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Modelling future private car energy demand in Ireland

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ABSTRACT

Targeted measures influencing vehicle technology are increasingly a tool of energy policy makers within the EU as a means of meeting energy efficiency, renewable energy, climate change and energy security goals. This paper develops the modelling capacity for analysing and evaluating such legislation, with a focus on private car energy demand. We populate a baseline car stock and car activity model for Ireland to 2025 using historical car stock data. The model takes account of the lifetime survival profile of different car types, the trends in vehicle activity over the fleet and the fuel price and income elasticities of new car sales and total fleet activity. The impacts of many policy alternatives may only be simulated by such a bottom-up approach, which can aid policy development and evaluation. The level of detail achieved provides specific insights into the technological drivers of energy consumption, thus aiding planning for meeting climate targets. This paper focuses on the methodology and baseline scenario. Baseline results for Ireland forecast a decline in private car energy demand growth (0.2%, compared with 4% in the period 2000–2008), caused by the relative growth in fleet efficiency compared with activity.

1. Introduction

Despite developments in technology and the prevalence of greenhouse gas reduction targets, energy demand and associated emissions from transport continue to rise (1.3% per annum anticipated globally for the period to 2035 in the IEA Current Policies Scenario (IEA, 2010)), and the sector's disproportionately large oil dependence persists (94% in 2007). Private cars are the most significant mode in terms of energy consumption in transport, so many hard measures for tackling the sustainability of transport focus on improving the energy efficiency of the private car fleet. Quantifying the impact of specific governmental policies is important firstly for planning and evaluation (i.e. to compare different measures and ensure that targets may be met in a cost effective way), and secondly for assessing how individual sector specific measures combine to contribute to overall targets (for example minimum share of renewable energy or maximum levels of emissions).

This paper builds a model of future private car energy demand using a bottom-up car stock approach, which can be used to quantify the impacts of technology focussed policy energy efficiency measures. The model developed here builds on previous work by the authors (Daly and Ó Gallachóir, 2011), which modelled historical private car energy from a similarly disaggregated, technology-focussed perspective. The advantage of the approach adopted here is the level of detail achieved, which firstly provides specific insights into the technological drivers of energy consumption, for example the ageing of the car fleet, the switch to diesel cars and secondly allows the development of scenarios based on different technology futures. This latter characteristic points to the usefulness in quantifying the impacts of technology focussed policies.

As pointed out by Hull et al. (2009), among the different approaches to energy demand modelling, one major division is between so-called "top-down" models, which are typically based on macro-economic social accounting matrices, and "bottom-up" models, which can describe in greater detail the expected impact of changes in technology or input costs within particular product markets. Arguably, bottom-up models are more appropriate for incorporating the immediate and direct impacts of specific energy-efficiency policies, which generally target savings at a disaggregated level and cannot be readily incorporated into a top-down model. For example, incorporating into a model EU Regulation 443/2009, which mandates an improvement in new-car emissions to 130 g CO_2/km by 2015, requires that private car transport energy demand be separated from other transport modes and that new cars be distinguished from existing cars. However, top-down approaches are better suited for assessing other policy impacts related to economic focussed policies such as carbon taxation.

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The methodology developed here begins with modelling car fleet activity (i.e. passenger kilometres) and sales using econometric equations and published figures for income and price elasticities. A feedback loop incorporates rebounding sales and activity due to increasing efficiency. Then, a car stock model determines the composition of the stock in a given year in terms of age and technology type, depending on the sales scenario and the turnover from previous years. It distributes mileage across the stock while maintaining the relative distances driven across different vehicle types according to age and technology. The stock model is essentially an energy simulation model, which calculates total private car energy demand using data and assumptions, which disaggregate the vehicle stock, mileage and specific energy consumption (SEC) completely by vehicle technology and age.

In this way, the activity and technological profile of the car fleet according to age and engine type is developed for each year in the time horizon, and trends can be analysed in a similar way to historic stock analysis: Daly and Ó Gallachóir (2011) used this disaggregated calculation and observed that Irish cars consumed 37% more energy in 2008 than in 2000. This increase in demand was found to be mainly caused by the dramatic increase in car ownership, a 45% increase in the car stock and in particular diesel cars (a 112% increase over the period), which became less energy efficient over time. Furthermore, the ageing of the fleet and the shift towards activity in cars with larger engines led to almost stagnant overall energy efficiency, with a 0.6% improvement over the whole period. This historic model underpins the derivation of key forecasting variables for this study: the survival profile of different technology types, the activity profile, and the calculation of on-road energy efficiency.

According to the taxonomy of energy-economy models put forth by Mundaca et al. (2010), the historic model is an accounting model, managing and analysing data and results, while the projection model presented here is a simulation model, which is capable of describing futures based on alternative scenarios.

This kind of simulation stock modelling can calculate energy efficiency improvements or energy or emissions' savings as a result of a given measure by comparing the results of two scenarios with different input assumptions—in this way it has advantages over straightforward energy savings' calculations. Bohler and Rudolph (2009) calculate energy savings from the introduction of a new technology to a fleet directly, as the difference in energy efficiency between two types of potential cars multiplied by the annual distance, subtracting a rebound factor. The stock simulation method presented here gives a more dynamic and detailed picture of alternative technology scenarios by taking account of the ageing of the fleet, the difference in distance driven by different technologies and cars of different vintages. DeCicco (1995) describes a stock turnover model similar to that presented here, using on-road factor estimates, disaggregated mileage and survival rates and assuming constant baseline fuel economy to forecast the impact of different imposed CAFE standards on baseline energy. Wohlgemuth (1997) describes an approach used by the International Energy Agency in forecasting transport energy demand: A two-step approach is used, where the total activity (the sector's energy service demand) is determined econometrically, while a detailed stock model based on technological efficiencies and turnover rates are used to simulate energy demand. This is a similar approach to that taken in this paper and points to the advantage of modelling the energy service demand and efficiencies separately, as well as the complexity of interactive factors governing car ownership and travel. By Wohlgemuth (1997) however, the modelling described is largely top-down with little technological detail and depends on elasticities derived for different regions.

In this paper, the methodology is applied to the Irish car stock as a case study. Energy forecasts in Ireland are currently generated using aggregate, top-down models, which determine total energy consumption on the basis of economic forecasts (Walker et al., 2009). Increasingly however, policies are being introduced that focus on technology change. Recent examples include a change in the taxation system in 2008, leading to a shift towards more efficient vehicles (Rogan et al., 2011), a target for 10% road vehicle electrification by 2020, a car scrappage scheme in 2010, an obligation on biofuel mixing in transport fuels and EU Regulation 443/2009, which mandates an improvement in new-car emissions to 130 g CO_2/km by 2015. Our model can incorporate these and other measures either separately, in order to evaluate them individually, or else incorporate them all into a baseline. The baseline scenario presented here incorporates the trends and compulsory policy measures that have been legislated for by December 31 2009.

