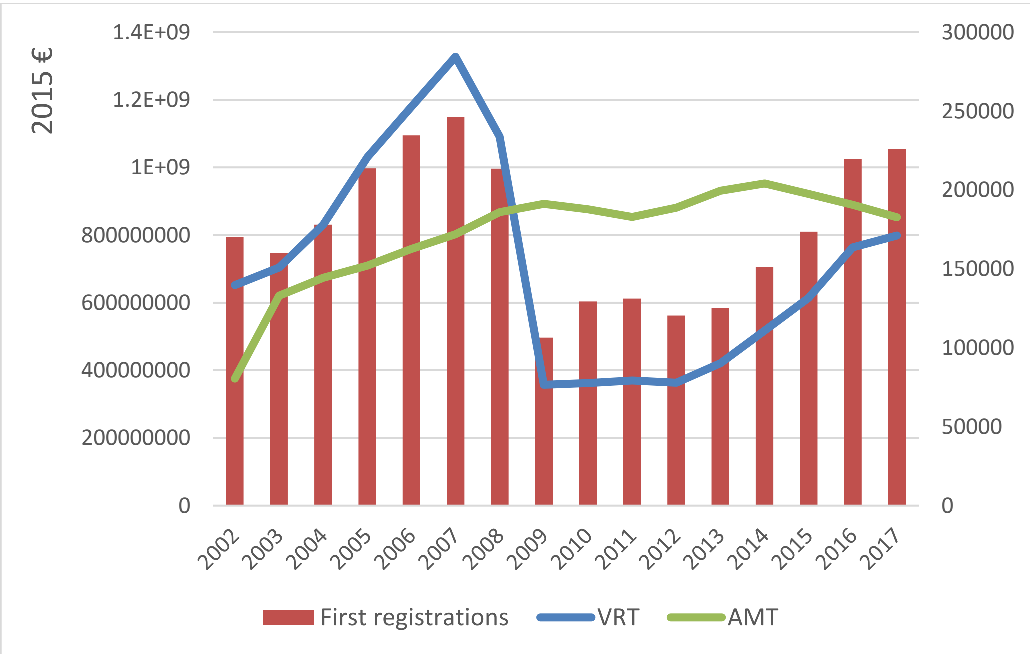
6. Assessing the impact of the measures on net public revenue

69. Changes in taxes and tax provisions typically lead to changes in net public revenue. In the case of the Irish vehicle tax reform, this analysis accounts for a change in revenue from vehicle taxes as the result of two effects: (i) the change in consumer preferences due to the tax modification; and (ii) the change in calculation basis from engine size to CO_2 emissions. The tax was designed to be revenue neutral and therefore the second effect should not be important, though this report investigates it nonetheless.

70. Revenue from passenger cars under the VRT and AMT steadily increased up to 2008, mainly due to an increase in total vehicle registrations and the share of larger vehicles in the affluent period before 2008. In 2008, the economy crashed and with it vehicle tax receipts – in particular vehicle registration taxes – as vehicle sales plummeted (Section 3). As AMT is levied on the entire vehicle stock, the drop in new registrations and any tax change introduced have a marginal effect on AMT receipts. The recessionary effect dampens the change in vehicle tax receipts which can be attributed to the vehicle tax reform alone.

Figure 8: Vehicle registration taxes and registrations for passenger cars 2000-2017



71. This analysis estimates VRT and AMT based on engine size for the current profile of vehicles using annual first registration data broken down into emissions bands and engine size.

72. For the VRT analysis, the average open market selling price (OMSP) for registrations is grouped in three engine size bands (<1.4L, 1.4-1.9L, and >1.9L), enabling the calculation of the VRT based on engine capacity for new registrations from 2008. This can then be compared with the tax receipts over the six months in the year of the reform (2008) and over the whole period to date. The new tax regime favoured low CO_2-emitting vehicles regardless of engine size. This encouraged a shift to diesel passenger cars, which generally have larger engine size but lower CO_2 emissions and fuel consumption for equivalent horsepower. Table 12 shows the estimated VRT revenue based on engine size compared with the revenue actually collected under CO_2 emissions the period from Q3 2008 to Q2 2018. One can see that if the VRT were estimated using engine size based on the current profile of new registrations, diesel VRT revenue would be nearly doubled and petrol receipts would be increased by more than 60% in the period since the shift in 2008. The total revenue gap would be €5.25 billion.

Table 12. Actual and estimated passenger car VRT receipts

Period	VRT (million €)	
	Revenue collected	Estimated revenue
Diesel Q3- Q4 2008	160.64	276.14
Diesel Q3 2008 - Q2 2018	4533.71	8460.79
Petrol Q3- Q4 2008	66.09	114.73
Petrol Q3 2008 - Q2 2018	1107.37	1768.06
Total revenue gap Q3 2008 – Q2 2018	**5248.46**	

73. The same methodology is also used to examine the impact of the tax reform on AMT revenue. The AMT is levied on the whole stock but in this case only the marginal effects are assessed, namely the impact of the change in tax structure on the newly registered passenger cars joining the stock on an annual basis. The effect is cumulative, as the vehicles remain in the stock and their owners are liable for the AMT throughout the lifetime of the vehicle. One can see in Table 13 that the tax revenue from AMT would have been higher based on engine capacity. There are some discrepancies in the estimated values and the actual receipts for AMT over the period that are partly due to additional charges from more frequent payments or arrears but the trends are similar to the VRT analysis. In all cases, the AMT based on engine size (row 4) would have raised more revenue than the CO_2-based taxes. In 2016, the Comptroller and Auditor General noted that the change in vehicle tax system has led to “significantly lower average tax paid in respect of newer private cars taxed on the basis of engine emissions, compared to those taxed on the basis of engine size” leading to an estimated loss of “around €29 million” annually until 2024 in motor tax receipts (C&AG, 2016).

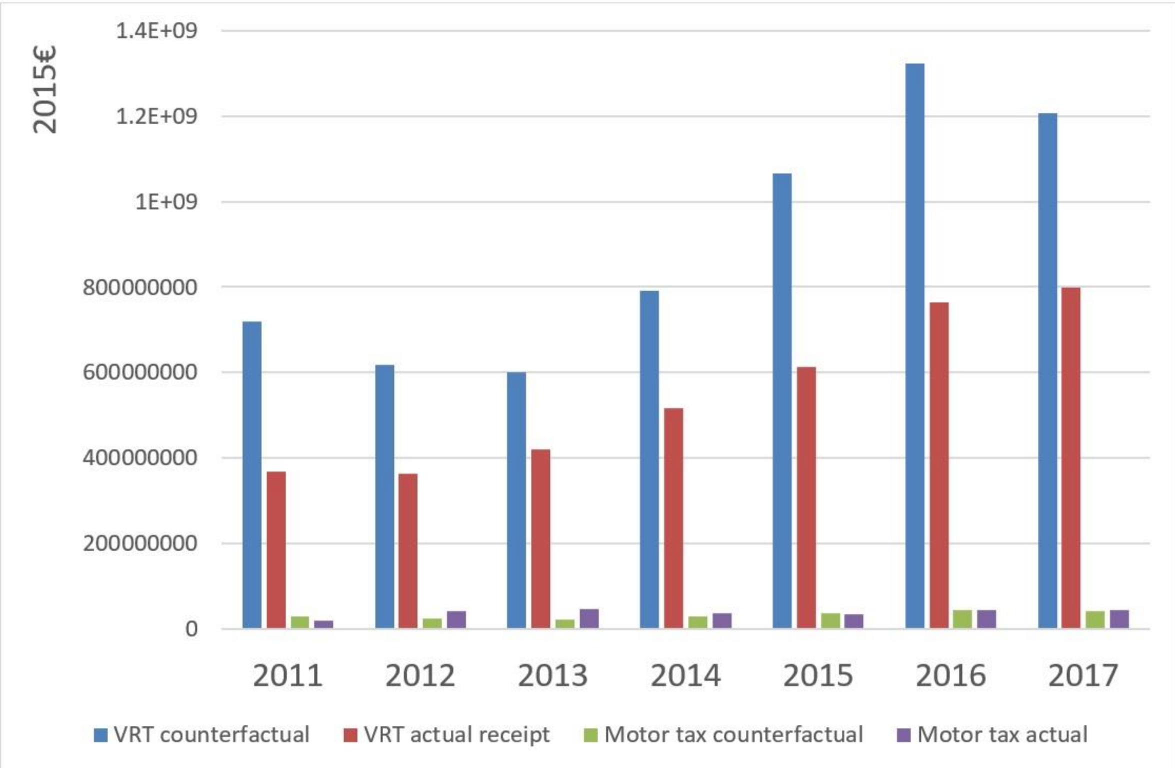
Table 13. Estimated AMT revenues with CO_2 and engine cc and compared to actual receipts

