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Title	Transport energy demand: techno-economic modelling and scenarios for Irish climate policy
Authors	Daly, Hannah E.
Publication date	2012
Original Citation	Daly, H. E. 2012. Transport energy demand: techno-economic modelling and scenarios for Irish climate policy. PhD Thesis, University College Cork.
Type of publication	Doctoral thesis
Link to publisher's version	http://library.ucc.ie/record=b2075085
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Download date	2026-11-05 12:41:20
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Transport Energy Demand: Techno-Economic Modelling and Scenarios for Irish Climate Policy

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Thesis submitted for the degree of Doctor of Philosophy

October 2012

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I, Hannah Daly, certify that this thesis is my own work and I have not obtained a degree in this university or elsewhere on the basis of the work submitted in this thesis.

Hannah Daly

Acknowledgements

I am very fortunate to have benefited from the supervision of Dr. Brian Ó Gallachóir and would like to express huge gratitude for his mentorship, which made these three years an interesting, fruitful and enjoyable time, and for his advocacy of my research and for energy policy modelling research in Ireland.

I also am grateful to have been part of the Energy Policy and Modelling Group in UCC and would like to warmly thank my fellow EPMG PhD students – Caiman Cahill, Fionn Rogan, Denis Dineen, Paul Deane, James Glynn, Aoife Foley and Alessandro Chiodi, as well as others in the ERI – for the support, cakes and distractions. I learned a lot from the group, particularly from Maurizio Gargiulo, who I thank especially for giving guidance on the TIMES model.

For the productive and interesting collaborations, I thank Kieran Whyte, Gregg Patrick, Stephan Leinert, Sonia Yeh, Kalai Ramea, Patrick Calnan, along with the above mentioned colleagues in UCC.

Several anonymous referees spent their time giving genuinely thoughtful and useful feedback on journal papers, which I appreciate.

This research would not have been possible without good national data and expertise, and in this I would like to acknowledge the support provided by the Environmental Protection Agency, the Sustainable Energy Authority of Ireland (particularly the Energy Policy Statistical Support Unit), the National Roads Authority, the Department of Transport and the Central Statistics Office. I would particularly like to acknowledge the following individuals: Mairead Griffin, Martin Howley, Emer Dennehy, Neil Cammish, Patrick Callanan, Jim Scheer and Ken Jordan.

I am grateful to the Irish Research Council for the scholarship which supported this doctoral research, and to all at the Environmental Research Institute for providing good research facilities.

On a personal level, I owe an enormous amount to my parents. Mom and Tom, thank you so much for your constant loving support in everything I do, and for being such inspiring people.

Finally, great love and thanks to Mirek: Happiness is only real when it's shared.

Executive Summary

The case for energy policy modelling is strong in Ireland, where stringent EU climate targets are projected to be overshot by 2015. Policy targets aiming to deliver greenhouse gas and renewable energy targets have been made, but it is unclear what savings are to be achieved and from which sectors. Concurrently, the growth of personal mobility has caused an astonishing increase in CO_2 emissions from private cars in Ireland, a 37% rise between 2000 and 2008, and while there have been improvements in the efficiency of car technology, there was no decrease in the energy intensity of the car fleet in the same period. This thesis increases the capacity for evidenced-based policymaking in Ireland by developing techno-economic transport energy models and using them to analyse historical trends and to project possible future scenarios.

A central focus of this thesis is to understand the effect of the car fleet's evolving technical characteristics on energy demand. A car stock model is developed to analyse this question from three angles: Firstly, analysis of car registration and activity data between 2000 and 2008 examines the trends which brought about the surge in energy demand. Secondly, the car stock is modelled into the future and is used to populate a baseline "no new policy" scenario, looking at the impact of recent (2008-2011) policy and purchasing developments on projected energy demand and emissions. Thirdly, a range of technology efficiency, fuel switching and behavioural scenarios are developed up to 2025 in order to indicate the emissions abatement and renewable energy penetration potential from alternative policy packages. In particular, an ambitious car fleet electrification target for Ireland is examined.

The car stock model's functionality is extended by linking it with other models: LEAP-Ireland, a bottom-up energy demand model for all energy sectors in the country; Irish TIMES, a linear optimisation energy system model; and COPERT, a pollution model. The methodology is also adapted to analyse trends in freight energy demand in a similar way.

Finally, this thesis addresses the gap in the representation of travel behaviour in linear energy systems models. A novel methodology is developed and case studies for Ireland and California are presented using the TIMES model.

Units and abbreviations

AFV	Alternatively fuelled vehicles
BAU	Business as usual
BKT	Bus kilometres travelled
cc	Cylinder capacity
CKT	Car kilometres travelled
CNGV	Compressed natural gas vehicle
CO_2	Carbon dioxide
CSO	Central Statistics Office
E4	4% mixture of ethanol
E4	Energy/Engineering/Economy/Environment
EPA	Environmental Protection Agency
ESRI	Economic and Social Research Institute
ETS	Emissions trading scheme
ETSAP	Energy Technology Systems Analysis Programme
EU	European Union
EV	Electric vehicles
GDP	Gross domestic product
GVA	Gross value added
HGV	Heavy goods vehicle
IA	Integrated assessment
ICE	Internal combustion engine
IEA	International Energy Agency
ktonnes	Kilotonnes
kWh	Kilowatt hour
LEAP	Long-range energy alternatives planning system
LF	Loading factor
LGV	Light goods vehicles
mhs	Million hours
MJ	Megajoules
MNL	Multinomial logistic
Mt	Megatonnes

NCT	National car test
NEC	National emission ceiling
NEEAP	National energy efficiency action plan
NETS	Non-Emissions trading scheme
NOx	Mono-nitrogen oxides
OM	Operation and maintenance
OMSP	Open market selling price
ORF	On-road factor
PJ	Petajoules
PKT	Passenger kilometres travelled
RES	Reference energy system
RES-T	Renewable energy in transport
SEAI	Sustainable Energy Authority of Ireland
SEC	Specific energy consumption
SFC	Specific fuel consumption
SV model	Schafer-Victor model
TIMES	The Integrated MARKAL/EFOM System
tkm	Tonne-Kilometre
TKT	Train kilometres travelled
TTB	Travel time budget
TTBmot	Motorised travel time budget
TTI	Travel time investment
vkm	Vehicle kilometres
VKT	Vehicle kilometres travelled
VRT	Vehicle registration tax
VRU	Vehicle registration unit

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Chapter 0

Introduction

0.1 Background

Climate change poses a grave threat to humans on Earth. The current rate of temperature rise as a result of greenhouse gas emissions is causing hotter summers and more unpredictable severe weather events, water shortages, lower agricultural output and sea level rise. Aside from the catastrophic economic impact this is expected to have globally, climate change is causing a crisis of the environment and a crisis of justice: Habitat destruction is leading to a mass extinction of species, and the poorest and most vulnerable inhabitants of the planet are expected to be effected the worst (IPCC 2007).

Global emissions need to be cut by 50% by 2050 to ensure a good chance of temperatures increasing no more than 2 degrees above pre-industrial levels (CCC 2008). Assuming nine billion inhabitants and a fair distribution of emissions per person, this implies an annual carbon budget of 2.5 tonnes of CO_2 per person. In Ireland, where nearly one and a half times this budget is emitted per person from transport alone, this target for Ireland implies an 82% cut in emissions by 2050 (King 2011).

Despite developments in technology and the prevalence of greenhouse gas reduction targets, energy demand and associated emissions from transport continue to rise, and the sector's disproportionately large oil dependence persists (94% in 2007 (Howley, Ó Gallachóir & Dennehy 2009)). In Ireland, there has been an exceptional increase in transport energy demand relative to other EU Member States, both in absolute terms and as a proportion of overall energy consumption. Transport in 2008 accounted for 43% of overall final energy demand, an increase of 277% on 1990 demand. Irish per-capita emissions for transport are now the highest in Europe at 3.2 tonnes of CO_2, coming from one of the lowest positions in 1990 (Howley, Dennehy & Ó Gallachóir 2009).

Private cars are the most significant mode in terms of energy consumption in transport, and many measures for tackling the sustainability of transport focus on improving the energy efficiency of the private car fleet. Furthermore, there are nearly one billion cars on the planet, which use almost half of the oil produced annually. Transport's huge dependence on fossil oil leaves the economy very vulnerable to

price shocks as a result of scarcity or political volatility – implications for energy security and cost competitiveness are strong incentives for improving the sustainability of car fleets and mobility in general.

Ireland has a number of medium term obligations for 2020 which will have to guide how private car energy plays out in future. These obligations include a reduction of non-emissions traded GHG emissions by 20% based on 2005 levels by 2020, approximately a third of which are accounted for by transport. Approximately half are emitted by agriculture, a sector which is known to be very difficult to decarbonise. This target is projected to be exceeded by 2015. A second obligation is a commitment that 10% of terrestrial transport energy demand comes from renewables by 2020; without a large penetration of biofuels in the coming eight years, this target is unlikely to be met.

There is ample scope in Ireland for improving energy modelling tools. Energy forecasts are currently generated using aggregate, top-down models, which determine total energy consumption on the basis of economic forecasts. 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, 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 130g CO_2/km by 2015.

Basing potentially expensive, technologically-oriented policy measures on sound, fact-based analysis is very important for governments facing economic and climate constraints, and this thesis addresses these issues in a quantitative manner, improving the knowledge-base and modelling capacity underpinning policy decision making in Ireland.