2. Methodology: stock model and energy baseline

2.1. Overview

This model forecasts annual private car energy consumption by iteratively simulating the car fleet each year, projecting the fleet's size and technological structure, the range of activity across the fleet and the energy efficiency of each vehicle type.[1] Energy demand for each fuel type is then calculated for each year according to the bottom-up equation:

$$E_f = \sum_{t,v,f} S_{t,v,f} \times M_{t,v,f} \times SEC_{t,v,f} \tag{1}$$

where $S_{t,v,f}$, $M_{t,v,f}$ and $SEC_{t,v,f}$ are, respectively, the stock, the mileage and the energy intensity (specific energy consumption, SEC, in MJ/km) of vehicle technology t, vintage v,[2] consuming fuel f in that year. Fleet CO_2 emissions are calculated according to

$$Emis = \sum_{f} E_f \times fact_f \tag{2}$$

where $fact_f$ is the emissions factor (in gCO_2/MJ) for fuel f.

Each variable, stock, mileage and energy intensity is generated for the whole fleet profile, described in detail in the next section.

The next section will describe the econometrics underpinning the stock model. Subsequent sections describe the modelling of number of vehicles, their mileage and energy intensity.

2.2. Activity and sales forecast

In the model, rising oil prices affect sales, activity and new engine size negatively, while increased energy efficiency of the stock reduces the cost of travel and causes a rebound. Increasing national income also causes a rise in car sales, in total activity and on the average size of engines entering the fleet.

A simple econometric equation is firstly used to generate baseline vehicle activity and sales, shown in Eq. (3). The year-on-year percentage change in national income, ΔGNP, and fuel price in €/km, ΔP, are explanatory variables. Income and price elasticities with respect to sales and activity (δI_{Sales}, δI_{Vkm}, δP_{Sales} and δP_{Vkm}) are taken from a study of car energy demand (Johansson and Schipper, 1997), and shown in Table 1. These represent the percentage variation in the number of vehicle kilometres driven or cars sold for each 1% increase in national income

[1] *Activity* in this paper refers to the activity of the private car fleet, in vehicle kilometres per year. *Mileage* is a vehicle type's average distance driven in a year.

[2] *Vintage* refers to the year of manufacture; *Sales* refers to new-car sales.

Table 1
Fuel price and income elasticities used for forecasting car sales and vehicle activity.

	Fuel price elasticity δP	Income elasticity δI
Car sales	−0.1	1.0
Vehicle kilometres (*Vkm*)	−0.3	1.2

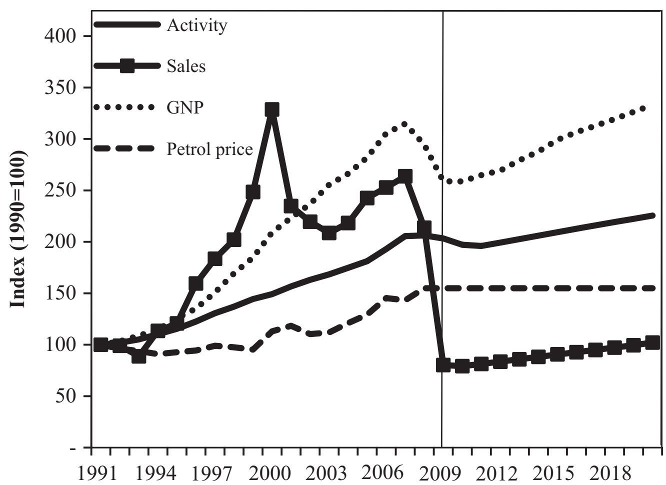

Fig. 1. Indexed historic and projected income, price, activity and sales.

and fuel price

$$Vkm^T = Vkm^{T-1} \times (1+\Delta GNP^T \times \delta I_{Vkm}) \times (1+\Delta P^T \times \delta P_{Vkm})$$

$$Sales^T = Sales^{T-1} \times (1+\Delta GNP^T \times \delta I_{Sales}) \times (1+\Delta P^T \times \delta P_{Sales}) \qquad (3)$$

Future GNP is based on the "Revised Recovery Scenario" baseline economic projections from the Economic and Social Research Institute (Barrett et al., 2011), which incorporate the Irish recession between 2008 and 2010, and imply a slow recovery (2.6% average growth between 2011 and 2020). Transport fuel price is correct up to early 2011, after which a conservative oil-price growth scenario used in EU projections (Capros et al., 2008) is applied to the price of transport fuel. As stock efficiency is necessary for calculating per-kilometre fuel costs and is itself a product of the stock model, the model is first run without rebound (just taking fuel price per litre) to determine fleet energy efficiency. Historic and projected figures for GNP, fuel price, activity and new car sales are given in Fig. 1, indexed on 1990.

Similarly, the evolution of engine size in new cars is extrapolated using historic regression based on income (GNP). Table 2 contains the income elasticities used on the shares of car sales by engine size, which is derived from another Irish study (Hennessy and Tol, 2010). Each elasticity represents the percent variation in the percentage of cars sold in each engine cc band for each 1% increase in national income (in GNP). The shares are then normalised so that the sum of shares is equal to 100%. It is assumed that the share of diesel and petrol cars is assumed to remain constant from 2010.

Fig. 2 shows the projection of car engine shares up to 2025 using this method. Projecting forward from 2010 shares, the share of > 1.7 L new cars bought in 2025 is 31% according to the model, up from 26% in 2010 and 21% in 2000. It is clear that factors external to fuel price and income play a role in determining the profile of new cars bought, for example, a change in the vehicle taxation regime in Ireland in 2008 from being based on engine size to based on CO_2 emissions, which caused a shift in purchasing trends towards diesel cars, and smaller engines as seen in Fig. 2 (Rogan et al., 2011).

Table 2
Income elasticities of engine size sales shares.