EUR2015 million

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Estimated cc-based AMT revenue	102.27	52.85	60.22	61.68	55.27	57.42	68.15	77.14	97.63	101.36
Estimated CO_2-based AMT revenue	88.46	31.98	30.95	27.1	29.92	34.83	38.94	42.2	50.83	52.35
Receipts new registrations	79.44	27.15	21.12	20.11	44.24	47.26	37.2	36.2	44.24	47.26
Difference	-22.83	-25.7	-39.1	-41.57	-11.03	-10.16	-30.94	-40.94	-53.39	-54.1

74. The assumption in the calculations for Table 12 and Table 13 is that the profile of passenger car model registrations has not changed with the change in tax structure. This assumption is not likely to hold and it can be expected that without the change in vehicle tax structure, the fleet profile would have been different. Therefore the VRT and AMT revenues are now estimated for the counterfactual scenario with the SIBYL model outlined in Section 4 for three categories of engine size >1.4L, 1.4-2.0L and >2.0 L in the years 2008-2017. Aside from 2008, when the year was split between engine and CO2-based taxes, in all other years both AMT and VRT would have been higher in the counterfactual scenario. In particular, one can see that the VRT revenue would have been significantly higher under the old system. Summed up over 2009-2017, there is a revenue loss for AMT and VRT of €2 billion compared with the counterfactual scenario.

Figure 9. Comparison of estimated counterfactual and actual AMT and VRT receipts



75. Fuel excise duty receipts from private cars have not dropped since the tax reform, ranging between €1.6-1.8 billion since 2008. Fuel excise duty rates have always been lower

by 11-15% for diesel fuel compared with petrol fuel, cf. Table 14. Fuel excise duty rates were increased for both fuels in 2012 and the recovery of the economy since 2014 has led to a steady revenue from fuel excise and VAT over the 10 year period.

Table 14. Fuel excise duty and VAT rates and receipts

2008-2017, constant 2015 money value

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Petrol rate (€/L)	0.71	0.74	0.80	0.86	0.90	0.88	0.86	0.83	0.83	0.85
Diesel rate (€/L)	0.57	0.62	0.69	0.74	0.78	0.76	0.74	0.70	0.71	0.72
Petrol receipts (million €)	1 241	1 203	1 198	1 208	1 181	1 102	1 031	917	812	731
Diesel receipts (million €)	332	387	481	590	694	744	804	817	878	919

Source: EPSSU, SEAI.

76. The revenue from excise duty and value added tax (VAT) is estimated from the SIBYL output for petrol and diesel vehicle stock and mileage by engine size under the counterfactual scenario; this is multiplied the actual fuel consumption by engine size each year and the excise duty and VAT rates. The revenue was then compared with estimated excise duty receipts from the policy scenario and the results are presented in Table 15.[27]

Table 15. Difference between estimated policy measure and counterfactual excise duty receipts

2008-2017, constant 2015 money value.

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2009-2017
Petrol	-261.2	-303	-307.6	-306.1	-306.7	-275.2	-262.1	-238.9	-229.1	-225.1	-2453.78
Diesel	101.1	121.95	155.8	187.6	223.6	243.8	263.9	274.8	316.7	380.9	2169
Net change	-160.1	-181.1	-151.7	-118.5	-83.1	-31.4	1.8	35.9	87.6	155.9	-284.8

Note: negative values imply excise duty and VAT receipts are lower with the policy measure than might have been expected in the counterfactual scenario without the policy changes.

77. It is clear that receipts from petrol sales have been reduced, while diesel fuel receipts have increased, as can be expected with the shift to diesel vehicles since the tax reform. The net impact was initially negative but the diesel sales have proportionately increased leading to net increase in fuel excise duty and VAT revenue since 2015. For the period 2009-2017, there is a net revenue loss of approximately €280 million.

78. There has been no increase or change in administration or compliance costs recorded with the change in the vehicle tax basis (Comptroller and Auditor General, 2016). The administration system remains unchanged and, if anything, costs have reduced over time, as more customers choose to pay their vehicle taxes online.

[27] The estimated policy scenario receipts are used for comparison rather than the actual receipts, as there are other factors driving real-world fuel sales, primary of these is the exchange rate between the UK sterling and the Euro. A significant amount of fuel tourism occurs between Northern and the Republic of Ireland, which distorts the fuel receipts

7. Assessing the marginal cost of public funds

79. The application of a tax provision that reduces net public revenues causes a social cost per unit of revenue foregone equal to the marginal cost of public funds of the instrument actually used to raise the necessary additional revenue in the country concerned. As a rough estimate, it has been assumed that the marginal cost of funds in general is in the order of 1.3, in accordance with the Irish Public Expenditure code, Barrios et al. (2013), and Dahlby and Ferede (2011). Based on the estimated loss of revenue from AMT and VRT of €2 billion and a loss of €284 million in fuel excise duty over 2009-2017, this would give a true social marginal cost of public funds of approximately €3 billion, mainly due to the estimated loss of VRT revenue over the period.

8. Assessing distributive impacts

80. It is important to understand the distribution of costs and benefits of tax reforms. Before considering the potential social costs of the fiscal transfer needed to fund the deficit created by the tax reform, it is useful to consider who, if anyone, benefitted from the vehicle tax reform in Ireland. It has not been possible to estimate the distributive effects of the vehicle tax reform in Ireland, therefore this discussion is mainly qualitative.

81. Comparing the average VRT paid per vehicle under the CO_2 vehicle tax shift in 2009, €3513, with the average engine size VRT paid, €5793 in 2007, it is clear that the average VRT paid per new registration has decreased significantly.[28] There has been less difference in average AMT paid between the periods before and after the tax change -€179 - €207 in 2006-2007 vs €174 - €261 in 2009-2010 per new registration, but this is extremely variable year-on-year.[29] This means that car owners overall have benefited from the reform by paying less vehicle taxes. The welfare of non-car owners on the other hand has reduced, as there has been less revenue collected and therefore less public funds available for public goods, such as education, health, etc. The distributional implications can change depending on how the fiscal deficit is funded in practice.[30]

82. It is also interesting to understand which car owners have benefitted most. The tax shift benefitted those buying new cars and importing used cars first registered after July 2008. Since lower-income households are less likely to buy new cars in the first place, it

[28] All monetary values adjusted to 2015 money.