0.2 Aims

This thesis sets out to address the following questions:

1. How can we improve the quantification of energy demand and detection of trends from transport in Ireland?
2. What were the technological parameters that contributed to a dramatic rise in transport energy demand in the past?
3. What policy interventions have been successful in reducing emissions in the past, and what were the unintended negative consequences arising from these?
4. What model will best project these trends to examine a future in which they continue?
5. What will be the relative impact of different policy interventions and targets on meeting Ireland's climate goals?
6. How can transport techno-economic models be improved, particularly by integrating with broader energy demand models and soft-linking with other model types?

7. How can we improve the representation of behaviour and modal choice within technological models, and how important is travel behaviour compared with technology improvement in mitigating for climate change?

The following section summarises the thesis and describes where each aim is addressed.

0.3 Thesis in brief

- Part I: A car stock model used to analyse historical energy demand in Ireland (2000 – 2008) and developed into a simulation of the vehicle fleet, which is used to make a baseline projection of private car energy demand and examine future scenarios (2008 – 2030).
  - Chapter 1: *Aims 1 and 2*. An analysis of historic private car energy demand in Ireland using techno-economic modelling. The explanatory variables of fleet structure, the profile of activity, and fleet efficiency. Variables are disaggregated by vehicle technology and age to give a detailed bottom-up picture of energy demand and trends leading to a 37% rise in energy demand over the period 2000 – 2008.
  - Chapter 2: *Aims 3 and 4*. A baseline car stock and activity model for Ireland to 2025 using historical parameters, taking into account the lifetime survival profile of different car types, the trends in car activity over the fleet profile, economic projections and income and price elasticities of new car sales and activity. This chapter focuses on the methodology and baseline scenario, and contains an ex-post analysis of the impact of car tax reform and of a rebound effect.
  - Chapter 3: *Aim 5*. The car stock model from Chapter 2 is used to simulate the impact of a range of policy measures on the baseline trend in energy demand in the period to 2030. Measures include the deployment targets of a large number of electric vehicles and compressed natural gas vehicles for 2020, an EU regulation for the improvement of vehicle efficiency, as well as several behavioural measures. The impact of measures is quantified in terms of their contribution to meeting Ireland's climate and renewable energy obligations for 2020.
- Part II: Two broader energy demand models for Ireland were created: LEAP Ireland and the Irish TIMES model. The car stock model from Part I contributes to each in different ways, and a simple TIMES model which includes a novel methodology for representing modal choice behaviour is described.
  - Chapter 4: *Aims 5, 6 and 7*. A bottom-up baseline energy demand model for Ireland is built by UCC's Energy Policy and Modelling Group to contribute to Ireland's 2010 energy forecast report. This Chapter introduces the model and results broadly, and describes in detail the methodology behind passenger and freight transport energy demand in the model. Scenarios for EV deployment and for energy efficiency policies across the sectors highlight the use of the tool.

  - Chapter 5: *Aims 4 and 6*. Compares different approaches to projecting private car energy demand using two techno-economic models developed for Ireland, the car stock model, described in Part I, and passenger transport within the Irish TIMES model, a least-cost linear optimisation framework. The models are complementary, and inputs of each are informed by outputs from the other.
  - Chapter 6: *Aim 7*. Addresses the poor representation of modal switching behaviour within TIMES and other techno-economic optimisation models. Introduces a novel modelling approach based on travel time budgets to represent modal switching in such a model for the first time. Results show the significance of modal switching in a climate mitigation scenario.
- Part III: Collaborations leading from the core work of the thesis lead to two papers analysing different aspects of transport energy demand.
  - Chapter 7: *Aims 3 and 6*. The current focus of policy on climate change has diverted attention from air pollution. This chapter looks at the unintended consequences of a car taxation change in 2008 with regard to NOx emissions because of a fuel switching effect towards diesel.
  - Chapter 8: *Aims 1 and 2*. The economic boom and property construction bubble in Ireland between 1990 and 2007 caused an unprecedented rise in freight energy demand, followed by a dramatic drop between 2008 and 2011. This chapter applies some of the methodologies developed for private cars in Part I to heavy goods vehicles' energy demand and looks in detail at the impact of building activity on freight energy demand.
- Chapter 9 concludes, discussing the policy and modelling recommendations arising from this research.

0.4 Methodology

Researchers interested in mitigating the effects of transport on climate are asking: What is achievable from technology, from behaviour and from city design? This thesis looks in detail at the first of these areas and tries to grapple with how we should represent behaviour in technologically oriented modelling studies. In order to increase the evidence base for policy making with respect to private car transport, robust energy modelling tools are required to understand the interplay between the different factors affecting private car energy trends. The contributions of the factors influencing transport energy demand need to be understood before any level of fuel reduction can be achieved. Among these key drivers is technological efficiency. We need to know for example, how the technological structure of the car fleet and, furthermore, the mileage profile influence final energy demand.

0.4.1 Techno-economic modelling

Energy modelling tools are generally broken into two categories: "Top-down" models, which are typically based on macro-economic social accounting matrices and can take into account the impact of global economic interactions, and "bottom-up"

models, which can describe in greater detail the expected impact of changes in technology or input costs on particular energy demands. 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.

The modelling methodology employed in this thesis is largely bottom-up: The impacts of many policy alternatives may only be simulated by such an 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, and helps to project the future trends of energy demand in depth.

Several studies review different approaches to techno-economic models: Mundaca et al. (2010) use the household sector as a case study, and Schafer (2012) describes a range of transport energy models. Both studies highlight the difference between *simulation* and *optimization* modelling approaches: The former type of model produces a descriptive illustration of energy production and/or consumption, based on exogenously determined scenarios, and generally aims to replicate historical decision-making and technology behaviour, and not determine an optimal path. Optimisation models, on the other hand, are prescriptive, generating an optimal future, such as a least-cost energy system, given constraints. Both modelling methods are used in this thesis, and Chapter 5 compares the two approaches for modelling private car energy demand in Ireland.

The simultaneous consideration of macroeconomic impacts and specific technology detail is a desirable goal of energy analysts, but a trade-off always exists between technological detail and the representation of the economy. Different models address different questions. To study technology-specific questions, we develop models which explicitly represent many types of transport technologies and characterises their activity, efficiency and stock. This level of detail necessitates a weaker representation of economic feedback – transport service demand is exogenous in these models, and there is no equilibrium achieved between demand and fuel price.

0.4.2 Future projections and scenario analysis

It is impossible to make long-term projections with any degree of certainty; indeed, even short term macroeconomic models in 2008 did not foresee the economic downturn, and subsequent forecasts predicted a faster recovery than reality (Bergin et al. 2009, 2010). Looking back prior to the 1973 oil shock, energy scarcity and climate change were not on agenda, and the oil crises had not yet created such a concern over energy dependence and volatile energy markets: It is impossible to predict such unexpected global events which could occur in the next 40 years.

Notwithstanding the uncertain future, it is important to think through energy futures in order to seek to bring about change and plan to meet desirable and agreed goals. Scenario analysis is a process of analysing possible future events by considering alternative possible outcomes. We do not try to show one exact picture of the future, but present several alternative future developments based around specific changes in parameters. Energy modellers generally present a "baseline" or "reference" scenario, which is not a projection per se, in that we do not state with any confidence that this

scenario will actually occur or how likely it is to occur, but is consistent with macroeconomic forecasts and extrapolates historical trends. This creates a rational and transparent starting point with which to compare alternative scenarios.

Scenario and futures analysis is a commonly used to analyse possible future events, giving a scope of possible consequences based on uncertainties. Among the most significant for energy related scenario analysis is the Energy Technology Perspectives, published by the International Energy Agency, which analyses scenarios that look at energy demand, supply and CO_2 emissions to 2050.

In this thesis, alternative scenarios are generated by varying technology or behavioural parameters from the baseline assumptions, deviations which are assumed to occur as a result of a policy intervention (stimulating the sales of electric vehicles, for example) or technology breakthroughs. Techno-economic modelling lends itself well to creating scenarios based on alternative technological futures.

Of all aspects of the energy system, transport probably has the most wide-reaching societal impacts. The nature of transport systems and policies reaches into every person's everyday environment, and much of the transport sector features negative externalities which are not included in price, for example time lost to commuting, traffic noise, pollution and deaths and injuries from road traffic collisions. Because of the complexities of transport impacts, quantitative modelling research such as that described here tends to focus largely on technological 'fixes' and ignored behavioural effects or societal impacts.

We address this shortcoming in several ways: In Chapter 3 we compare the impact of technological measures with travel demand reductions and eco-driving; in the LEAP model in Chapter 4 we extend this to include modal shifting. Finally, Chapter 6 makes a significant step towards representing modal shift in the linear model TIMES, which puts behavioural change in competition with technological measures for achieving climate change mitigation targets.

0.5 Role in collaborations

While a large majority of this thesis is solely my own work, collaboration was an important and valuable aspect of this research. The core model presented in Part I contributed to several interesting studies and journal papers which were led by colleagues, but in which I played a role. Parts II and III of the thesis contain a selection of these collaborations to which I made a significant contribution. This section specifies the extent of my contribution to these chapters. A full list of my collaborations and publications is contained in section 0.6.

Manuscript suggestions and feedback was provided by Dr. Brian Ó Gallachóir on all aspects of this thesis.

Part I is a collection of three journal papers (two published, one in press, chapters 1–3) whose content was researched and written by me.

Chapter 4 is based on a collaborative research project with UCC's Energy Policy and Modelling Group. Sections 4.1 and 4.2 are summaries of a report and paper in

preparation (Rogan et al. 2012), while sections 4.3 and 4.4 are my own work, except for the modelling of HGV energy demand.

Chapter 5 is solely my own work, but uses outputs from the Irish TIMES project.

Chapter 6 is based on a collaborative paper which was presented at a conference and is in preparation for submission to a journal. The research question was developed by me, I wrote, edited and prepared the majority of the manuscript for publication and I produced most results, figures and tables. Coauthors contributed to the development of the computer model, some data collection and writing/editing the paper.