Engine (cc)	Income elasticity
< 900	−0.33
900–1200	−0.33
1200–1500	−0.08
1500–1700	0.49
1700–1900	0.57
1900–2100	0.73
> 2100	0.93

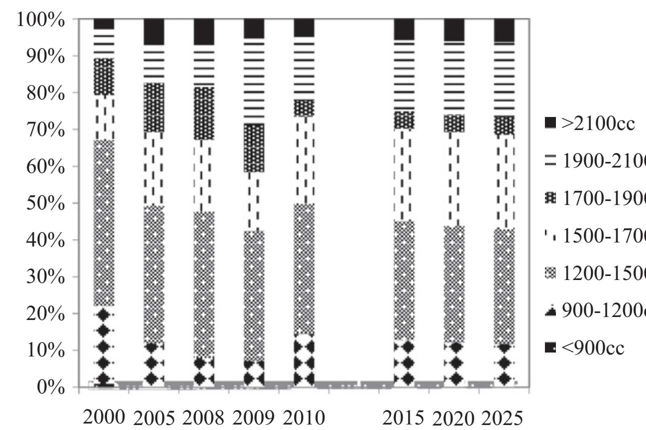

Fig. 2. Historic and projected new car engine sales shares.

2.3. Stock

The fleet is disaggregated according to vehicle technology type (petrol and diesel cars are further divided by engine sizes, as in Fig. 2) and vintaged up to 25 years. Vintage is derived from the year of manufacture as opposed to the year of first registration, as second-hand imported vehicles are commonly imported from the UK, and age is a model parameter. The stock model generates this fleet structure, shown in Fig. 3, by simulating the number of vehicles in each technological category and vintage each year, using sales and survival assumptions.

Firstly, within a given technology type t, the number of cars of a given vintage v is calculated for year T using the equation:

$$Stock_{t,v}^{T} = Stock_{t,v}^{T-1} \times (Surv_t(T-v)+1) \qquad (4)$$

where $Surv_t(T-v)$ is the year-on-year survival rate of vehicles at age $T-v$ between one year $(T-1)$ and the following year. For example, for the year T=2008, cars with a 2000 vintage v are aged 8. This factor represents the net changes in the existing car stock (excluding new car sales), incorporating retirements, second-hand imports and exports. This was derived for each technology type for Ireland from the vintage profile of each technological class of cars for each year 2000–2008, using Eq. (5):

$$Surv_t(T-v) = \underset{Y}{Avg}\left(\frac{Stock_{t,Y-(T-v)}^{Y} - Stock_{t,Y-(T-v)}^{Y-1}}{Stock_{t,Y-(T-v)}^{Y-1}}\right) \qquad (5)$$

The probability that a vehicle of vintage v will survive year T depends on age $(T-v)$, and was derived from the average historical survival rate, calculated using available historical vehicle registration data (years Y from 2000 to 2008). Fig. 4 shows the survival rate of different engine bands for petrol and diesel; it generally rises to above 1 for younger cars, indicating greater second-hand imports than retirements from those car types.

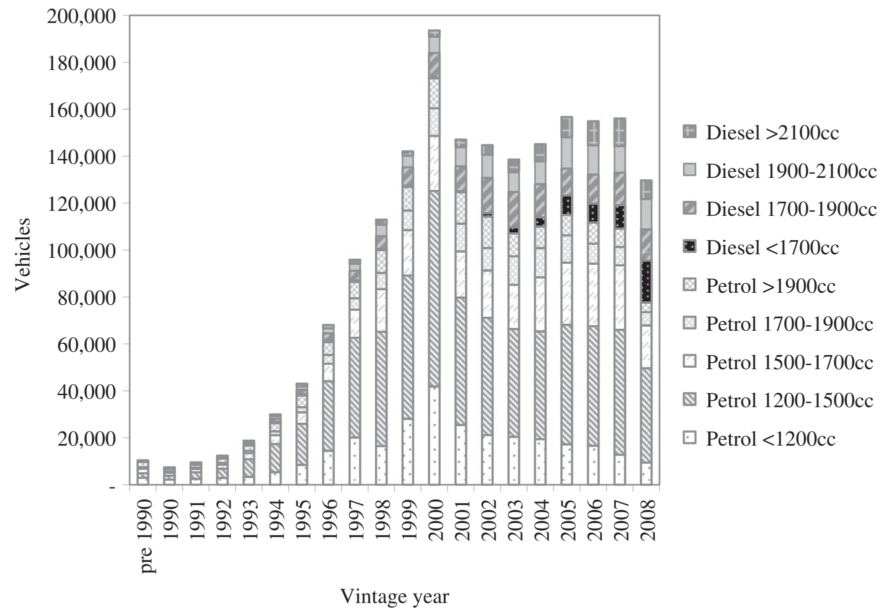

Fig. 3. Disaggregated 2008 fleet profile by fuel and engine size. Notable trends include the spike in 2000 registered cars and the trend towards larger and diesel engines.

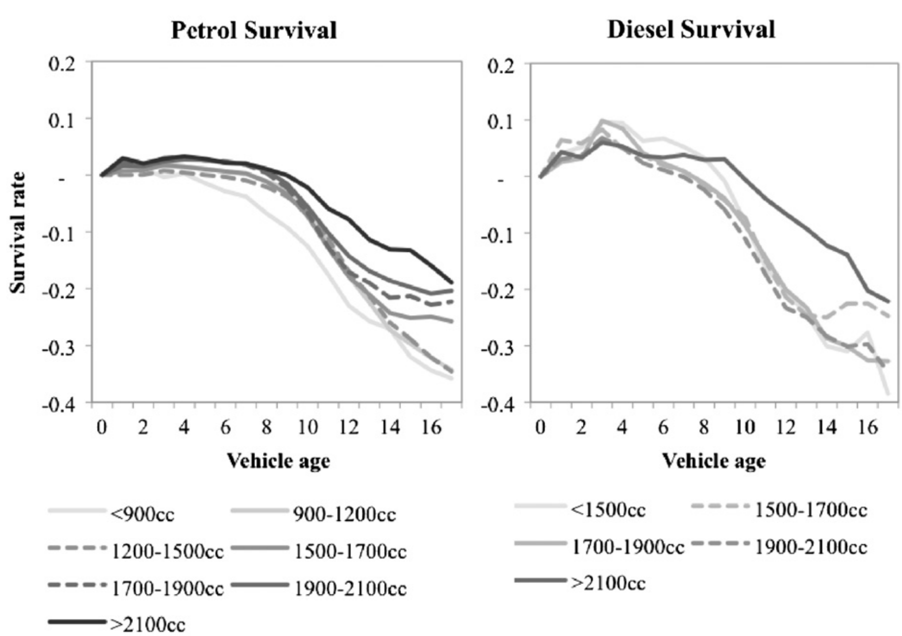

Fig. 4. Survival rates of different engine bands for petrol and diesel.

This curve is an average over a number of years, and actual imports and car retirements depend on factors such as currency exchange rates (most importantly between the euro pound sterling, with UK being a major source of Irish second hand imports) and scrappage schemes (Greenspan and Cohen, 1996).