[29] This result merits further investigation as it indicates that there is an average AMT amount that people are used to paying and perhaps their car purchasing decisions converge around this amount.

[30] Durrmeyer analyses two concrete scenarios that seek to shed some light on how net consumer surplus (after a tax to fund the revenue gap is levied on consumers) is affected by the feebate in France. In the first scenario the direct fiscal cost of the feebate is funded by a lump sum tax on consumers. The other scenario considers a proportional income tax.

can be assumed that middle- and upper-class households were the beneficiaries of the tax reform in the initial years. Over the years, as these cars have trickled into the second-hand market, lower-income groups have also benefited from the lower AMT associated with these cars.

83. High-income earners are more likely to purchase high-value cars with large engine sizes and correspondingly higher CO_2 emissions that benefitted least from the tax shift (Kurz and Li, 2015). The highest tax rate on the new CO_2 emissions AMT scale in 2008 (€2,000) was meant to penalise high emitting vehicles, in many cases SUVs. The tax rate was higher than previously paid for private cars with engines above 2400cc under the engine size AMT (€899-1499). In 2009, only 1% of new registrations fell into this category, as compared with 6% in the top AMT rate under the engine size-based tax. Similarly, the VRT rates were increased at the top end of the scale under CO_2 taxes but fewer vehicles were liable in this category. However, VRT was reduced from 22.5% to 14% at the lower end of the scale, meaning that smaller, low-emitting vehicles paid significantly less than under the engine size VRT. However, the diesel effect created some ambiguity. As discussed in Section 3, the tax shift encouraged people to move to larger sized diesel vehicles with lower CO_2 emissions ratings inter alia.[31] Therefore, people who previously would have purchased cars with relatively small engines, moved to larger diesel engines and therefore increased their utility through better comfort and lower costs.[32] Nonetheless, in general, small car purchasers benefitted under the CO_2 taxes more than larger car purchasers.

84. In fact, on average, the greatest reduction in AMT paid has taken place for vehicles with engine sizes in the range of 1.6-2L. This is due to the shift to the purchase of diesel vehicles, often with engine size 1.9L but with relatively lower CO_2 emissions. The econometric analysis in Section 3 shows that the tax regime change in 2008 led to an increase in diesel share of 18% in the first year. Even owners of vehicles with the smallest engine sizes will have reduced their taxes, as the lowest point on the CO_2-based VRT and motor tax scales are lower than the previous engine size tax rates.

9. Consumer surplus

85. Under the tax reform, car purchasers have paid lower taxes than they would have paid had the old system remained in place. While there is a social cost associated with this loss of revenue, there is also a private benefit to the reform. Consumers now pay lower taxes of approximately €2.3 billion, which can be assumed to be a consumer surplus.

[31] There is not a direct correlation between CO_2 emissions and engine sizes due to the diesel fact where diesel engines are likely to be larger with lower CO_2 emissions compared with their equivalent powered petrol car.

[32] Although diesel vehicles are on average more expensive, people also imported used diesel vehicles from the UK where the favourable exchange rate and used market led to significant reductions in prices compared to Irish new car prices.

86. There are possibly other effects that impact the consumer surplus that are difficult to quantify. On the negative, the new policy potentially distorts consumer choices as the new tax schedule could induce consumers normally favouring polluting vehicles to instead buy cleaner ones and e.g. suffer from lower technical performance than they would prefer. In addition, consumers could be affected by supplier price changes, as car suppliers adjust their price offering to match the tax reform. On the positive, there is some evidence to show that consumers may undervalue future fuel costs (Teusch and Braathen, 2018). Empirical analysis on US data suggests that consumers may in fact only value approximately 75% of the (discounted) cost of gasoline when they buy vehicles (Allcott and Wozny, 2014). This tax reform could have incentivised consumers to buy vehicles that are in their long-term private interest. These effects have not been estimated numerically and are therefore not included in the cost benefit analysis.

10. Producer surplus

87. Ireland has no indigenous car manufacturing industry and therefore is relatively open competition between brands on the market. No brand has a market share greater than 11%. The analysis therefore assumes that there is perfect competition and that producer surplus is not affected by the tax reform.

11. Full cost-benefit analysis

88. The estimated costs and benefits of the tax reform are presented in Table 16. The ex-post impacts of the tax reform due to the change in vehicle tax revenue and the economic value of emissions are estimated over the period 2009-2017. The loss of VRT revenue outweighs all other impacts at €1.8 billion, however most of this is a transfer to those consumers who now benefit from lower vehicle taxes. The value of reduced CO2 emissions is only €18 million, and is offset by the external costs due to increased NOx emissions at €85 million. The net value of the social costs and benefits of the tax reform is estimated at €770 million over the period 2009-2017.

Table 16. Estimated value of economic impacts of vehicle tax reform

2009-2017, constant 2015 money value.

	2009	2010	2011	2012	2013	2014	2015	2016	2017	Total
Revenue										
AMT	-9	-22	-28	0	1	-17	-26	-33	-33	-166
VRT	-110	-166	-182	-156	-159	-199	-223	-326	-315	-1,837
Fuel excise duty and VAT	-181	-152	-118	-83	-31	2	36	88	156	-285
Public funds										-€2,970
Consumer surplus										€2,290
Emissions										
NO_x	-2.5	-4.6	-6.5	-8.3	-10.2	-12.5	-12.9	-13.5	-13.7	-85.4
SO_2	0	0	0	0	-0.1	-0.1	-0.1	-0.1	-0.1	-0.6
NMVOC	0.4	0.7	1	1.2	1.5	1.8	2.1	2.5	2.8	14.1
$PM_{2.5}$	-2	-2.4	-2.7	-3	-3.3	-3.6	-4	-4.6	-5.1	-31.2
NH_3	0.2	0.2	0.3	0.3	0.3	0.4	0.4	0.5	0.5	3.1
CO_2	0.4	0.8	1.1	1.4	1.7	2.1	2.4	2.9	3.3	16.3
Total net impact										-€770

Notes: negative values represent costs and positive values are benefits

12. Conclusions

89. The Irish vehicle tax reform was successful in encouraging consumers to switch to lower-emitting cars from a CO_2 emissions perspective. The average national CO_2 emissions rating dropped from 152gCO_2/km in 2009 to 112gCO_2/km in 2017 for new passenger cars. This study uses a difference-in-difference econometric model to establish in more detail the causality of the drop in emission ratings and finds that the vehicle tax reform caused a drop of approximately 10gCO_2 /km in its first year, with further decreases caused by subsequent policy changes in later years. This reduction in emissions was primarily caused by a shift to diesel vehicles. Further modelling with the SIBYL model generated counterfactual and policy scenarios to estimate the impact on other emissions and the related health implications. The fleet simulation was also used to calculate the tax revenue change due to the tax reform and finds a significant loss over the last ten years, amounting to over €2.3 billion.

90. Summing the overall costs and benefits gives a net cumulative social cost of the policy of approximately €770 million over the period 2009-2017. The findings of a modest impact on CO_2 emissions and interim increases in NO_X and PM are consistent with earlier related modelling work (Fu and Kelly, 2012; Hennessy and Tol, 2011). This longer *ex post* analysis highlights the importance of broader *ex ante* assessments (*e.g.* considering air and health impacts) and simultaneously the dangers of focusing on a narrow issue (e.g. CO_2 emissions) in the policy instrument design.