Chapter 7 is a submitted journal paper of which I am the second and corresponding author. The study uses outputs from the car stock model, which I prepared for inputting into a pollution model. The lead author ran the main model, outputted data and wrote the initial paper draft. I wrote large parts of the introduction and conclusion and sections 7.5 and 7.2.3, and I prepared the text and figures for publication.

Chapters 8 is also a journal paper in review of which I am the second and corresponding author. The paper is based on a minor thesis completed by Kieran Whyte for an MEng in Sustainable Energy in 2011. I contributed to developing the econometric forecasting methodology, which links different commodity groups to different economic drivers (section 8.3). I redrafted large parts of the paper and wrote a literature review (section 8.1) and the discussion in section 8.5. I prepared the paper and figures for publication. I also presented the paper to an ESRI seminar, feedback from which contributed to the econometrics in the paper.

0.6 Thesis outputs

Journal papers

Daly, H.E. & Ó Gallachóir, B.P. (2011), 'Modelling private car energy demand using a technological car stock model', *Transportation Research Part D: Transport and Environment* 16(2), 93–101.

Daly, H.E. & Ó Gallachóir, B.P. (2011), 'Modelling future private car energy demand in Ireland', *Energy Policy* 39, 7815–7824.

Daly, H.E. & Ó Gallachóir, B.P. (2012), 'Future energy and emissions policy scenarios in Ireland for private car transport', *Energy Policy*, DOI:10.1016/j.enpol.2012.08.066

Daly, H.E., Ramea, K., Chiodi, A., Yeh, S., Gargiluo, M. & Ó Gallachóir, B.P. (2012) 'Modelling modal choice behaviour within a linear energy system model.' Submitted to *Energy* on September 20th 2012.

Rogan, F., Dennehy, E., **Daly, H.E.**, Howley, M. & Ó Gallachóir, B.P. (2011), 'Impacts of an emission based private car taxation policy - first year ex-post analysis', *Transportation Research Part A: Policy and Practice* 45(7), 583–597.

Whyte, K., **Daly, H.E.** & Ó Gallachóir, B.P. (2012), 'Modelling HGV freight transport energy demand in Ireland and the impacts of the property construction bubble', *Energy*, In review, submitted on June 6th 2012.

Leinert, S., **Daly, H.E.**, Hyde, B. & Ó Gallachóir, B.P. (2012), 'Co-benefits? Not always. Quantifying the negative effect of a CO_2-reducing car taxation policy on NOx emissions', *Transportation Research Part A: Policy and Practice*, In review, Submitted on July 26th, 2012.

Patrick, G., Dineen, D., **Daly, H.E.** & Ó Gallachóir, B.P. (2012), 'Improved Modelling of Aviation Energy Use and CO_2 Emissions'. In preparation.

Rogan, F, Cahill, C.J., **Daly, H.E.**, Deane, J.P., Dineen, D., Heaps, C. & Ó Gallachóir, B.P., (2012), 'LEAPs and Bounds – A Hybrid Energy Demand and Constraint Optimization Model of the Irish Energy System'. In preparation.

Conference and workshop papers and presentations

Daly, H.E., Ramea, K., Chiodi, A., Yeh, S., Gargiluo, M. & Ó Gallachóir, B.P. (2012) 'Modelling Transport Modal Choice and Its Impacts on Climate Mitigation.' *31st International Energy Workshop*, June 19 – 21st 2012, Cape Town, South Africa.

Daly, H.E. & Ó Gallachóir, B.P., (2011). 'Private car energy modelling: Comparing two techno-economic approaches for Ireland.' Poster, *eceee Summer School*, June 6th – 10th 2011.

Daly, H.E., Gargiulo, M, & Ó Gallachóir, B.P., (2011). 'An integrated energy systems and stock modelling approach for modelling future private car energy demand.' *International Energy Agency ETSAP meeting*, July 9th 2011, Stanford, USA.

Daly, H.E. & Ó Gallachóir, B.P., (2010). 'Forecasting Private Car Energy Demand Using Bottom-Up Car Stock Modelling.' *Young Energy Economy Engineer Seminar*. November 26th – 27th, TCD, Dublin, Ireland

Daly, H.E. & Ó Gallachóir, B.P., (2010). 'Private Car Transport and the 10% RES-T Target - Quantifying the Contribution of EVs and Biofuels.' *Irish Transport Research Network*, September 1st 2010. University College Dublin, Ireland.

Daly, H.E. & Ó Gallachóir, B.P., (2010). 'Assessing energy and GHG impacts of the car scrappage scheme in Ireland.' *Environ 2010: 20th Irish Environmental Researchers' Colloquium.* February 20th 2010, Limerick Institute of Technology, Ireland.

Daly, H.E. & Ó Gallachóir, B.P. (2010). 'Evaluating the Impact of Energy Efficiency and CO_2 Emissions Measures on Private Car Transport Using a Stock Model.' *International Energy Program Evaluation Conference.* June 8th - 10th 2010, Paris, France.

Foley, A., **Daly, H.E.**, McKeogh, E. & Ó Gallachóir, B.P. (2010), 'Quantifying the energy and carbon emission implications of 10% electric vehicle target'. *29th International Energy Workshop*, June 2010. Stockholm, Sweeden.

Invited talks

Daly, H.E., Chiodi, A. & Ó Gallachóir, B.P. (2012) 'Transport – Technologies and Policies. What Can Be Achieved From Cars?' *UCD NESC Workshop on GHG Reductions.* June 11th 2012, Dublin, Ireland.

Whyte, K., **Daly, H.E.** & Ó Gallachóir, B.P. (2012). 'Modelling Freight Transport Energy Demand in Ireland and the Impacts of the Property Construction Bubble', *ESRI UCC Energy Modelling Research Seminar: Informing Policy, Economic and Engineering Perspectives*, June 11th 2012, the Economic and Social Research Institute, Dublin, Ireland.

Daly, H.E. & Ó Gallachóir, B.P. (2011) 'Irish Car Energy Demand: Future Scenarios', *DIT Energy and Emissions Seminar*. April 8th 2011, the Dublin Institute of Technology, Dublin, Ireland.

Reports

Daly, H.E., Dineen, D., Rogan, F., Cahill, C. (2011) 'Bottom-Up Energy Demand Modelling - LEAP Ireland.' In *Energy Forecasts for Ireland to 2020, 2010 Report*, Sustainable Energy Authority of Ireland, Dublin

Daly, H.E., Ramea, K., Chiodi, A., Yeh, S., Gargiluo, M. & Ó Gallachóir, B.P. (2012) 'Modal choice in a TIMES model'. Report submitted to IEA-ETSAP, May 2012.

Daly, H.E., Chiodi, A. & Ó Gallachóir, B.P. (2012) 'Transport – Technologies and Policies. What Can Be Achieved From Cars?'. Submission to National Economic and Social Council, June 2012.

Part I

Irish Car Stock Model, 2000 – 2030

Chapter 1

Modelling Private Car Energy Demand Using a Technological Car Stock Model

Abstract

A technological stock model of private car energy demand is built, using as explanatory variables, fleet structure, the profile of activity, and fleet efficiency. Disaggregating the three variables by vehicle technology and age produces a detailed profile of private car activity and energy consumption, giving accurate energy calculations and allowing detection of the technological drivers of energy consumption. Methods for calculating fleet on-road energy efficiency in terms of an "on-road factor" are developed. The methodology is applied in an Irish case study and results show a 37% increase in private car energy demand between 2000 and 2008, and that driving this increase was a growth in diesel and larger engine activity and the ageing of the fleet.[1]

Keywords: Private car; Stock model; Transport energy; CO_2 emissions

[1]Chapter published as Daly, H.E. & Ó Gallachóir, B.P. (2011), 'Modelling private car energy demand using a technological car stock model', *Transportation Research Part D: Transport and Environment* 16(2), 93–101.

1.1 Introduction

Accounting for 23% of global energy-related CO_2 emissions, the transport sector is increasingly the focus of policy measures aimed at addressing climate change and energy security concerns. The increase in transport CO_2 emissions is largely a result of increasing demand for individual mobility, in particular private car transport, already a key component of transport energy demand in developed countries. Private cars are a significant focus of energy efficiency and climate change policy, with a range of policy measures seeking to encourage modal shifts, technological improvements and behavioural change (Mandell 2009). Technological improvements have certainly been achieved by car manufacturers, which have lead to improved fuel economy of cars and in many countries this has improved the overall efficiency of private car fleets (Clerides & Zachariadis 2008). While the efficiency of individual car models has improved, this however does not always lead to an improvement in the efficiency of the overall car stock, for example, in the Netherlands (Van den Brink & Van Wee 2001) and Ireland (Ó Gallachóir et al. 2009), where purchasing trends towards larger and heavier cars offset the efficiency gains as a result of standards and taxes.

In order to increase the evidence base for policy making with respect to private car transport, robust energy modelling tools are required to understand the interplay between the different factors affecting private car energy trends. Analysis of energy trends with regard to changes in the characteristics of transportation as a whole have disaggregated the transportation system by mode, and used activity and efficiency factors for each mode to calculate energy consumption and trends, for example Scholl et al. (1996). Focussing on private car energy modelling, disaggregation of the car stock by age and technology has been used as an analytical tool in other studies, for example Van den Brink & Van Wee (2001), who modelled the age distribution of Dutch vehicle kilometres from bottom-up data and modelled the technological characteristics of the fleet from top-down methods to determine the changes in the car fleet efficiency.