Next, overall stock in that technology type is found by summing over all vintages and adding sales:

$$Stock_t^T = Sales_t^T + \sum_v Stock_{t,v}^T \quad (6)$$

For calculating the car stock, two crucial inputs are the number of new car sales and the types of cars sold across technology types. The calculation of new car sales, based on national income and fuel price, and the profile of new engine sizes based on income, is described in Section 2.2. This baseline projection model assumes no new technologies be significantly introduced to the fleet (battery electric or compressed natural gas vehicles, for example). In 2010, sales of alternatively fuelled vehicles (AFV) were about 3%, with approximately two-thirds of this attributable to E85 vehicles (ethanol/petrol) and the remainder hybrid electric cars. These shares are preserved in the baseline.

Table 3 and Fig. 5 show the projected stock in 2025 compared with that of 2008. Of note is the increased share of diesel and an annual stock growth of 2.3%. Table 3 also shows the implications this projection has for vehicle ownership, which rises from 433 to 526 per thousand people, using population forecasts from the ESRI demographic model. A comparison with passenger vehicle saturation in the USA (827 vehicles per thousand people)

Table 3
Projected baseline stock and fuel shares, 2008–2025.

	2008	2025
Total stock (thousand)	1917	2696
Population (thousand)	4418	5120
Car saturation (veh/1000 people)	433	526
Petrol car share	0.80	0.56
Diesel car share	0.20	0.44

indicates that saturation of vehicles may not be reached even with this growth.

Total activity is the primary driver of energy demand in this stock model, not the quantity of cars in the fleet, as average mileage is calculated as a function of fleet activity and total stock. This stock model does however produce a demographic description of activity by technology type, which is a crucial determinant of energy demand.

2.4. Activity

The authors have previously shown the significance of modelling the profile of activity over the vehicle fleet in calculating transport energy, for example, the average mileage of large cars (> 1900 cc) rose by 2% between 2000 and 2008, whereas smaller engine mileage (< 1200 cc) fell by 17% (Daly and Ó Gallachóir, 2011). Because of the differences in energy efficiency across technology types, these changing mileages affect energy consumption in a way that more straightforward or top-down calculations do not capture.

The simulation of the structure of car activity over technology and vintage starts with a top-down calculation of total car activity, described in Section 2.2. The total activity of a car fleet (in vehicle kilometres, or vkm) in a country is largely subject to factors external to the condition of the fleet—lifestyle choice, settlement patterns, the availability of alternative transport, for example. Other models based on spatial planning and behaviour can produce more sophisticated forecasts of activity, and these figures could be used as inputs into the model we present in this paper. The purpose here is not to study the total activity of the fleet, but rather to study the patterns of travel demand and the consequent energy consumption across the technological structure of the fleet. Hence total activity is used to provide a benchmark upon which different stock patterns can be compared. For example, if new car sales are high in a given year, the model simulates new-car mileage as higher than the fleet average, following observed trends from the past. If higher fuel standards are imposed on these cars then this will increase the efficiency of the fleet as a whole because of the larger representation of efficient cars in the fleet, and furthermore because of the greater mileage of these cars. Conversely, if larger engine sized cars, which also drive more than average, with low fuel economy are purchased in a given year then this will adversely affect the fleet fuel performance.

The methodology for creating a demographic model of activity, using total activity, the structure of the fleet as determined in the previous section, and historic trends of comparative mileage, follows.

Firstly, the historic trends in the comparative driving distances of cars at each of the three levels of disaggregation of the technology profile are compiled: the first level is the average mileage of cars in each fuel type (M_f); the second level is mileage of cars in each CC band within fuel types ($M_{f,c}$), and within each CC band, the third level refers to the mileage of each vintage ($M_{f,c,v}$). For Ireland, these data were made available from the Sustainable Energy Authority of Ireland's Energy Policy Statistical Support Unit (SEAI EPSSU) from analysis done on odometer readings from the National Car Test (NCT), which cars go through 4 years after registration, and every 2 subsequent years; the analysis is described by Howley et al. (2009).

The mileages at each level are created into weighted profiles in order that relative activities across different categories are carried through in the forecasting model. The weighted profiles at the level of fuel type, engine category and age are, respectively, created using Eqs. (7), (8) and (9):

$$w_f = \frac{M_{f^*}}{M} \tag{7}$$

$$w_{f,c} = \frac{M_{f,c^*}}{M_f} \tag{8}$$

$$w_{f,c,v} = \frac{M_{f,c,v^*}}{M_{f,c}} \tag{9}$$

In our calculations, M_{f^*}, M_{c^*} and M_{v^*} are the "base mileages" and represent "petrol", "< 900 cc" and cars aged 0, respectively. The weight of each other category is benchmarked on these three base mileages.

In 2008, overall average mileage was 16,119 km/year; for petrol it was 14,090 km/year and for diesel it was 19,870 km/year. Table 4 shows the weighted profile of 2008 mileage across CC bands: larger engine size cars show greater mileage than the < 900 cc category. Data availability restricts the generation of a full vintage profile of activity as the NCT does not test cars for their first four years. Using the average mileage figures of cars that are tested, it was observed that on average, cars' mileage decays at rate of 2% for every vintage year. This corresponds with the profile of decay derived for UK cars (Kwon, 2006). This profile was applied to each CC band.

In order to simulate these profiles into the future, given the total activity as determined by the econometric equations and disaggregated stock, determined by the stock model, the mileage in each category is calculated using the following set of equations, where w represents the mileage weight of each level. Firstly the "base mileage" is calculated for the given category, then the weighted profiles are used to generate all other mileages for that category, according to Eq. (10)

$$\text{Overall average mileage:} \quad AvM^T = \frac{vkm^T}{S^T}$$

Level	***Base mileage***	***Other mileages***	***Average mileage***
Fuel type	$M^T_{f^*} = \frac{AvM^T \times S^T}{\sum_{i=\text{fuel types}}(w_i \times S^T_i)}$	$M^T_f = w_f \times M^T_{f^*}$	$AvM^T_f = \frac{\sum_{i=\text{fuel types}}(M^T_i \times S^T_i)}{S^T}$
CC band	$M^T_{f,c^*} = \frac{AvM^T_f \times S^T_f}{\sum_{i=\text{CC bands}}(w_{f,i} \times S^T_{f,i})}$	$M^T_{f,c} = w_{f,c} \times M^T_{f,c^*}$	$AvM^T_{f,c} = \frac{\sum_{i=\text{categories}}(M^T_{f,i} \times S^T_{f,i})}{S^T_f}$
Vintage	$M^T_{f,c,v^*} = \frac{AvM^T_{f,c} \times S^T_{f,c}}{\sum_{i=\text{vintages}}(w_{f,c,i} \times S^T_{f,c,i})}$	$M^T_{f,c,v} = w_{f,c,v} \times M^T_{f,c,v^*}$	