91. The real-world variation in air pollutant emission factors for petrol and diesel vehicles remained pronounced in the early parts of these policy interventions. However, the impact of Dieselgate in 2015, and subsequent actions to regulate the euro 6 standard on the basis of real driving emissions (RDE) as part of euro 6 temp, should mean that from this point forward the gap between diesel and petrol vehicles in terms of air pollutant emissions will be small. As such, future policy interventions should arguably focus on the greater marginal gains that can be achieved by trip reduction and shifts from internal combustion engine vehicles of all kinds to an electrified alternative.

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References

Alberini, A. and A. Bigano (2015) "How effective are energy-efficiency incentive programs? Evidence from Italian homeowners", *Energy Economics*, Vol. 52, pp. S76-S85, http://dx.doi.org/10.1016/j.eneco.2015.08.021

Allcott, H. and N. Wozny (2014), "Gasoline Prices, Fuel Economy, and the Energy Paradox", *Review of Economics and Statistics*, Vol. 96/5, pp. 779-795, http://dx.doi.org/10.1162/REST_a_00419

Amann and Wagner (2014) A flexibility Mechanism for Complying with National Emission Ceilings for Air Pollutants, TSAP Report 15, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

Angrist, J. D., & Pischke, J.-S. (2008) Mostly Harmless Econometrics: An Empiricist's Companion. Princeton University Press.

Arlinghaus, J. (2015) "Impacts of Carbon Prices on Indicators of Competitiveness: A Review of Empirical Findings", *OECD Environment Working Papers*, No. 87, OECD Publishing, Paris, http://dx.doi.org/10.1787/5js37p21grzq-en.

Barrios, S., J. Pycroft and B. Saveyn (2013) "The marginal cost of public funds in the EU: the case of labour versus green taxes", *Taxation Papers*, No. 35 - 2013, European Commission, Brussels, http://dx.doi.org/10.2778/15847.

Chen, C., W. Hu and C. Knittel (2017) "Subsidizing Fuel Efficient Cars: Evidence from China's Automobile Industry", NBER Working Paper Series, No. 23045, National Bureau of Economic Research, Cambridge, MA, http://www.nber.org/papers/w23045.

Cohen, A. et al. (2017) "Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015", The Lancet, Vol. 389, pp. 1907-1918, http://dx.doi.org/10.1016/S0140-6736(17)30505-6.

Comptroller and Auditor General (2016) Administration and Collection of Motor Tax, Comptroller and Auditor General Special Report, Report number 97, December 2016

Dahlby, B. and E. Ferede (2011) "What Does it Cost Society to Raise a Dollar of Tax Revenue? The Marginal Cost of Public Funds", C.D. Howe Institute Commentary, No. 324, C.D. Howe Institute, Toronto, https://www.cdhowe.org/sites/default/files/attachments/research_papers/mixed//Commentary_324.pdf.

Department of Finance (2012) Taxation Annexes to the Summary of 2012 Budget and Estimates Measures. Available at <http://www.budget.gov.ie/Budgets/2012/Documents/Taxation%20Annexes%20to%20the%20Summary%20of%202012%20Budget%20and%20Estimates%20Measures.pdf>

Department of Finance (2013) Budget Annex C: Revision to VRT and Motor Tax Rates and Related Issues. Available at <http://www.budget.gov.ie/Budgets/2013/Documents/Annex%20C%20-%20VRT%20and%20Motor%20Tax.pdf >

Department of Transport, Tourism, and Sport (DTTAS). Motor Tax Factsheet: New CO2 RATES. Available at <https://www.motortax.ie/OMT/pdf/co2_emissions_rates_en.pdf>

D'Haultfœuille, X., P. Givord and X. Boutin (2014) "The Environmental Effect of Green Taxation: The Case of the French Bonus/Malus," Economic Journal, Royal Economic Society, vol. 124(578), pages 444-480.

Dimitropoulos, A., W. Oueslati, C. Sintel (2018) 'The rebound effect in road transport: A meta-analysis of empirical studies', Energy Economics, 75, p. 163-179. https://doi.org/10.1016/j.eneco.2018.07.021

Dineen, D., L. Ryan & B. Ó Gallachóir (2017) "Vehicle tax policies and new passenger car CO2 performance in EU member states", Climate Policy, DOI: 10.1080/14693062.2017.1294044

Dubourg, R. (Forthcoming), *Economic assessments of the benefits of regulating mercury*, OECD Publishing.

Duffy, P., Black, K., Hyde, B., Ryan, A.M, Ponzi, J. and Alam, S. (2018). Ireland National Inventory Report 2018. Greenhouse Gas Emissions 1990-2016. Reported to the United Nations Framework Convention on Climate Change. Environmental Protection Agency, Johnstown Castle, Wexford, Ireland.

EnvEcon (2015), Marginal Damage Valuations for Air Pollutants in Ireland - 2015, Dublin: EnvEcon Decision Support Series 2015/1

EnvEcon (2016), Marginal Damage Valuation for Air Pollutants – Methodological Report - 2016, Dublin: EnvEcon Decision Support Series 2016/1

Fu, M. and Kelly, J.A (2012) Carbon related taxation policies for road transport: Efficacy of ownership and usage taxes, and the role of public transport and motorist cost perception on policy outcomes, Transport Policy, (22), 57-69.

Gerlagh, R., I. van den Bijgaart, H. Nijland, & T. Michielsen (2016) "Fiscal policy and CO2 emissions of new passenger cars in the EU", CPB discussion paper 302: CPB Netherlands bureau for economic policy analysis. Environmental and Resource Economics, 1–32. doi:10.1007/s10640-016-0067-6

Hennessey, H. and R.S.J. Tol,, 2011. The impact of tax reform on new car purchases in Ireland. Energy Policy, 39(11):7059-7067.

Hunt, A. et al. (2016), "Social Costs of Morbidity Impacts of Air Pollution", *OECD Environment Working Papers*, No. 99, OECD Publishing, Paris, http://dx.doi.org/10.1787/5jm55j7cq0lv-en.

Kelly, J. A., Ryan, L., Casey, E. and O'Riordan, N. (2009) "Profiling road transport activity: Emissions from 2000 to 2005 in Ireland using national car test data, Transport Policy (16), 183-192.

Kurz, C. and G. Li (2017) Who Drives Luxury Cars (Only for a While)? Finance and Economics Discussion Series Notes, the Federal Reserve, June 1st 2015. https://www.federalreserve.gov/econresdata/notes/feds-notes/2015/who-drives-luxury-cars-20150601.html

Navrud, S. (2017), “Possibilities and challenges in transfer and generalisation of monetary estimates for environmental and health benefits of regulating chemicals”, *OECD Environment Working Papers*, No. 119, OECD Publishing, Paris, http://dx.doi.org/10.1787/95c2b371-en.

NEEDS Project (2006) - http://www.needs-project.org/

O’Gallachoir, B., Howley, M., Cunningham, S., Bazilian, M., 2009. How private car purchasing trends offset efficiency gains and the successful energy policy response. Energy Policy, 37 (10):3790-3802.

O’Halloran, M., 2007. Gormley reforms car tax based on emissions: Dáil Report. Irish Times, 7 December 2007.

OECD (2012), Mortality Risk Valuation in Environment, Health and Transport Policies, OECD Publishing, Paris, http://dx.doi.org/10.1787/9789264130807-en.

OECD (2014), The Cost of Air Pollution: Health Impacts of Road Transport, OECD Publishing, Paris, http://dx.doi.org/10.1787/9789264210448-en.