This paper extends the bottom-up methodology employed by extending the disaggregation of vehicle kilometres to the efficiency of activity in terms of technology as well as age profile: a technological car stock model is build by disaggregating the private car fleet according to 'categories" defined by engine size, fuel type and car age. Then, a model of fleet activity is derived from the average number of kilometres driven by cars in each technological and age category. We also consider the calculation of on-road energy consumption, with an ageing factor applied to reflect vehicle vintage and an "on-road factor" to reflect the gap between actual and test vehicle efficiency.

This model is applied to Ireland covering the period 2000-2008, but the methodology may readily be applied to other countries provided similar data is available. The model is used to examine how trends in energy consumption of each vehicle type are influenced by activity and intensity and how they have contributed to overall private car transport energy trends. Finally the Irish car stock model is used to explore different metrics in portraying energy trends and to highlight the difference between weighting key variables by stock-average and by activity-average, resulting from differences in the mileage of each vehicle type.

1.2 Methodology

1.2.1 Technological stock model

Ireland's yearly vehicle licensing data from 2000 to 2008 is used to generate a technological stock profile by disaggregating the cars by fuel type, by engine size bands (0-900 cc, 901-1000 cc, etc.) and by vintage. Age, engine capacity and fuel type are strong determinants of a car's efficiency. The engine size profile of a fleet is an important technological parameter, as a car's cc is directly proportional to its power output. Specific fuel consumption then depends on the engine's efficiency, which depends on individual vehicle technology. Age is also influential: with average new-car energy intensity decreasing over time and with ageing cars' intensity increasing over their lifespan, a younger fleet with a higher turnover rate will be more efficient. Also, due to the different technologies behind diesel and petrol vehicles and the higher energy content of diesel, the fuel mix is an important parameter in the fleet's intensity.

The 2008 Irish stock profile is shown in Fig. 1.1 with engine sizes aggregated into larger bands. It should be noted that measuring the stock of in-use cars can be difficult because of the discrepancies that typically exist between the number of cars registered in a year, the number of cars taxed at any particular time, and the average number of cars in-use.

The Irish stock model is created from databases including the fuel type, engine capacity and year of manufacture of cars taxed for each year between 2000 and 2008. If data on the age profile of the fleet are not collected, it may be modelled using historical scrappage rates (Zachariadis et al. 2001). If the retirement rate of the fleet is known, the age profile of the fleet can be derived from sales data. Stock for year Y in technology type t is then

$$S_t = \sum_{k \leq Y} sales_{k,t}(1 - \phi_t(y - k)) \tag{1.1}$$

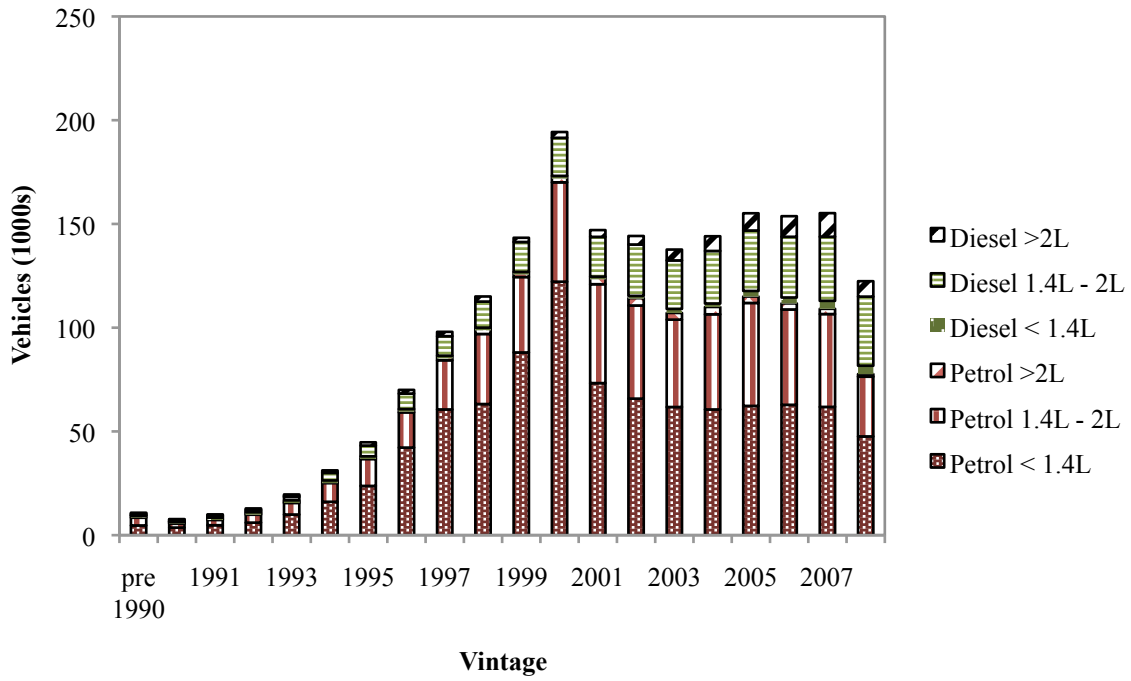


Figure 1.1: Ireland's 2008 fleet by engine type and vintage.

where $\phi_t(a)$ is the probability that cars of type t are scrapped by the time they are age a.

1.2.2 Activity profile

The model uses disaggregated mileage data to identify the average annual mileage of cars in each specific band. Studies have shown that cars in different classes display different mileage patterns: Kwon (2006) shows the greater average mileage of diesel cars over petrol cars in the UK due to greater efficiency; Zachariadis et al. (2001) shows the effect of age on mileage; and Van Wee et al. (2000) showed the decay of mileage over the lifetime of a car and the possible effects of scrappage schemes on this and resulting fleet energy consumption. Technological parameters not only effect final energy consumption through specific fuel consumption, but also through mileage, therefore there is a need to analyse trends of average mileage per class.

For Ireland's energy model, the annual average mileage of cars by each fuel type and engine capacity band was made available by the Sustainable Energy Authority of Ireland (SEAI) (Howley, Dennehy & Ó Gallachóir 2009). Calculations were based on the odometer readings from Ireland's National Car Test (NCT), which was introduced on 4th January 2000, using a process similar to that described in Kelly et al. (2009). Private cars are first tested under the NCT after 4 years and every 2 years thereafter.

To profile the distribution of activity of cars in a certain engine capacity band over the

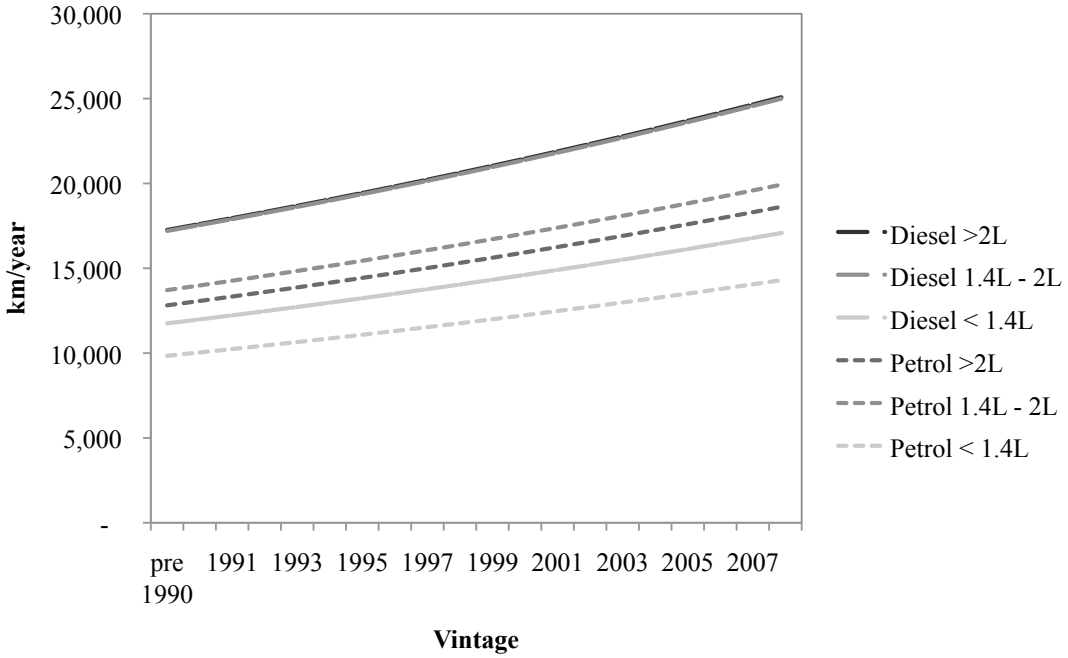


Figure 1.2: Mileage by vintage, fuel and engine capacity (2008).

vintage profile, a "mileage decay rate" is derived. Values for annual mileage of cars tested by the NCT between four and 8 years old indicate an approximate mileage decay rate of 2% per annum. Eq. 1.1 is used to model mileage according to car age within the engine capacity band assuming a 2% annual mileage decay rate:

$$M_{t,0,f} = \frac{m_{t,f} \times S_{t,f}}{\sum_y 0.98^y \times S_{t,y,f}} \tag{1.2}$$

$$M_{t,v,f} = 0.98 \times M_{t,v-1,f} \tag{1.3}$$

where, for technology t and fuel f, $M_{t,0,f}$ is the new-car mileage, $m_{t,f}$ is the annual average mileage of cars in that category (derived from the NCT tests), $M_{t,v,f}$ is the average mileage of cars of vintage v, $S_{t,f}$ is the total stock and $S_{t,v,f}$ is the stock of cars of vintage v. Fig. 1.2 graphs the values used for annual mileage of cars in 2008 by vintage and engine type.