(10)

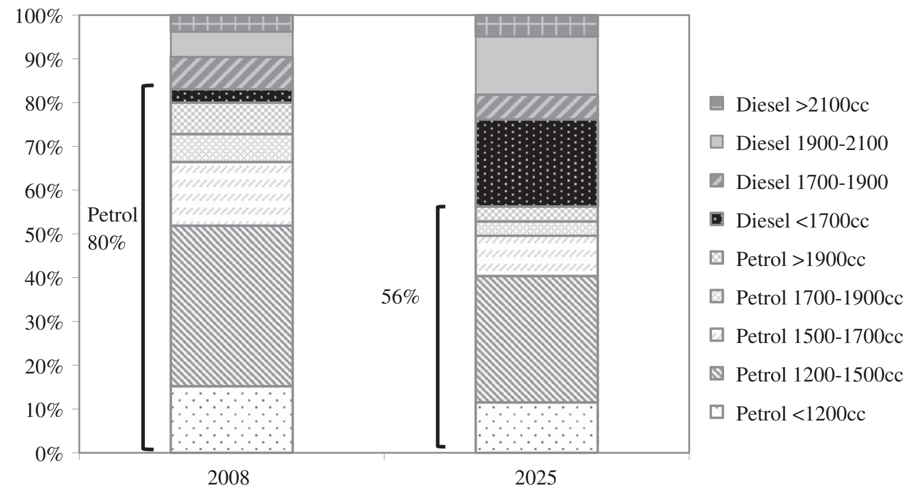

Fig. 5. Share of stock by technology, 2008 and 2025.

Table 4
2008 mileage profile across CC bands and fuel types.

	Petrol		Diesel	
	Mileage: $M_{f,c}$	Weight: $w_{f,c}$	Mileage: $M_{f,c}$	Weight: $w_{f,c}$
Total	14,090		19,870	
< 900 cc	7731	1.00	1407	1.00
900–1200 cc	11,460	1.48	11,668	8.29
1200–1500 cc	13,811	1.79	19,640	13.96
1500–1700 cc	15,948	2.06	18,576	13.20
1700–1900 cc	16,350	2.11	20,210	14.37
1900–2100 cc	15,779	2.04	19,848	14.11
> 2100 cc	15,220	1.97	20,783	14.77

In scenario analysis, the weighted activity profiles $w_{f,c,v}$ can change over time to analyse behavioural variations. For example, because of a change in taxation system diesel cars have been incentivised over petrol; if diesel cars, traditionally bought for country use because of their greater fuel efficiency, become more popular for city driving, it might be determined that the gap between petrol and diesel mileage decreases.

2.5. Energy intensity

The specific energy consumption (SEC, measured in MJ/km) of cars at the most disaggregated level of the stock model ($SEC_{f,c,v}$) is based on new-car SEC, which is the average fuel performance of cars in each fuel type/CC by vintage year. This figure comes from official fuel consumption tests, which are based on a standardised driving cycle required by the EU for each new car model for sale, recorded in the UK's Vehicle Certification Agency (VCA). The driving cycles represent idealised and standardised driving conditions for both urban and highway driving so as to give the same standard for each car tested, but there is a well established gap between cars' rated performances and on-road fuel consumption (Schipper et al., 1993). In this model we adjust new-car SEC by applying an ageing factor based on the vintage year, estimated by Van den Brink and Van Wee (2001) to be a 0.3% per year increase in intensity, and for the gap between on-road and test fuel consumption, represented as an "on-road factor" (*ORF*) for each fuel type. This factor was calculated by calibrating personal car transport fuel consumption in 2005 with that calculated from the Household Budget Survey (Central Statistics Office, 2005), in a process described by Daly and Ó Gallachóir (2011). SEC is

Table 5
Change in sales share and efficiency of different technology types between 2007 and 2009.

Fuel	CC band (cc)	Sales share		Intensity-new car SEC (MJ/km)	
		2007	2009	2007	2009
Petrol	< 900	0.00	0.00	1.88	0.83
Petrol	**900–1200**	0.08	0.07	1.97	1.87
Petrol	**1200–1500**	0.35	0.23	2.26	2.14
Petrol	**1500–1700**	0.18	0.08	2.51	2.44
Petrol	**1700–1900**	0.05	0.03	2.74	2.61
Petrol	**1900–2100**	0.03	0.01	2.82	2.71
Petrol	**> 2100**	0.02	0.00	3.55	3.48
Diesel	< 900	0.00	0.00	1.85	1.85
Diesel	**900–1200**	0.00	0.00	1.85	1.85
Diesel	**1200–1500**	0.04	0.12	1.91	1.83
Diesel	**1500–1700**	0.03	0.08	1.94	1.87
Diesel	**1700–1900**	0.08	0.10	2.18	2.06
Diesel	**1900–2100**	0.07	0.22	2.43	2.10
Diesel	**> 2100**	0.07	0.05	3.20	2.67

calculated by

$$SEC_{f,c,v} = N_{f,c,v} \times (1.003)^{T-v} \times ORF_f \tag{11}$$

where $N_{f,c,v}$ is new-car SEC, T is the year of calculation and $T-v$ is the age of the car. The stock's disaggregated new-car SEC for cars manufactured between 2000 and 2008 was provided by EPSSU (Howley et al., 2009) and was linearly extrapolated back to 1990 based on the average annual rate of new-car intensity change by engine size between 2000 and 2008.

New-car SEC in the future is an important assumption for the forecasting model, which can reflect a change in purchasing trends, improving technology or imposed standards. New-car SEC is corrected using data up to 2010; a significant improvement in efficiency is evident. This has been ascribed to a change in the taxation system to incentivise lower emitting vehicles as opposed to smaller engine sizes (Rogan et al., 2011); there was also an economic recession between 2008 and 2010, a scrappage scheme in 2010 and a new carbon tax, which may have influenced this improvement. Table 5 compares the sales share and the energy intensity of new cars by fuel type and engine size between 2007 and 2009, before and after this taxation change; it clearly shows improved average efficiency across the bands and a higher share of diesel cars.