OECD (2018), *Cost-Benefit Analysis and the Environment: Further Developments and Policy Use*, OECD Publishing, Paris. http://dx.doi.org/10.1787/9789264085169-en

Office of the Revenue Commissioners, 2017. Vehicle Registration Tax Section 2: Reliefs and Exemptions. Available at <https://www.revenue.ie/en/tax-professionals/tdm/vehicle-registration-tax/vrt-manual-section-02.pdf>

Rivers, N. and B. Plumptre (2016), “The effectiveness of public transit subsidies on ridership and the environment: Evidence from Canada”, University of Ottawa, http://dx.doi.org/Rivers, Nicholas and Plumptre, Bora, The Effectiveness of Public Transit Subsidies on Ridership and the Environment: Evidence from Canada (January 29, 2016). Available at SSRN: https://ssrn.com/abstract=2724768 or http://dx.doi.org/10.2139/ssrn.2724768.

Roy, R. and N. Braathen (2017), “The Rising Cost of Ambient Air Pollution thus far in the 21st Century: Results from the BRIICS and the OECD Countries”, *OECD Environment Working Papers*, No. 124, OECD Publishing, Paris, http://dx.doi.org/10.1787/d1b2b844-en.

Ryan, L., S. Ferreira, S., and F. Convery, (2009) “The impact of fiscal and other measures on new passenger car sales and CO2 emissions intensity: Evidence from Europe”, *Energy Economics*, 31(3), 365–374. doi:10.1016/j.eneco.2008.11.011

Smith, S. and N. Braathen (2015), “Monetary Carbon Values in Policy Appraisal: An Overview of Current Practice and Key Issues”, *OECD Environment Working Papers*, No. 92, OECD Publishing, Paris, http://dx.doi.org/10.1787/5jrs8st3ngvh-en.

Stapleton, L., S. Sorrell, and T. Schwanen (2016) “Estimating direct rebound effects for personal automotive travel in Great Britain”, Energy Economics, 54, p.313-325. https://doi.org/10.1016/j.eneco.2015.12.012

Teusch, J. and N. Braathen (2018) “Ex-post appraisal of environmentally related tax policies: Building on programme evaluation studies”, COM/ENV/EPOC/CTPA/CFA(2018)2.

Wing, C., Simon, K. I., & Bello-Gomez, R. A. (2018). Designing Difference in Difference Studies: Best Practices for Public Health Policy Research. Annual Review of Public Health, 39, 453–469. https://doi.org/10.1146/annurev-publhealth-040617-013507

World Health Organisation (2014) WHO Expert Meeting: Methods and tools for assessing the health risks of air pollution at local, national and international level, Meeting report, World Health Organisation Regional Office, Denmark.

Annex A Additional explanation of policy measures in Section 2

Table A1. Interim policy adjustments

Emissions rating bands with Annual Motor Tax (AMT) and % change, effective 1 January 2009 and 1 January 2012

Rating	CO_2 g/km		2009		2012	
	Lower Limit (>)	Upper Limit (<=)	Annual Motor Tax (AMT)	% Change from 2008	Annual Motor Tax (AMT)	% Change from 2009
A	0	120	€104	4%	€160	54%
B	120	140	€156	4%	€225	44%
C	140	155	€290	4%	€330	9%
D	155	170	€430	4%	€481	8%
E	170	190	€600	5%	€677	7%
F	190	225	€1 000	5%	€1 129	8%
G	225	225+	€2 000	5%	€2 258	8%

Source: DTTAS and Department of Finance (2012).

Table A2. Final policy change (Current policy)

Updated emissions bands with Annual Motor Tax (AMT), Vehicle Registration Tax (VRT) rate, and % change from 2008, effective 1 January 2013

Rating	CO_2 g/km		Annual Motor Tax (AMT)	AMT % Change from 2008	VRT as % of selling price	VRT % Change from 2008
	Lower Limit (>)	Upper Limit (<=)				
A0	0	0	€120	20%	14%*	0%
A1	1	80	€170	70%	14%	0%
A2	80	100	€180	80%	15%	7%
A3	100	110	€190	90%	16%	14%
A4	110	120	€200	100%	17%	21%
B1	120	130	€270	80%	18%	13%
B2	130	140	€280	87%	19%	19%
C	140	155	€390	34%	23%	15%
D	155	170	€570	33%	27%	14%
E	170	190	€750	25%	30%	7%
F	190	225	€ 1200	20%	34%	6%
G	225	225+	€2 350	18%	36%	0%

Note: *14% is the nominal rate of VRT for cars with emissions of 0-80 CO_2 g/km, however, with tax relief up to €5 000, the effective VRT rate for most zero-emission vehicles (i.e. electric cars) is 0%.
Source: Department of Finance (2013).

Annex B Marginal Damage Valuation Methodology

95. As a part of prior work supported by the Irish Environmental Protection Agency, the EnvEcon team developed a marginal damage valuation (MDV) methodology (EnvEcon, 2015 and 2016) to afford analysts the capacity to apply a monetised weighting to air pollution emission changes in Ireland with relative ease.33 The EnvEcon team developed the guidebook as many policy intervention or investment appraisals opted to exclude any weighting for air pollution impacts on the grounds that the technical requirements and costs for such detailed case specific studies (e.g. spatial emission estimation, dispersion modelling, concentration modelling, exposure and human health impact assessments) were a substantial barrier to non-specialist analysts within the various line ministries of Government. The MDV methodology and guidebook allow us to generate a conservative estimate of the marginal damage in terms of health and environmental impacts that would be associated with a tonne change in the emissions of a given pollutant in a given type of area (e.g. major city or rural) in Ireland. Broadly, it is estimated that more than 90% of the impact valuation is related to human health impacts. Box 1 outlines the approaches taken in the guidebook.

Box 1. Summary methods associated with the MDV guidebook development

Excerpt from EnvEcon 2015.

Method: Spatial Distribution of Emissions

Pollution sources were initially divided into either point sources (e.g. power stations) or area sources (e.g. residential). Emissions from the point sources were spatially allocated using an improved inverse distance model that considered Irish meteorological data and other parameters. Emissions from the area sources were allocated evenly along the relevant areas for that source, such as along a road network line. Prior work by the EPA regarding spatial distribution of air pollutant emissions was also considered. Residential sector emissions were allocated utilising census data and other work. These area and point sources of pollution were then summed to generate an aggregate spatially allocated level of emissions. This work utilised and is consistent with the 2014 version of the 2010 EPA emission inventory.

Method: From Emissions to Concentrations

To move from spatially allocated levels of emissions to concentrations of pollution, EnvEcon conducted extensive 'spatial' regression work to reconcile refined estimates of nationally distributed emissions with empirical estimates of pollutant concentrations from the national air quality monitoring network. This approach takes estimates of where

[33] Similar to the environmental appraisal and evaluation guidance offered in the United Kingdom's 'Green Book' that can be accessed here: https://www.gov.uk/government/publications/the-green-book-appraisal-and-evaluation-in-central-governent.

pollution is occurring, and then marries this with observed data which implicitly captures key factors such as weather patterns, dispersion, background concentrations and natural sources. The relationships estimated for the spatial emissions and the monitored readings over time were then used to estimate concentrations in areas where comparable monitoring stations are not available. This empirical approach is believed to offer a robust and novel method to estimate concentrations, but is constrained by the quantity and quality of monitoring.