1.2.3 Specific energy consumption

The model calculates the energy efficiency of the fleet over time to track improvements. The metric used is the weighted average specific energy consumption (SEC, in MJ/km) for cars in each class of the technological profile. Calculating this is not straightforward because of the number of variables affecting the SEC. To deal

with this the authors separate these factors into two sets within the model, those relating to the technical composition of the car and engine, and those relating to environmental/other factors and deal with them separately.

Firstly, we use aggregated new-car average energy efficiency values for each technological class for cars manufactured in each year 1990-2008. Each new-car model is associated with a *new-car specific fuel consumption* (SFC, typically expressed in l/100 km), measured by a legislative fuel consumption test under controlled conditions in a laboratory using standardised test procedures and driving cycles (Andre et al. 2006). For example, in the EU, all new cars on sale after 1 January 2000 have been required to take an official fuel consumption test described by EU Directive 93/116/EC (amended by 1999/100/EC) consisting of 'urban' and 'extra urban' driving cycles said to be representative of typical European driving patterns[2]. The energy required for a vehicle to drive in a set pattern is governed by factors such as the vehicle's weight, frontal area, shape and its engine efficiency, which is determined by many factors including the driver's gear changing behaviour, the engine age, fuel type and the cylinder capacity (cc).

We use values for the SFC of new cars of each engine type compiled by SEAI for each year between 2000 and 2008. This was achieved by SEAI by linking vehicle registration unit (VRU) data on the engine capacity and car model of each year's newly registered cars with the UK's Vehicle Certification Agency's database of official vehicle fuel consumption test results. SFC was then converted to SEC using the calorific content of petrol and diesel (34.9 MJ/l and 38.6 MJ/l respectively).

To calculate the SEC of new cars manufactured before 2000 we extrapolate figures in each band based on the average growth of new-car SEC in each band from 2000 to 2008. Fig. 1.3 shows the average new-car SEC for 1990-2008 used to calculate Ireland's private car energy consumption.

To reflect the decreasing fuel economy of a vehicle over time, we introduce an ageing factor. There is little published work analysing the effects of engine ageing on fuel consumption, with some notable exceptions such as Van den Brink & Van Wee (2001) who estimated that the effect of ageing decreased fuel economy (i.e., increased SFC) in cars by 0.3% annually. It is assumed that a vehicle's SEC is "aged" by 0.3% for each year in its lifetime.

New-car SEC is reflective of the general performance of a vehicle, holding non-technological features constant, and is intended for customers as an indicator of a car's likely fuel consumption for a given journey compared to other models. Fuel

[2]Results are compiled by the VCA in the UK, `http://www.vcacarfueldata.org.uk`. The US Environmental Protection Agency conducts similar SFC tests on cars using five driving cycles; city driving, highway driving, high speed, cold start and air conditioning on (`http://www.fueleconomy.gov/FEG/fe_test_schedules.shtml`.) Similar tests are prescribed in Australia and Japan.

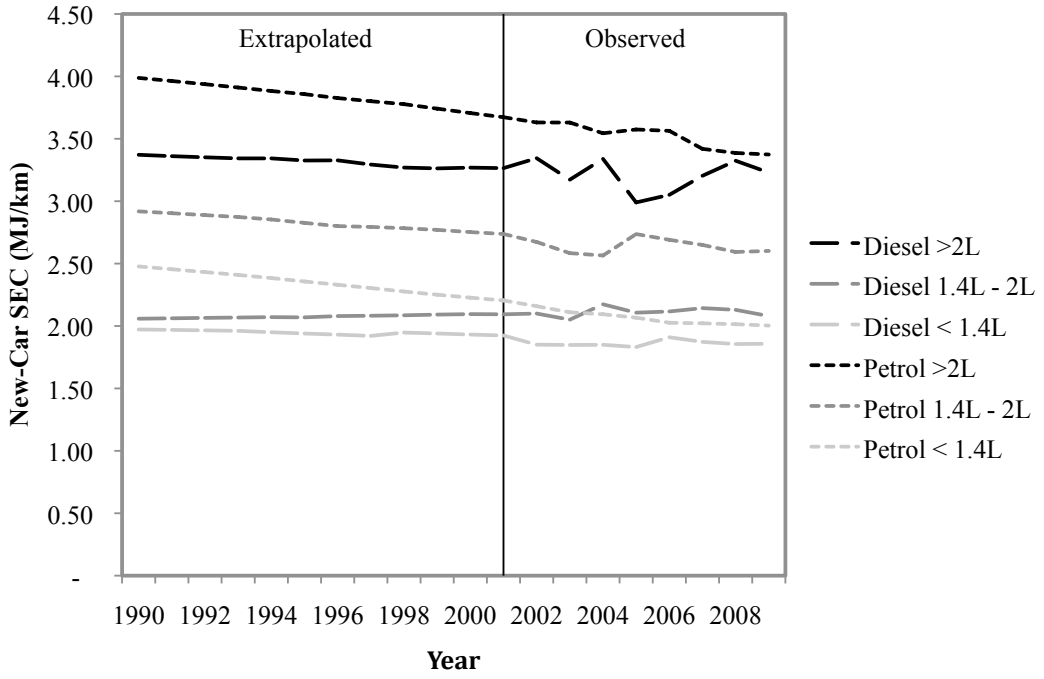


Figure 1.3: New-car specific energy consumption by engine type between 2000 and 2008 and extrapolated from 1990 from 1999.

consumption is also governed by traffic and road conditions, driver behaviour and other environmental conditions; because of this there is a well-documented gap between legislative test figures for fuel consumption and actual, on-road consumption (Kwon 2006), suggesting an underestimation of on-road SFC by legislative fuel tests at between 7% and 25%, depending on the region. The discrepancies caused by these 'other' factors are combined in this paper into an on-road factor, which varies annually by region and by fuel type, but here is estimated for one year and applied to all others. There are a number of ways of calculating this depending on the accuracy of available statistics.

Firstly, the national energy balance can serve as a top-down estimate of the on-road factor. This requires total transport fuel consumption in a given year to be disaggregated by transport mode with sufficiently accurate estimates of how much of this fuel is not used in private cars (taxis, freight vehicles, fuel tourism) and of how much fuel used in private cars is not bought at the pump (green diesel, fuel tourism). Comparing calculated bottom-up private car energy demand based on new SFC values (taking ageing into account) and mileage data with the energy balance estimate of private car energy consumption will indicate the 'on-road factor' on a year-by-year basis. This however is dependent on the accuracy of estimates of the fuel consumption of other transport modes.

A second method is the development of a driving cycle for each region or country (Casey et al. 2009, Tzirakis et al. 2007). This would require surveying typical driving

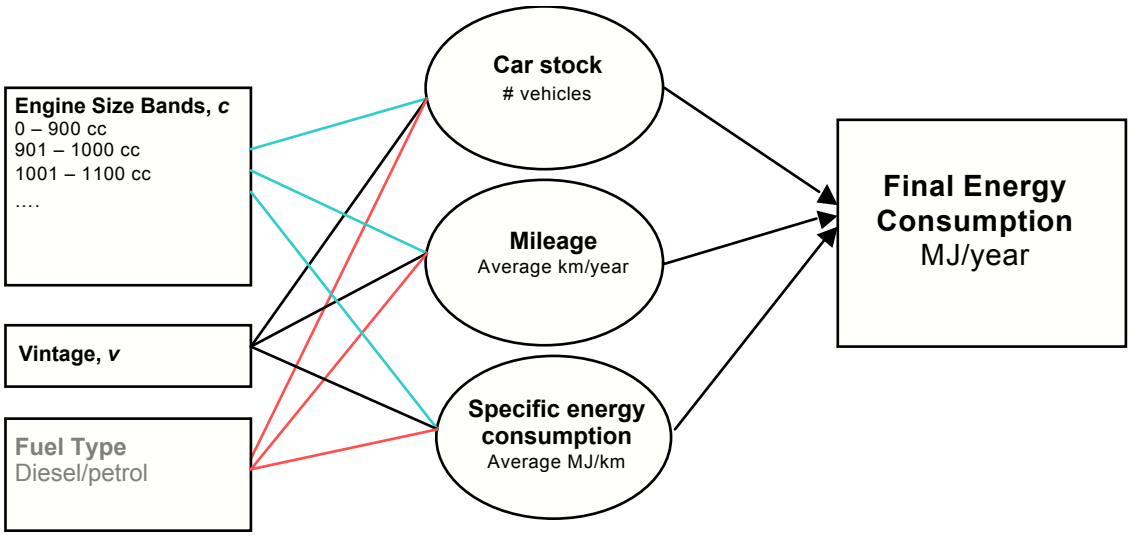


Figure 1.4: Private car energy consumption using disaggregated technological stock and specific energy consumption data.

conditions and behaviours in the region and testing a range of cars for fuel consumption using this driving cycle. The average difference between results for this regional driving cycle and legislative cycles for cars of the same type could then serve as an estimate of an on-road factor.

A final approach involves calculating the on-road factor using surveys. If a proportion of the population is surveyed on their mileage and on the amount of fuel they purchase in a given period, the discrepancy between the average on-road fuel use and what the estimated fuel use would be given their new-car SFC (taking ageing into account) can give an estimate for the on-road factor. The approach adopted for Ireland uses this method, taking results from a Household Budget Survey.

Multiplying the new-car SEC, the ageing factor and the on-road factor, the SEC of cars of fuel type f and engine technology type t of vintage v in year Y is then calculated to be

$$SEC_{t,v,f} = e_{t,v,f} \times (1.003)^{Y-v} \times ORF \tag{1.4}$$

where $e_{c,v,f}$ is the new-car SEC manufactured in year v ($Y - v$ is the age of the car) and ORF is the on-road factor, which may be defined by any engine type depending on its derivation.