For projecting SEC into the future, a baseline autonomous improvement factor of 0.3% per year is applied, which represents

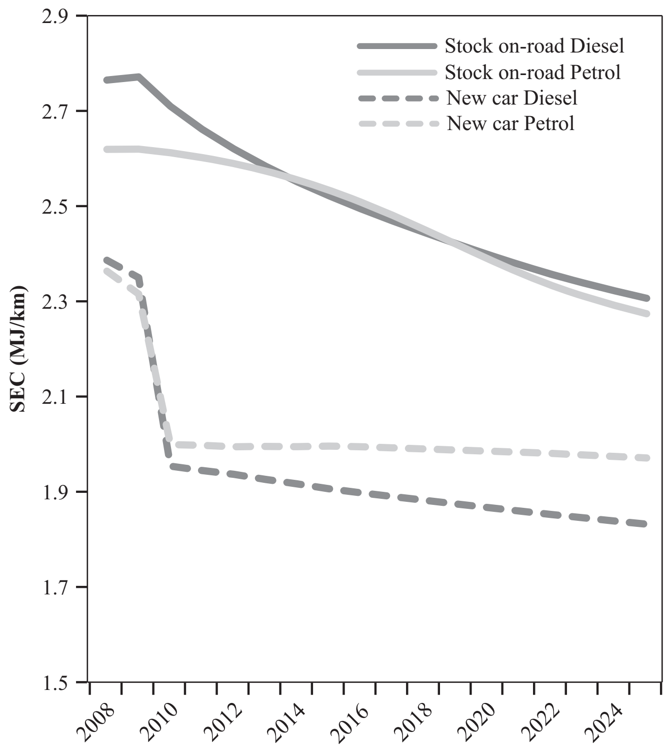

Fig. 6. On-road stock average and new-car SEC from 2008 to 2025.

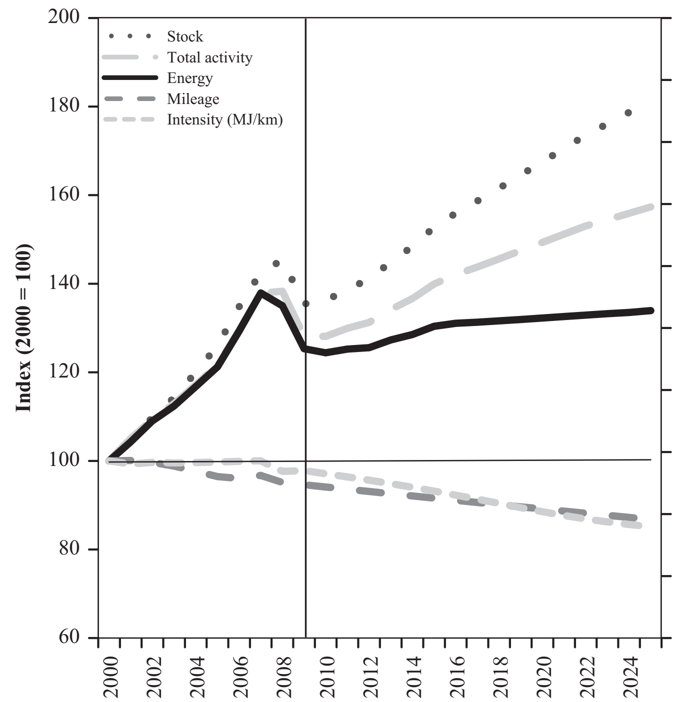

Fig. 7. Indexed historical and projected car energy, stock, activity and efficiency figures (2000=100).

the average annual change in new-car intensity between 2000 and 2008, and the engine size profile is determined by the process described in Section 2.2. Fig. 6 shows new-car SEC where the increasing share of large engine sizes negate the autonomous efficiency improvement, with new-car SEC almost flat after 2010. Zachariadis (2006) discusses the creation of a baseline energy demand scenario, saying that a baseline consistent with historical trends is an important tool on which to base policy analysis, despite the inherent uncertainty in this. This study proposes "business as usual" rates of change in baseline fleet intensities, proposing an improvement in the average EU state new-car intensity of 9% between 2010 and 2020, and in improvement of 5% between 2020 and 2030. These are higher rates of improvement but still consistent with the 0.3% annual growth used in this study. Whether this baseline is sufficient for the Irish car fleet to be in line with EU targets is discussed in Section 3.2.

Fig. 6 also shows the stock-average on-road intensity for petrol and diesel cars, which is calculated by averaging the disaggregated on-road SEC for each technological and vintage category from Eq. (11), weighted by the activity in each category. This is equivalent to the quotient of overall energy demand and number of kilometres driven for each fuel type. Intensity in both fuel types is continually falling, at an average rate of about 1% annually between 2010 and 2025.

Assuming a fuel emissions intensity of 66 gCO_2/MJ (assuming a 3% mix of biofuels, as required by the Irish Biofuels Obligation Bill (GoI, 2010)), the model forecasts new-car emissions at 130 gCO_2/km in 2015, satisfying EU Regulation 443/2009 (EC, 2009).

3. Results

This section presents and analyses results, including the implication of the recent rise in vehicle efficiency and share of diesel cars, explores the impact on emissions and EU targets, and finally looks at some of the uncertainties associated with scenario modelling.

3.1. Energy and trends

Applying Eq. (1) to the stock, mileage and efficiency assumptions, we simulate energy demand and CO_2 emissions up to 2025. Fig. 7 shows stock, activity, energy, intensity and average mileage of the car stock indexed on the year 2000. Table 6 shows the total energy demand in 2025 is almost unchanged from 2008 (87.2 PJ from 90.2 PJ). This static energy demand compared to a 4.5% energy growth in the years between 2000 and 2008.

Table 6 shows total energy demand in 2008 and 2025, and the share of energy demand in both years from technological and age angles. It shows that in 2025, the demand for diesel outstrips that for petrol, compared with petrol's 71% share in 2008. Overall energy demand over the whole 17-year period rises by 3.3%, 0.2% per year. The share of demand according to engine cc does not change substantially, and the energy share of older cars increases. Table 6 also disaggregates annual energy growth in the period according to its drivers, namely fleet activity growth (itself a product of stock and average mileage) and energy intensity, SEC, and shows each of these drivers according to technological and age category. Stock grows by 1.5% annually, driving a 0.8% annual growth in activity, which is again stronger in diesel and older cars.

Average mileage falls in the model by 0.5% per annum between 2008 and 2025, compared with an annual decline of 0.3% between 2000 and 2008. This is consistent with the growing car stock and increased wealth: as the number of multi-car households and car ownership increases in a country, the activity of individual cars tends to fall (Johansson and Schipper, 1997). Ireland's 2006 census indicates that 80% of households have one or more cars and 42% of households have two or more cars (Central Statistics Office, 2006). Compared with the USA, a country with high car ownership, the number of households with two or more cars is 62% (Giuliano and Dargay, 2006), suggesting that there is room for ownership to grow in Ireland, and for average mileage to decrease.