Method: Receptors and Relevant Parameters

There are two principal categories of receptors utilised in this work. These are people, for estimating human health impacts, and natural areas for ecosystem and environmental impacts. The population distribution used is drawn from the 2011 Census records. These data are paired with average income estimations derived from analysis of the Pobal HP Deprivation Index (www.pobal.ie). Mortality, Morbidity and hospital expenditure data are sourced from the Central Statistics Office (CSO), various national health statistics and reports, and the mortality indicator database of the World Health Organisation (WHO). Spatial land cover data, including arable lands (crops), pastures, natural areas (e.g. coniferous forests, deciduous forests, mixed forests, natural grasslands, and peat bogs) are derived from the URBIS database at University College Dublin (UCD). These data have also been supplemented or checked against records from other sources (e.g. Department of Agriculture, Forestry and the Marine). Market resource prices were used to support damage valuation estimation.

Method: Estimating Health and Environmental Impacts

For direct health damage caused by primary $PM_{2.5}$, ozone and NOX, the methods and parameters draw upon the Institute of Occupational Medicine model of life-tables adjusted by EnvEcon with Irish parameters and Irish input. Further information for the theoretical base and relevant parameters have been drawn from the major WHO EU work in 2013 and Holland (2014). The research has also considered the latest methods and tools for assessing health risks of air pollution and estimating Values of Statistical Life (VSL) (WHO EU, 2014). As for health damage caused by the precursors of secondary particulate matter, NO_x, NH_3, SO_2 and VOC, a primary “PM-equivalent” exchange rate and corresponding approaches from Amann and Wagner (2014) are used. The environmental damage from these air pollutants were derived from the international literature and some of the major EU research project outputs in this area such as “Assessment of Biodiversity Losses” (NEEDS, 2006)

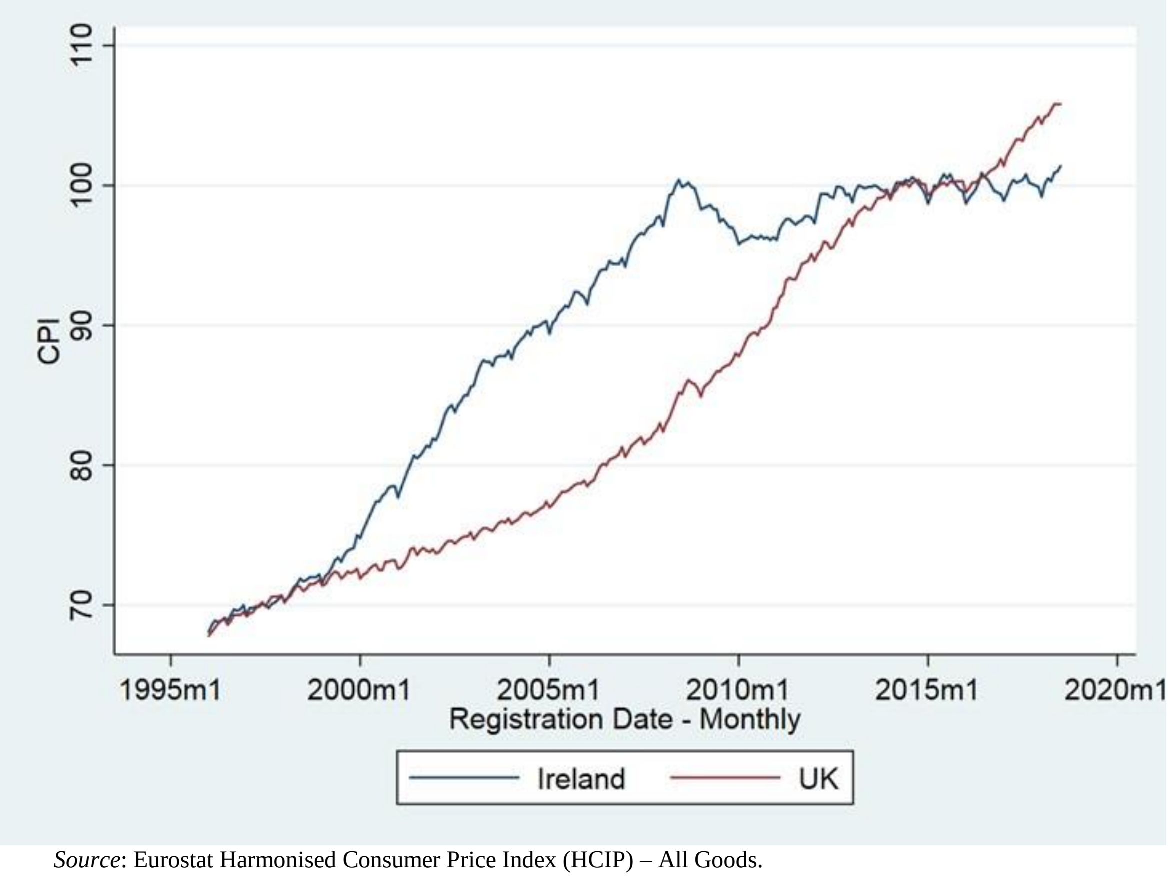
Annex C Description of control variables used in the analysis in Section 3

Consumer Price Index (CPI)

96. All of the control variables used in the analysis have been adjusted using CPI data to control for inflation. The monthly CPI data was obtained from Eurostat and covers all goods, with the base year set as 2015.

Figure 10. Monthly CPI

All items, base year = 2015.



Source: Eurostat Harmonised Consumer Price Index (HCIP) – All Goods.

97. Figure 10 shows that prices in Ireland grew at a much quicker pace between 1999 and 2008 when compared to the United Kingdom. After 2008, prices in Ireland appear to have fallen by about 5%, while in the United Kingdom during the same time-period prices were rising. All nominal control variables used with the above CPI data were therefore adjusted, in order to capture inflation differentials between the two countries.

Fuel prices

98. Petrol and diesel monthly pump prices including tax were obtained from the European Commission's Weekly Oil Bulletin,[34] which from 2005 onwards has data on the fuel prices of all European member states in Euro.

Figure 11. Unadjusted fuel prices in Ireland and the United Kingdom

Euro per 1000 litres

Source: European Commission's Weekly Oil Bulletin.

99. In Figure 11 it is clear that in euro terms, fuel prices in the United Kingdom were higher than in Ireland for much of the period under study. Fuel prices in the two countries converge significantly however in the wake of the 2008 economic recession, which sees both diesel and petrol prices tumble in both jurisdictions. From 2008 onwards fuel prices in both countries appear to follow a much more similar path.

100. It is also interesting to note that in the United Kingdom, diesel prices are consistently higher than petrol prices for the entire period of study while in Ireland the opposite is true. Although these differences in fuel prices within each country are small,