1.2.4 Fleet energy demand and CO_2 emissions

Fig. 1.4 and Eq. 1.5 show how the model computes the annual energy demand[3]of the car fleet. For each year's car stock and resulting fuel consumption, this provides a

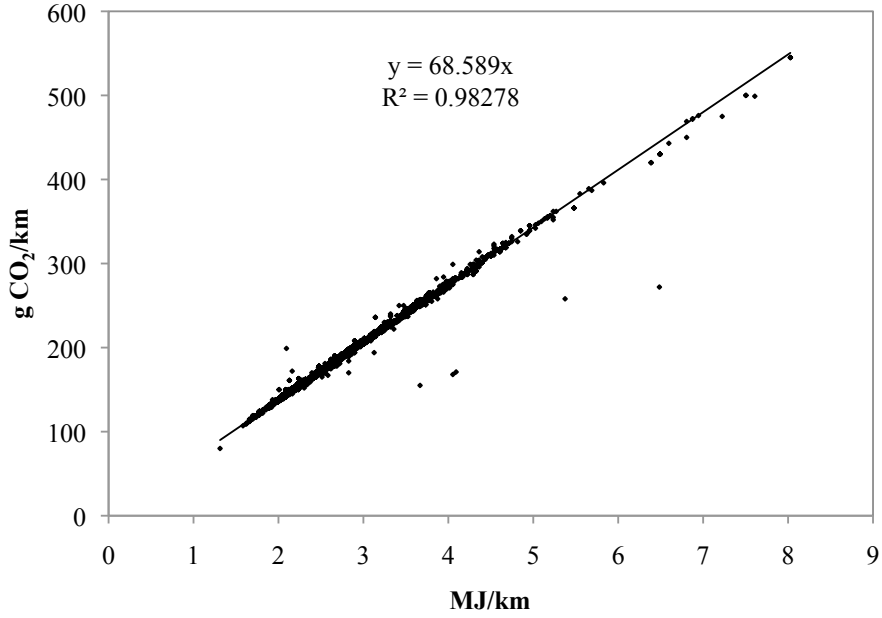


Figure 1.5: Emission factor using VCA test data.

complete picture of where fuel demand is coming from in terms of car age, engine size and fuel type.

$$E = \sum_{t,v,f} S_{t,v,f} \times M_{t,v,f} \times SEC_{t,v,f} \tag{1.5}$$

In this way, the main drivers of fuel consumption can then be separately assessed.

Fleet CO_2 emissions may be calculated from the fuel mix and each fuel's emission factor. Fig. 1.5 shows the estimation of the emission factor from legislative test data for specific emissions against SEC data provided by the UK Vehicle Certification Agency (VCA) based on tests carried out in accordance with EU Directive 93/116/EC. The emission factor is seen to be approximately 68 g CO_2/MJ, with no difference between diesel and petrol cars.

1.3 Results

1.3.1 On-road factor

To calculate fleet energy consumption according to Eq. 1.5 we must calculate the SEC of each engine type using Eq. 1.4, which requires the calculation of the on-road factor (ORF). We calculate ORF_f for each fuel type f for Ireland's car stock using an estimate of petrol and diesel consumption derived from Ireland's Household Budget Survey 2004/2005 carried out by the Central Statistics Office in 2004/2005 (Central

[3] "Energy demand" refers to final energy consumption.

Statistics Office 2005), which contains the average weekly spend of Irish households on each transport fuel. The estimate serves as an aggregate figure for the overall average difference between the weighted average in-use new-car fuel intensity according to the official driving test (including ageing) and actual usage. Eq. 1.6 shows the calculation of HBC, the number of litres of fuel f consumed in 2004 by households for private cars according to the survey, where *households* is the number of households in Ireland in 2004 according to census data, and *weeklyspend* is the average household's weekly spend on fuel f:

$$HBC_f = \frac{52 \times weeklyspend_{f,2004} \times households_{2004}}{fuelprice_{f,2004}} \tag{1.6}$$

ORF_f is the quotient of HBC_f and the 2004 bottom-up calculation for consumption of each fuel which is calculated using the fleet specific fuel consumption derived from the weighted average new-car specific energy consumption plus ageing converted from MJ to litres using fuel energy conversion factors. We find that the on-road factor for petrol is 1.06 and for diesel is 1.13. Table 1.1 shows these calculations.

Table 1.1: Estimate of on-road factor from Household Budget Survey 2004/2005.

Fuel type	Weekly spend (€)	Total spend (m€)	HBC_f (mL)	$FC_{f,2004}$ (mL)	ORF_f
Petrol	23.20	1783.07	1765.42	1662.8	1.0612
Diesel	5.40	416.1	433.4	383.7	1.12

1.3.2 Fleet energy consumption and CO_2 emissions

We calculate the energy consumption of private cars using Eq. 1.5 and this shows a strong increasing trend with 37.5% growth over the 9 year period. Fig. 1.6 displays the disaggregated 2008 energy consumption by vehicle type. When compared with Fig. 1.2 , which shows the 2008 car stock disaggregated in the same way, it can be seen that newer cars contribute proportionally more to energy consumption than older cars.

The corresponding contribution of private cars to CO_2 emissions in this time period follows almost the same trend, as transport fuels used in the mode have not been decarbonised. According to EU Directive 2009.23.EC on Renewable Energy, each member state is mandated to ensure that 10% of non-aviation and maritime transport fuel comes from renewable sources by 2020. The Irish government has responded to this by imposing an obligatory minimum biofuel mix on fuel suppliers, such that the biofuel content by energy of road and rail transport fuel was 1.5% in 2008 (Dennehy et al. 2010). Assuming that the CO_2 saving of biofuels used in the mix was 35%, the minimum required by the Directive, this translates to an overall CO_2 saving of 0.9%,

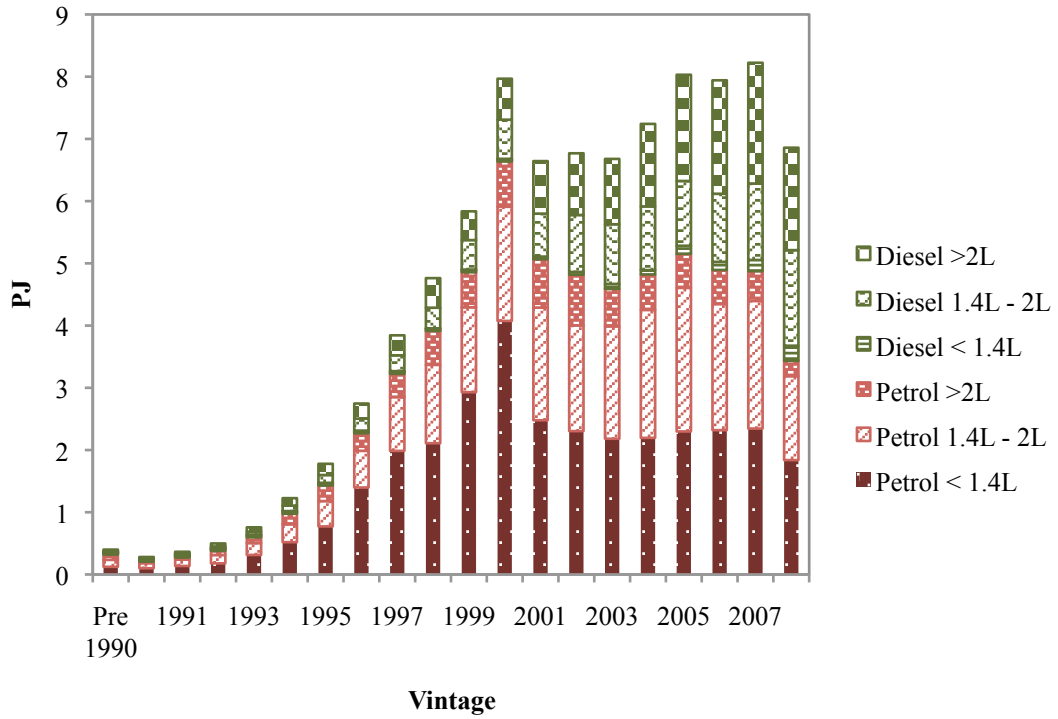


Figure 1.6: Energy consumption by vintage, fuel and engine capacity (2008).

which comes from the reduction of the emissions intensity of petrol and diesel from 68 g without the biofuel mix to 67.4 g CO_2/MJ in 2008. This translates into total emissions of 6 Mt CO_2 from private cars in 2008.

1.3.3 Fuel demand drivers

Table 1.2 shows the growth rates of energy in the stock divided in different ways by the three technological parameters, fuel type, engine size and vintage, with growth in energy demand in each technological category broken down by the fuel demand drivers, activity (a product of stock and mileage) and intensity (the on-road SEC).

From this table we see that total private car energy consumption has grown by 37% in between 2000 and 2008. The main driver of overall energy consumption is the increase in stock, which increased by 45% with a decrease in intensity and mileage. An examination of the "Energy" column shows the structural influence on energy demand growth: we see that growth in energy was driven by growth in diesel (112% growth) as opposed to petrol (20%). Similarly, growth in energy from larger engines and older cars is significant. Each column reveals the growth of drivers in each technological category: for example, the growth in total stock is mostly due to an increase in diesel.

Table 1.2: Percentage growth, 2000–2008, of energy consumption and drivers (activity, stock, mileage and on-road intensity) in the stock and by fuel, engine size and vintage.