Compared with historically high growth, energy demand slows substantially in the model because as newer, more efficient cars filter through the stock, overall efficiency improvements grow

Table 6
Forecasted growth rates of energy and drivers between 2009 and 2025, disaggregated in different ways.

			Energy		Annual growth rates 2008–2025				
			2008	2025	Energy (%)	Stock (%)	Activity (%)	Mileage (%)	SEC (%)
		Total	87.3 PJ	90.2 PJ	0.2	1.5	0.8	−0.5	−0.8
Shares	Fuel split	Petrol	0.71	0.48	−1.9	−0.8	−1.3	−0.6	−0.8
		Diesel	0.29	0.52	4.5	10.3	6.2	−1.5	−0.9
	Engine cc split	< 1200 cc	0.09	0.08	−0.9	0.7	0	−0.6	−0.9
		1200–1900 cc	0.66	0.62	−0.4	1.1	0.5	−0.5	−0.8
		> 1900 cc	0.25	0.30	1.1	3.6	2.3	−0.8	−0.7
	Vintage	0–3 years	0.39	0.26	−1.9	−0.8	−1.1	−0.3	−1.1
		4–7 years	0.31	0.28	−0.5	0.6	0.4	−0.1	−0.9
		8+ years	0.31	0.45	2.7	4.0	3.6	−0.2	−0.6

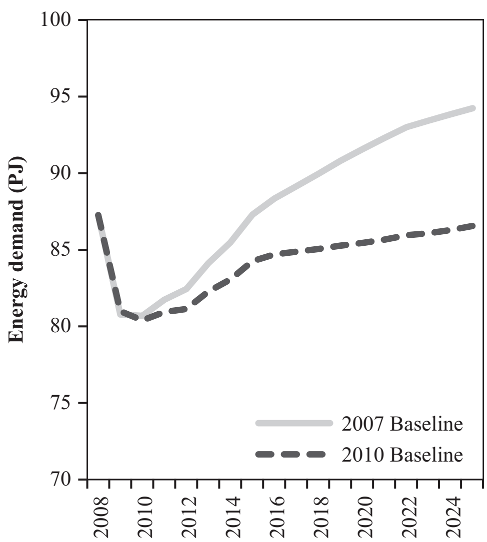

Fig. 8. 2007 baseline result comparison.

faster than an increase in activity, which stagnates due to pessimistic economic forecasts. Historically, demand rose because gains in efficiency were minimal compared with economically driven activity growth (Ó Gallachóir et al., 2009).

In order to highlight the impact of the recent step change in purchasing trends in the model, a second baseline is populated as a "2007 Baseline" sales scenario, where all parameters are held constant except for new-car SEC and sales profile, which is based on that from 2007. Fig. 8 compares energy demand from both scenarios, with the 2007 Baseline resulting in a rise in demand, 9% greater in 2025 than the 2010 Baseline scenario.

3.2. Emissions and EU targets

Baseline CO_2 emissions are calculated by applying an emissions factor of 65.8 gCO_2/MJ. Applying this to energy calculations, this gives emissions of 5.62 $MtCO_2$ in 2020 and 5.69 $MtCO_2$ from private cars in 2025. Transport GHG emissions in Ireland in 2009 totalled 13.1 $MtCO_2$, accounting for 29% of GHG emissions from non-emissions trading sectors (non-ETS, comprising transport, services, agriculture, residential and some industry). This is pertinent to Ireland's obligation to reduce non-ETS emissions to 20% below 2005 levels by 2020, according to Decision 406/2009/EC of the European Parliament and of the Council. According to the Environmental Protection Agency (EPA, 2010), this equates to a maximum level of 37.4 $MtCO_2e$ in 2020 from non-ETS emissions in 2020. Under a baseline forecast, emissions are projected to reach 46.3 $MtCO_2$ in 2020, an overshoot of the target by 8.9 $MtCO_2$. While car emissions are modelled using a different methodology to that described here, this gives a useful indication of the scale of the challenge to meeting the target, which will require significant reductions from transport.

Two further EU targets are relevant to private car energy demand. Firstly, according to the EU Directive 2009/23/EC on Renewable Energy, each Member State is mandated to ensure 10% of transport energy (excluding aviation and marine transport) by 2020 comes from renewable sources. This may be met with biofuel mixing (currently at 3%) or through alternatively or flexi-fuelled vehicles. Secondly, EC regulation No. 443/2009 requires a cap on new-car emissions of 130 gCO_2/km on average by 2015, with a target of reaching 95 gCO_2/km by 2020. While the former target is already almost met due to the shift in purchasing between 2008 and 2010, the latter will affect the profile of new cars in the fleet in the future. This target is not incorporated into the baseline, as it has not yet been legislated for.

3.3. Uncertainty and sensitivity

While a forecast for energy demand is derived for private cars in this model, the number of uncertainties associated with long term forecasting, namely the price of fuels, behaviour and technology availability, makes this forecast unreliable. This forecast is more accurately described as a baseline scenario, designed to compare alternative futures based on policy measures. This section approaches some of the uncertainties in the model.

Firstly, a rebound effect is endogenously modelled. The baseline model determines activity as a function of the cost of travel in €/km, as opposed to the cost of fuel (€/MJ or €/L). The increased efficiency of new cars between 2008 and 2010 brings down the cost of travel, and so increases the activity and hence the energy demand. The rebound effect is the relationship between the increase in energy demand due to an activity rebound and the increase in efficiency. The model has a feedback loop, where activity is related to the efficiency of the stock via the cost per kilometre of driving. The rebounded energy is calculated directly by performing a model run removing this feedback. Table 7 and Fig. 9 show the energy demand of the baseline ("with rebound") along with the effect of removing the activity response to efficiency ("without rebound"). The rebound effect is the quotient of the energy increase and the efficiency increase—38% in 2025. It should be noted that the effect of rebound is sensitive to the figure of price elasticity used. The rebound effect calculated here is on the high end of a review gathered by Sorrell et al. (2009); a range of long-run rebound effects between 6% and 40% were found.

Secondly, a sensitivity analysis of the model, examining the effect on energy by adjusting important parameters by $\pm$10%, is shown in Table 8. Most notable is the on-road factor, which as a direct multiplier of energy, gives a direct 10% effect. Other than

Table 7
Effect of rebound.