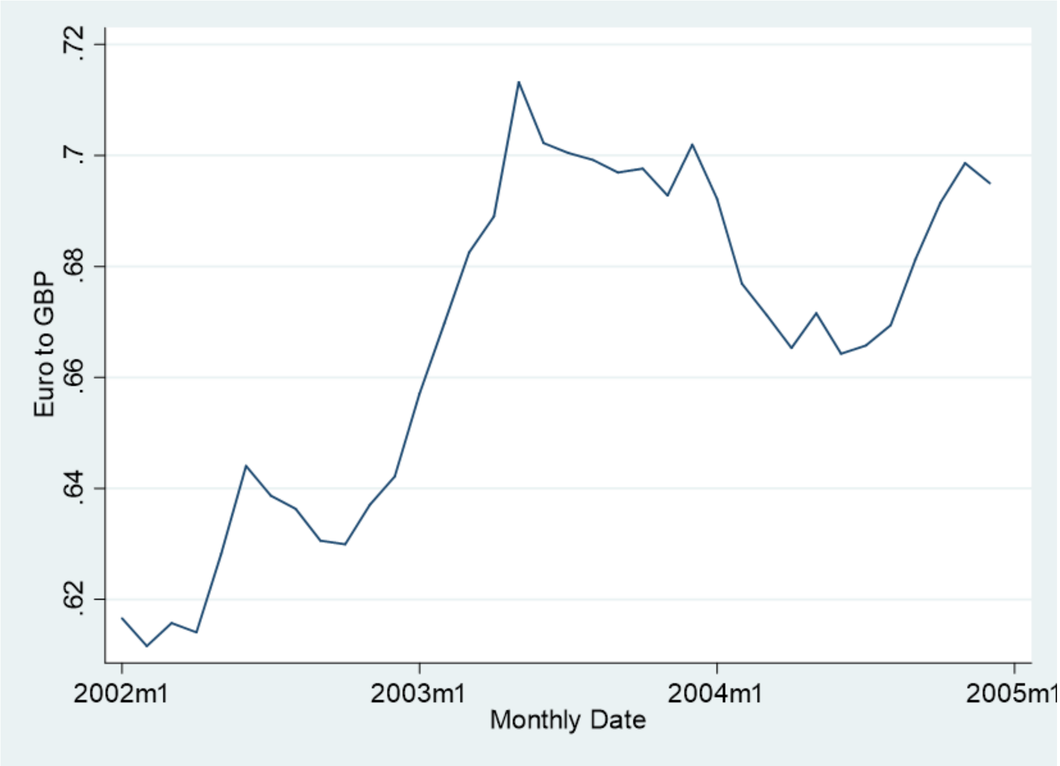
[34] Source: https://ec.europa.eu/energy/en/data-analysis/weekly-oil-bulletin.

they may have had an influence in purchasing decisions, both due to realised and perceived cost savings associated with vehicle fuel use.

101. Arriving at the numbers presented in Figure 11 presented a number of challenges. Firstly, the fuel price data (for both countries) was not presented in the same currency. All of the above fuel price data were transformed into euro. From January 2005 onwards, all the fuel price data is in Euro, and it is therefore no need to make any adjustments. From January 2002 to December 2004, however, the UK fuel price data is in GBP. These values have been converted to Euro using the monthly (average) GBP to Euro exchange rate (obtained from Eurostat).[35] The exchange rate for the period (Euro to GBP) is presented in Figure 12.

Figure 12. Exchange rate Euro to GBP

Monthly average



102. Prior to January 2002, the Euro currency had not yet been adopted by any countries in the EU. When the Euro was introduced, an irrevocable exchange rate was set by the ECB which fixed the participating countries' exchange rates to the Euro based on a single value. In the Irish case, this value was 0.787564 Irish Punts per Euro, which is the value used to convert all Irish fuel price data to Euro prior to January 2002.

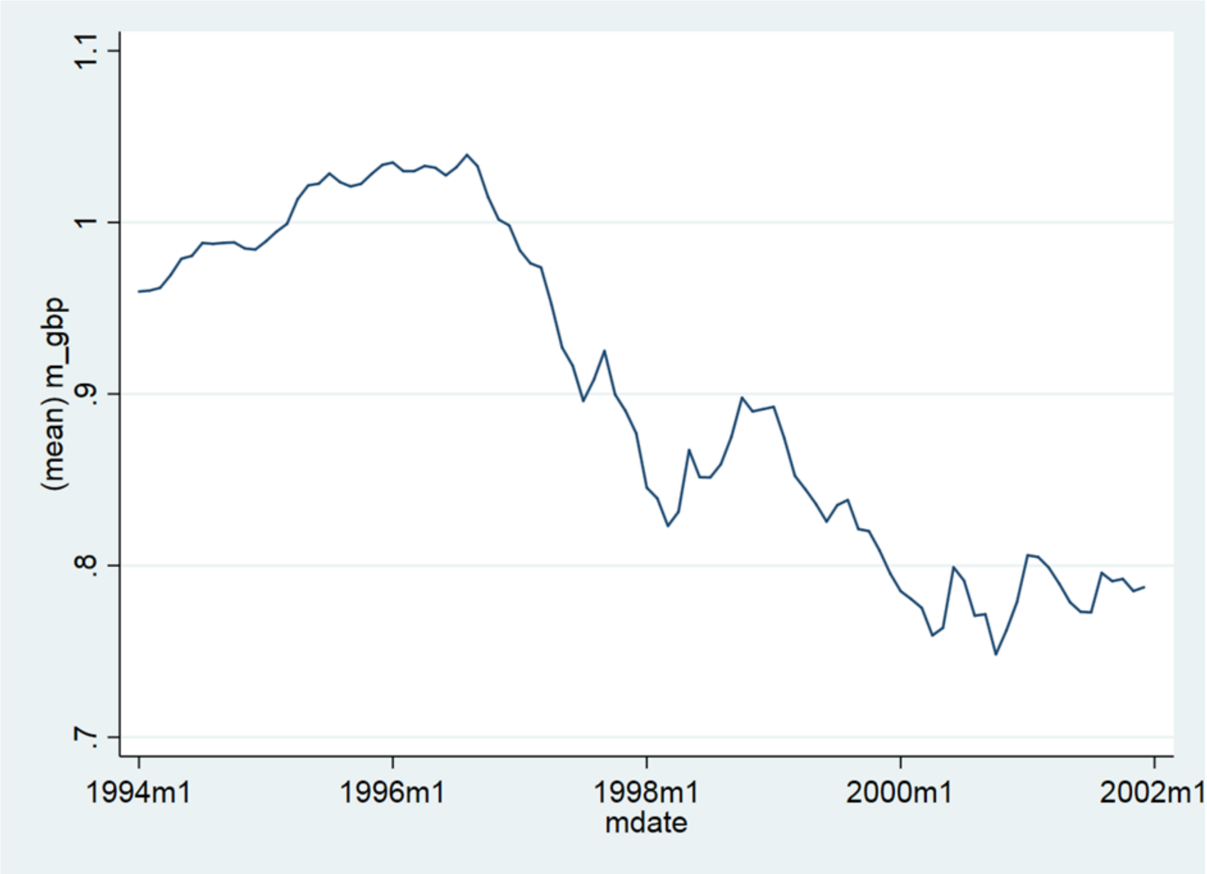
103. The Euro currency, however, was never adopted in the United Kingdom, and hence there is not an exchange rate for GBP to Euro prior to 2002. All UK fuel price data prior to 2002 is converted therefore first to Irish Punts (using historical exchange rates obtained

[35] Source: http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=ert_bil_eur_m&lang=en

from the Central Bank of Ireland), and then convert the fuel prices from Irish punts to Euro using the irrevocable exchange rate (in the same manner as Irish fuel prices). The monthly (average) exchange rate between Irish Punts and Pound Sterling (between 1994 and 2001) is presented in Figure 13.