		Fuel demand drivers				
		Energy (MJ)	Activity (vkm)	Stock (v)	Mileage (km)	Intensity (MJ/km)
Total		37	38	45	-2	-0.6
Technological parameters						
Fuel	Petrol	20	22	34	-5	-2
	Diesel	112	106	122	-7	3
Engine size	<1200 cc	-20	-15	-6	-17	-6
	1200–1900 cc	41	44	56	-4	-2
	>1900 cc	72	75	87	2	-2
Vintage	0–3 years	7	6	5	3	1
	4–7 years	60	63	70	-5	-2
	8+ years	65	72	80	-7	-4

1.3.4 Technological profile

Fig. 1.7 shows the Irish fleet's SEC from 2000 to 2008 and highlights the difference between new-car SEC and the activity weighted on-road SEC and including ageing and on-road factors. It can be seen that, despite a reduction in new-car SEC in the period, the activity weighted SEC (*actSEC*) has declined at a slower rate. The on-road SEC is calculated as the average of new-car specific energy consumption, including ageing and the on-road factor, weighted by the activity in each class:

$$actSEC = \frac{\sum_{t,v,f} S_{t,v,f} \times M_{t,v,f} \times SEC_{t,v,f}}{\sum_{t,v,f} S_{t,v,f} \times M_{t,v,f}} \tag{1.7}$$

We use the metric of fleet average SEC ($flSEC$), the weighted average new-car SEC of cars in the fleet:

$$flSEC = \frac{\sum_{t,v,f} S_{t,v,f} \times e_{t,v,f}}{\sum_{t,v,f} S_{t,v,f}} \tag{1.8}$$

The fact that the intensity of private car transport declined by only 0.6% in this period, while Table 1.3 shows that new-car and the stock-average SEC declined by 4.6% and 1.8% seems partly due to vehicle ageing. The more rapid decline of on-road SEC without ageing indicates that the ageing of the fleet has had an impact. There was also a trend in activity towards less efficient cars as shown in Fig. 1.7.

The stock and mileage technological profile is used to produce three metrics evaluating the composition of the fleet and of activity over time: the fuel mix, average fleet age and average engine size. For each metric the fleet average is compared to the on-road average, which differ due to differences in mileage across vehicle types. Fig. 1.8 shows that the difference between the diesel mix in the fleet is 41% less than

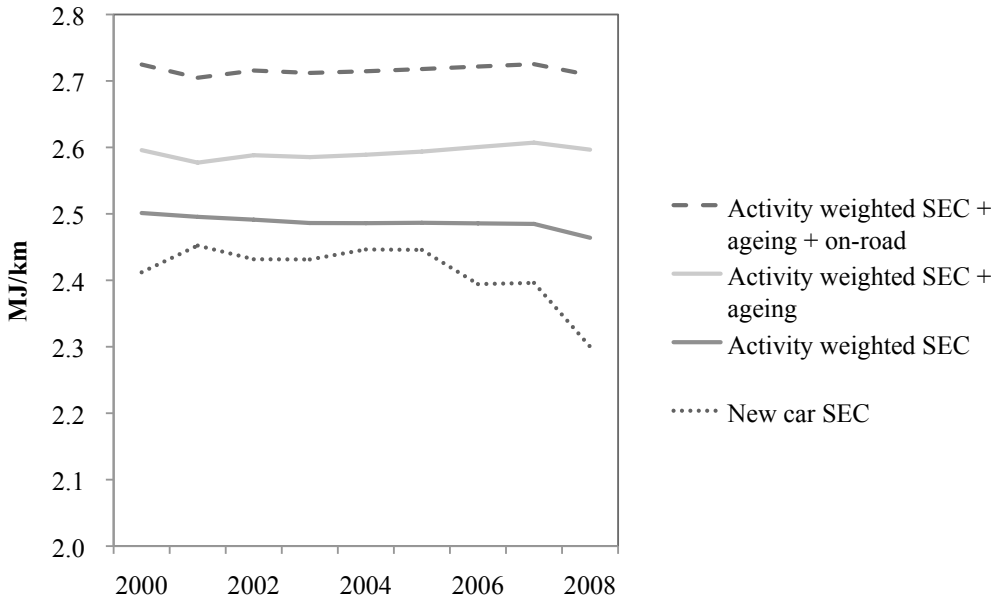


Figure 1.7: New-car SEC compared to the on-road activity weighted SEC, including the ageing factor and including the on-road factor.

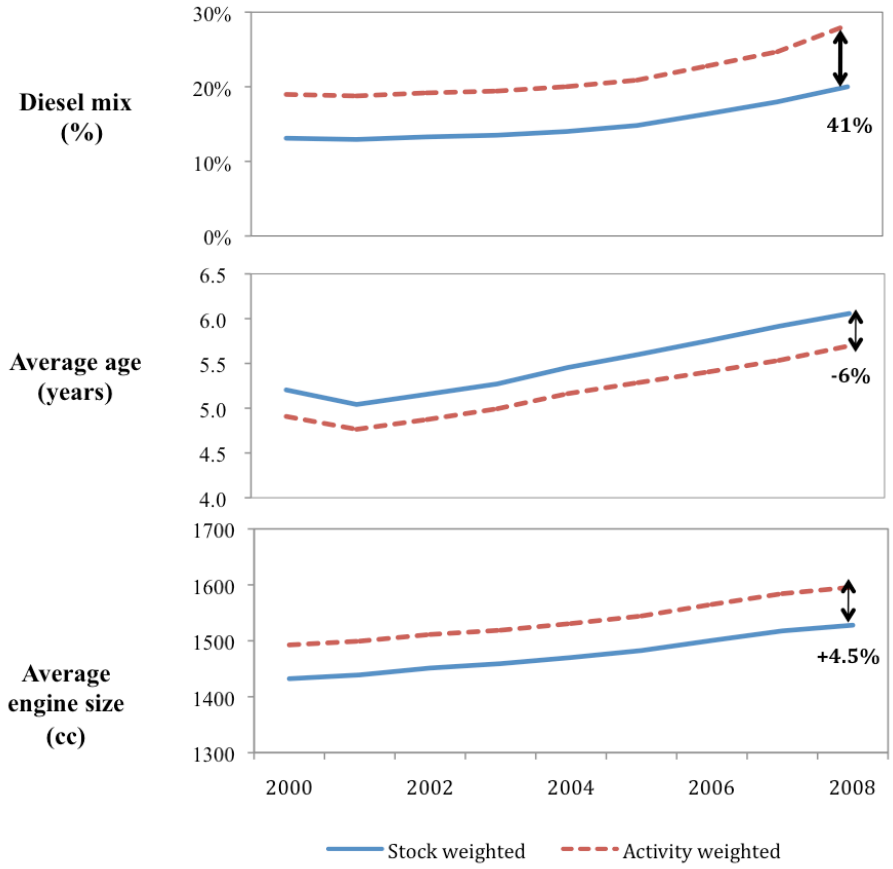


Figure 1.8: Average fleet engine size, age and diesel mix weighted by stock and activity.

Table 1.3: Comparison of the average new-car, stock and on-road average SEC and growth from 2000 to 2008.

	SEC (MJ/km)		% change
	2000	2008	2000–2008
New car	2.41	2.30	-4.6
Stock average	2.49	2.45	-1.8
On-road	2.72	2.71	-0.6
...Without ageing	2.50	2.46	-1.5

on-road used diesel cars; similarly, the average on-road age is 6% lower and average in-use engine size is 4.5% less than the fleet. This reinforces Table 1.2 showing that on average, younger, larger and diesel cars tend to be driven more. This shows the significance of disaggregating mileage by vehicle type in this methodology: stock-average metrics can be significantly different from when measured in-use, and therefore can distort energy consumption calculations and the analysis of trends.

1.4 Discussion

The contributions of the factors influencing transport energy demand need to be understood before any level of fuel reduction can be achieved. Among these key drivers is technological efficiency. We need to know for example, how the technological structure of the car fleet and, furthermore, the mileage profile influence final energy demand. The methods presented here provide an energy and CO_2 accounting model for a private car fleet that increases the accuracy of private car energy consumption estimates, enables the detection of fuel consumption trends which are associated with the technological and mileage profile of the vehicle stock, and facilitates the projection of technological trends and how these pertain to final energy consumption in the future.

Improving the quality and robustness of Ireland's transport CO_2 emissions modelling has been described as a key strategy in reducing Ireland's dependency on fossil fuels (Environmental Protection Agency 2009). The rise in car related energy consumption and emissions detected has consequences for Ireland's ability to meet its emissions reductions targets. Energy demand trends detected include the increasing contribution from larger and diesel engines, and the effect that the ageing of the fleet has on energy consumption. We find that there has been an overall increase in fleet efficiency by 1%, but this has been offset by an increase in stock by 45%, which has brought about an increase in activity in the mode. The small improvement in efficiency is a consequence of improvements in petrol and smaller cars, but this has been dampened through the shift towards larger and diesel cars.

Chapter 2

Modelling Future Private Car Energy Demand in Ireland

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]

Keywords: Car stock model; Transport demand; Baseline forecast

[1]Chapter published as Daly, H.E. & Ó Gallachóir, B.P. (2011), 'Modelling future private car energy demand in Ireland', *Energy Policy* 39, 7815–7824.

2.1 Introduction

Despite developments in technology and the prevalence of green- house 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*b*)), 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 & Ó Gallachóir 2011*b*), 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 gCO_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.

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 & Ó Gallachóir (2011*b*) 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 & 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. In 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 130g 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.

2.2 Methodology: stock model and energy baseline

2.2.1 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[2]. Energy demand for each fuel type is then calculated for each year according to the bottom-up equation:

$$E = \sum_{t,v,f} S_{t,v,f} \times M_{t,v,f} \times SEC_{t,v,f} \tag{2.1}$$

[2] *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.