	2015	2020	2025
A: Energy—PJ (baseline)	84	85	87
B: Energy—PJ (without rebound)	82	82	82
C: Energy increase = A/B − 1 (%)	2.1	3.7	5.3
D: Efficiency improvement compared to 2008 (%)	5.2	10.3	14
E: Rebound effect = C/D (%)	41	36	38

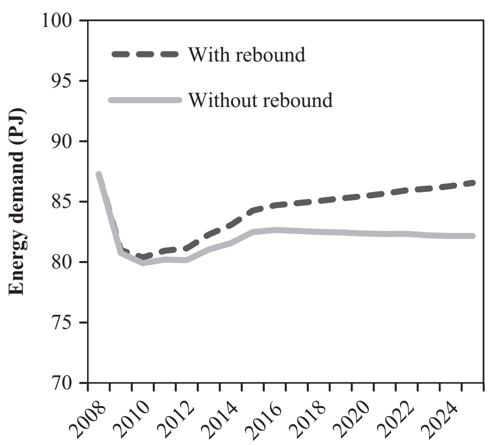

Fig. 9. Baseline energy demand with and without a rebound effect.

Table 8
Effect on 2025 energy demand of varying parameters by ±10%.

Effect on 2025 energy demand by varying:	+10%	−10%
1. Income sales elasticity (%)	0.00	0.00
2. Income act elasticity (%)	0.74	−0.74
3. Income engine size (%)	0.16	−0.16
4. Price sales (%)	0.00	0.00
5. Price activity (%)	0.00	0.00
6. GNP growth per year (%)	0.91	−1.81
7. Fuel price per year (%)	−0.01	0.01
8. On-road factor (%)	10.00	−10.00
9. Ageing factor (%)	0.22	−0.22
10. Survival rate per year[a] (%)	0.00	0.00
11. Activity vintaging (%)	−0.10	0.10

[a] 1% added/subtracted from each year of survival profile.

that, income growth and the income activity elasticity are most significant. This shows how sensitive this model is to the macroeconomic assumptions used.

The on-road factor was derived for 2005 and is based on a household budget survey, itself an uncertainty. As a direct multiplier however, it effects each scenario in the same way and also does not alter the trends in consumption. It would be of great benefit to study this parameter, which incorporates the non-technological aspects of fuel demand – driving style, road conditions, traffic – but individual studies on individuals' driving would be needed.

Another significant parameter is the scrappage and import profiles, which are static and based on 2000–2008 stock data; how these change in relation to economy and the second hand car market should be examined. Further work may integrate the impact of "soft" travel measures – ride sharing, e-working, public travel investment – on the activity profile. A final uncertainty is technology in the future. The Irish Government has made a commitment that 10% of vehicles are to be electrified by 2020, and if the 10% RES-T target is to be met, cars consuming renewables will need to be introduced. These eventualities are deferred to further scenario analysis.

This model does not take the distribution of vehicle activity between urban and non-urban roads: Efficiency is calculated in the European Test Cycle for both types of driving, but we use a "combined" cycle fuel intensity factor, as the data is not sufficiently disaggregated for Ireland to be of use. This may cause some biases in the model, since the Irish share of urban driving is not used for this combined factor, and changing demographics may change this in the future. Larger engines and diesel cars tend to be bought for driving longer distances for highway and rural driving, while small and lighter petrol cars tend to be bought for urban driving. As energy intensity per kilometre is higher for the urban cycle due to stop–start driving, it is likely that petrol fuel demand is underrepresented and diesel overrepresented in our results. In the analysis of policies encouraging modal shift, this bias may be of particular importance, as urban commuting is more straightforward to address via public transport.

Finally, vehicle stock and total activity are estimated separately using a turnover model and an econometric model, respectively. This would indicate that the implied forecast for average car mileage could serve as an indication as to the consistency of both models. An unexpected shape for mileage can indicate that either the activity or stock models need to be revised. Baseline results from this study show an average mileage decline of 0.5% per annum, which is greater than but roughly consistent with the average 0.3% per annum decline between 2000 and 2008, implying that both models are consistent with each other.

4. Discussion

This paper has developed a bottom-up car stock model for projecting baseline future private car energy demand. It takes the premise that total vehicle activity is a function of economic activity and factors largely external to the technological composition of the car stock, and is thus exogenously derived from historically derived elasticities and future projections of economic growth. Going beyond econometric modelling, a stock model is built, in which the composition of the fleet in terms of the technology and age of cars, as well as the profile of activity across different types of cars, has a large role in determining future energy demand. This model readily allows scenario analysis based on possible measures influencing these variables, such as tax incentives, scrappage schemes and the introduction of alternatively fuelled vehicles, and many policy scenarios can only be modelled using such a bottom-up approach.

This paper presents baseline results for the car stock and energy demand for Ireland up to 2025. As well as indicating energy demand and emissions under a "no new policy" scenario, the baseline provides insights into the likely demand drivers in the future, namely activity growth. An analysis of recent changes in new car purchasing attributable to a scrappage scheme and tax change is also included: while not a definitive analysis of these policies, Fig. 8 indicated that the model calculates a 9% saving in energy due to this purchasing shift by 2025. A rebound effect from the increase in efficiency is also calculated, finding that up to 40% of the savings from efficiency improvements are lost in rebounded activity. Finally, a discussion on the implications of these results for meeting 2020 EU climate targets is included in Section 3.2. As with all models of the future, the baseline energy demand is highly dependent on economic forecasts and other assumptions, and caveats have been outlined in Section 3.3.

In some senses, this is a good news story for car energy demand in Ireland. What had grown at a fast rate of 4.5% between 2000 and 2008 is forecast in this model to decline to a 0.2%

growth. While this is in part attributable to a lower activity caused by a downturn in the economy and pessimistic recovery, the declining energy intensity of the stock as a result in the step change in the purchasing pattern between 2008 and 2010, which, while taking place in a recession, is largely attributable to a change in taxation incentivising lower emitting cars. Rebound of 5% due to this change is however an important factor.

A strict EU target on non-ETS emissions for Ireland will have to guide how private car energy plays out in the future. In this baseline, 2020 car emissions are forecast to be 2% above those in 2005, while a reduction of 20% is required across all non-ETS sectors. If transport is to contribute its share of reductions, a combination of technological and behavioural modifications will be required from private cars. The EU new-car emissions goal of 95 gCO_2/km for 2020 may contribute towards this, as may the 10% renewable energy in transport target.

Bottom-up modelling of Irish energy demand has been identified as an area to develop for improving the evidence base for policy decision-making (Hull et al., 2009; Walker et al., 2009), and these models are imperative for the design and evaluation of effective and cost-effecting policies (Mundaca et al., 2010). Against a backdrop of rapid changes in policies, taxation and technology options, this demographic stock model is a tool for developing and evaluating measures for decarbonising transport.

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