Figure 13. Historical exchange rate Irish Punt to Pound Sterling

Monthly average



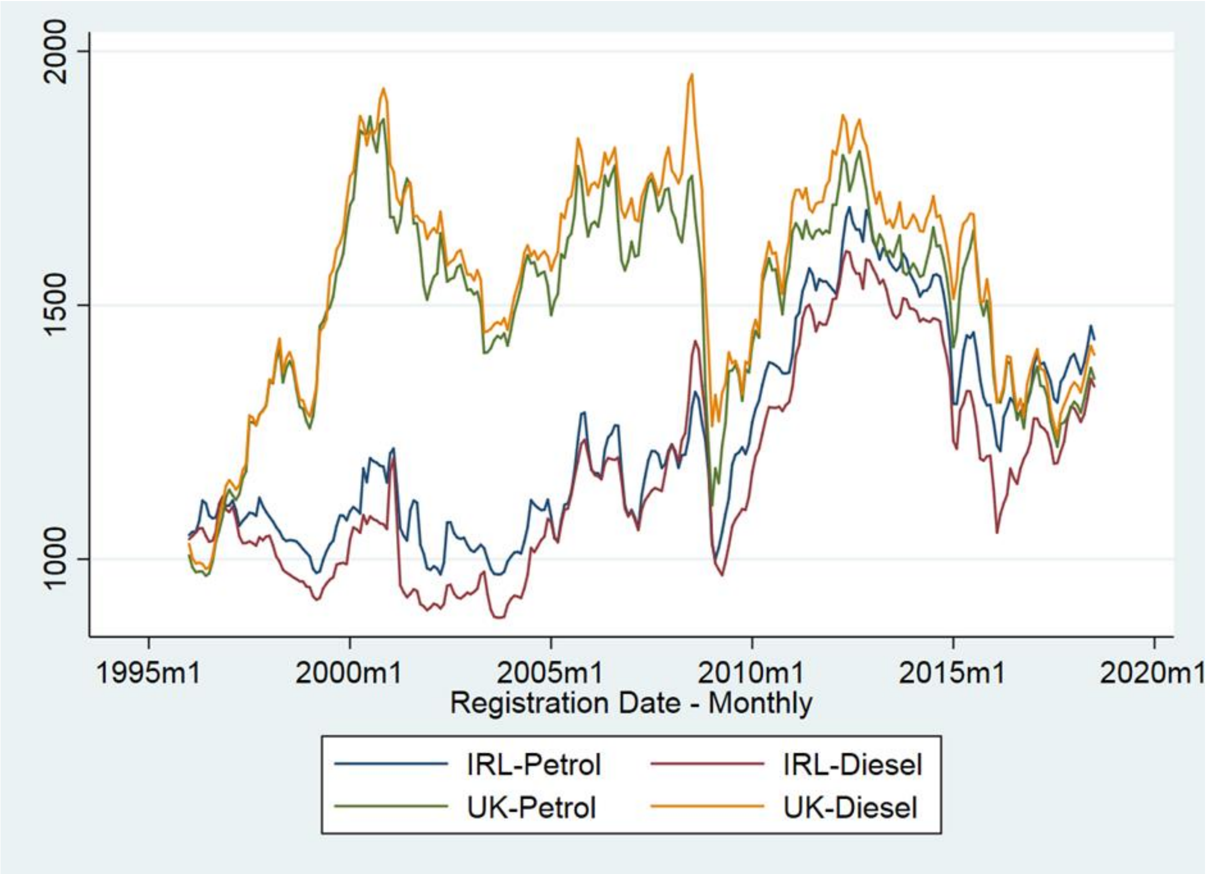
104. Figure 13 shows that the Pound Sterling strengthened relatively to the Irish punt in the period from 1996 to 2000, which explains some of the difference in nominal fuel prices observed in Figure 11. Converting the UK fuel price data to Irish punts, however, captures any exchange rate dynamics between the two countries prior to the introduction of the Euro in Ireland in 2002.[36]

105. Finally, the nominal fuel prices in Figure 11 were adjusted with the CPI in Figure 10 to account for inflation. Real fuel prices (in 2015 euro) are presented in Figure 14. These are the fuel prices control variables in Section 3 in the main body of the report.

[36] These nominal price values were cross-checked with the conversion factors provided from the European Commission (EC) Weekly Oil Bulletin Conversion factors from 2002-2005.

Figure 14. Adjusted fuel prices in Ireland and the United Kingdom

Base year = 2015



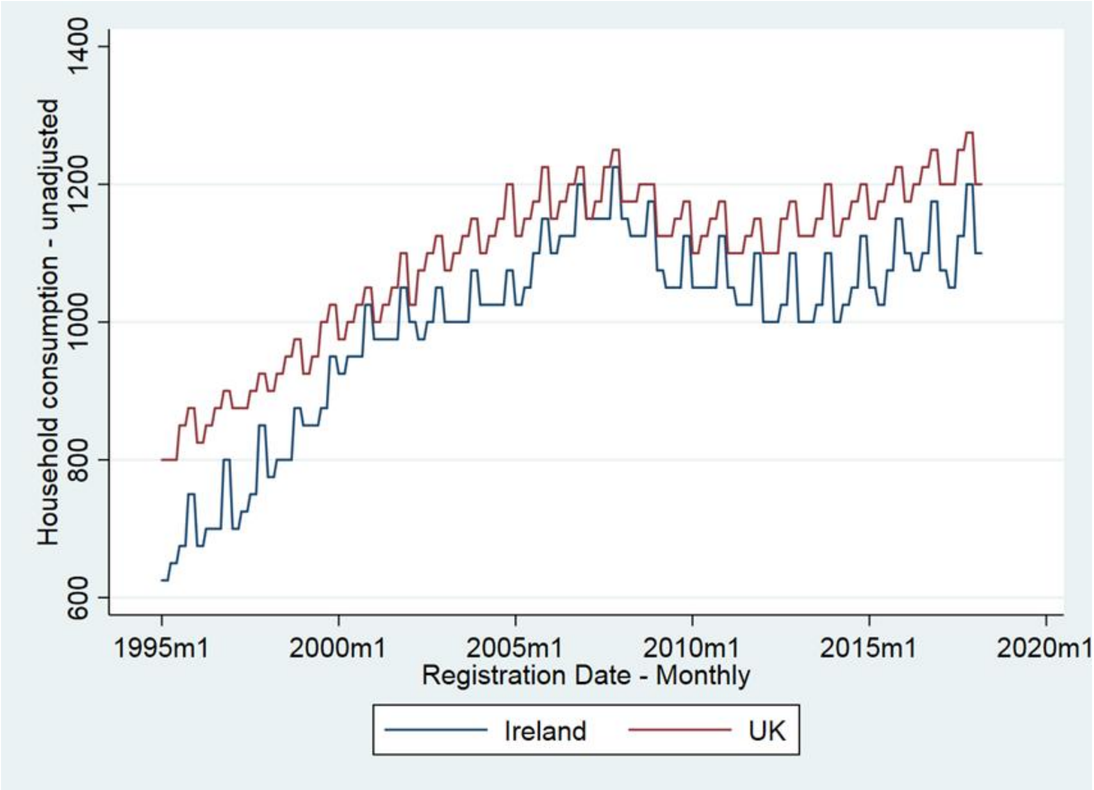
106. When the nominal fuel prices are adjusted using the CPI in Figure 14, there is an even bigger spread in fuel prices prior to 2008 between Ireland and the United Kingdom. This is attributable to the fact that prices grew much quicker prior to 2005 in Ireland, meaning that the nominal rates are adjusted by a relatively smaller factor than those in the United Kingdom.

Household consumption per capita

107. Quarterly household consumption per capita figures are used as a proxy for income to capture household purchasing power differentials between Ireland and the United Kingdom. This series (obtained from Eurostat) is presented in Figure 15.

Figure 15. Unadjusted quarterly household consumption per capita

Ireland and the United Kingdom



Source: Eurostat.

108. As these are quarterly data, in order to obtain monthly estimates, each quarterly point is divided by 3, and it is assumed that for each month within the quarter household consumption is constant.[37] Finally, as with fuel prices, nominal prices are adjusted using the CPI in Figure 10. The adjusted estimates are presented in Figure 16.

[37] This gives the stepped appearance of Figure 15.

Figure 16. Adjusted quarterly household consumption per capita

Ireland and the United Kingdom