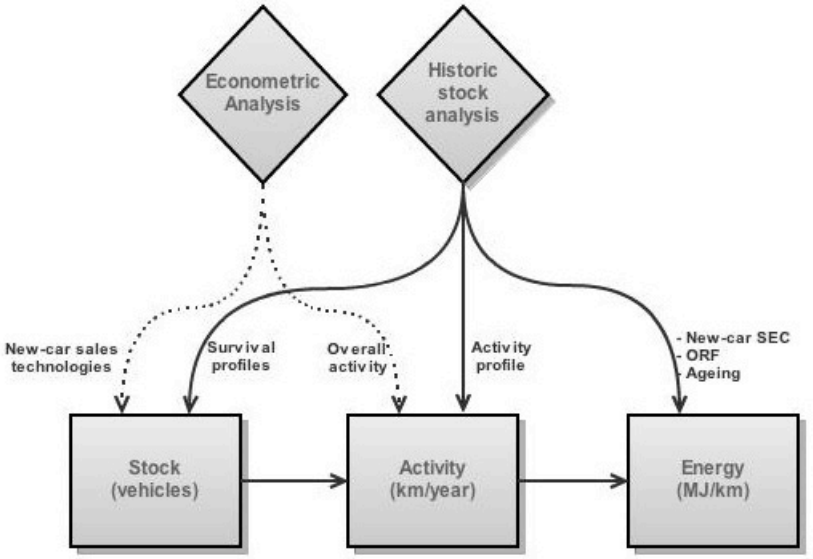


Figure 2.1: Modelling methodology overview.

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

$$Emis = \sum_{f} E_f \times fact_f \tag{2.2}$$

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

Each variable, stock, mileage and energy intensity, is generated for the whole fleet profile, described in detail in the next section. A methodological overview is shown in Figure 2.1.

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.

2.2.2 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 for year Y, shown in Equations 2.3 and 2.4.

$$Vkm^{Y} = Vkm^{Y-1} \times (1 + \Delta GNP^{Y} \times \delta I_{Vkm}) \times (1 + \Delta P^{Y} \times \delta P_{Vkm}) \quad (2.3)$$

$$Sales^{Y} = Sales^{Y-1} \times (1 + \Delta GNP^{Y} \times \delta I_{Sales}) \times (1 + \Delta P^{Y} \times \delta P_{Sales}) \quad (2.4)$$

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 & Schipper 1997), and shown in Table 2.1. These represent the percentage variation in the number of vehicle kilometres driven or cars sold for each 1% increase in national income and fuel price.

Table 2.1: 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	-0.3	1.2

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 Figure 2.2, indexed on 1990.

Similarly, the evolution of engine size in new cars is extrapolated using historic regression based on income (GNP). Table 2.2 contains the income elasticities used on the shares of car sales by engine size, which is derived from another Irish study (Hennessy & Tol 2011). 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.

Figure 2.3 shows the projection of car engine shares up to 2025 using this method.

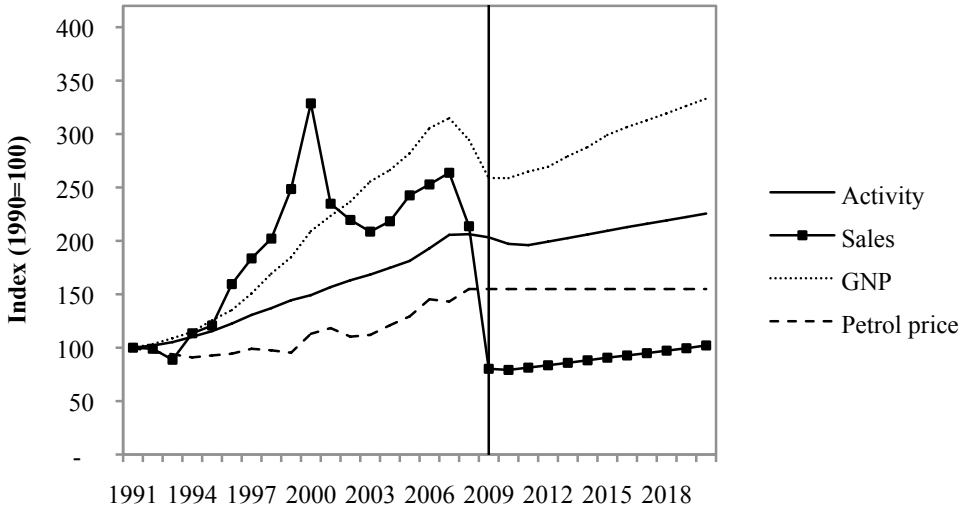


Figure 2.2: Indexed historic and projected income, price, activity and sales.

Table 2.2: Fuel price and income elasticities used for forecasting car sales and vehicle activity.

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

Projecting forward from 2010 shares, the share of >1.7 litre 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 Figure 2.3 (Rogan et al. 2011).

2.2.3 Stock

The fleet is disaggregated according to vehicle technology type (petrol and diesel cars are further divided by engine sizes, as in Figure 2.3) and vintaged up to 25 years. Vintage is derived from the year of manufacture as opposed to 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 Figure 2.4, by simulating the number of vehicles in each technological category and vintage each year, using sales and survival assumptions.

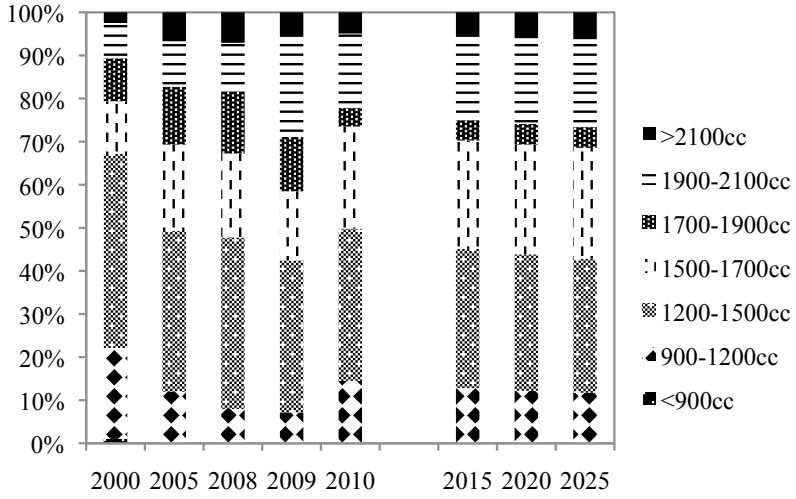


Figure 2.3: Historic and projected new car engine sales shares.

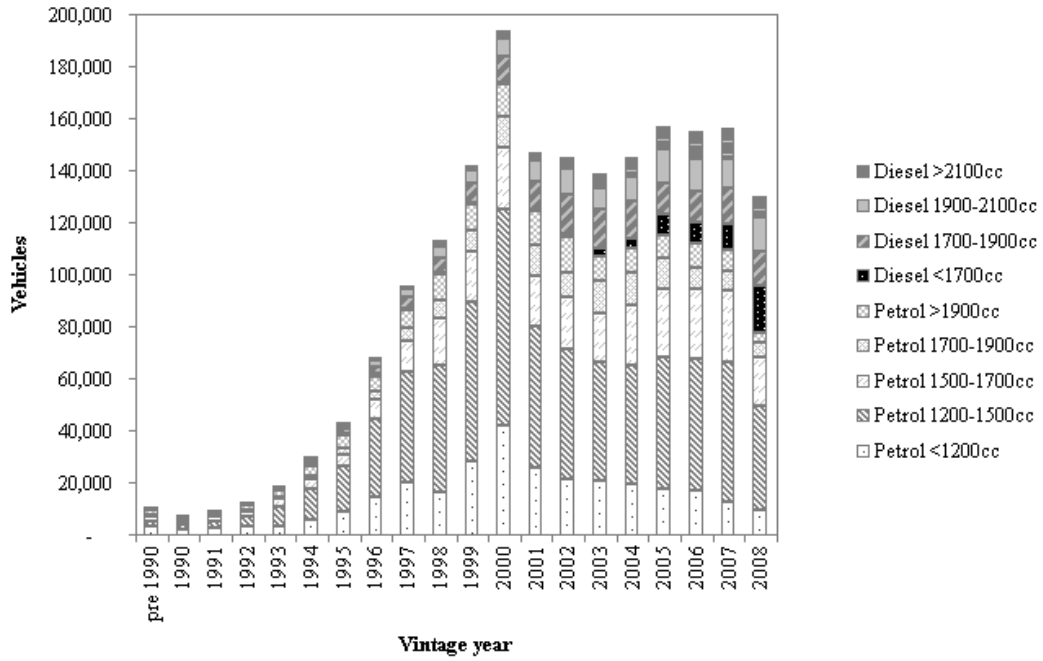


Figure 2.4: Disaggregated 2008 fleet profile by fuel and engine size.

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

$$Stock_{t,v}^{Y} = Stock_{t,v}^{Y-1} \times (Surv_t(Y-v)+1) \tag{2.5}$$

where $Surv_t(Y-v)$ is the year-on-year survival rate of vehicles at age $Y-v$ between one year ($Y-1$) and the following year. For example, for the year Y = 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 Equation 2.6

$$Surv_t(Y-v) = Avg_y\left(\frac{Stock_{t,y-(Y-v)}^{y} - Stock_{t,y-(Y-v)}^{y-1}}{Stock_{t,y-(Y-v)}^{y-1}}\right) \tag{2.6}$$

The probability that a vehicle of vintage v will survive year Y depends on age ($Y-v$), and was derived from the average historical survival rate, calculated using available historical vehicle registration data (years y from 2000 to 2008). Figure 2.5 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. 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 & Cohen 1996).

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

$$Stock_t^Y = Sales_t^Y + \sum_v Stock_{t,v}^Y \tag{2.7}$$

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 2.2.2. 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 2.3 and Figure 2.6 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 2.3

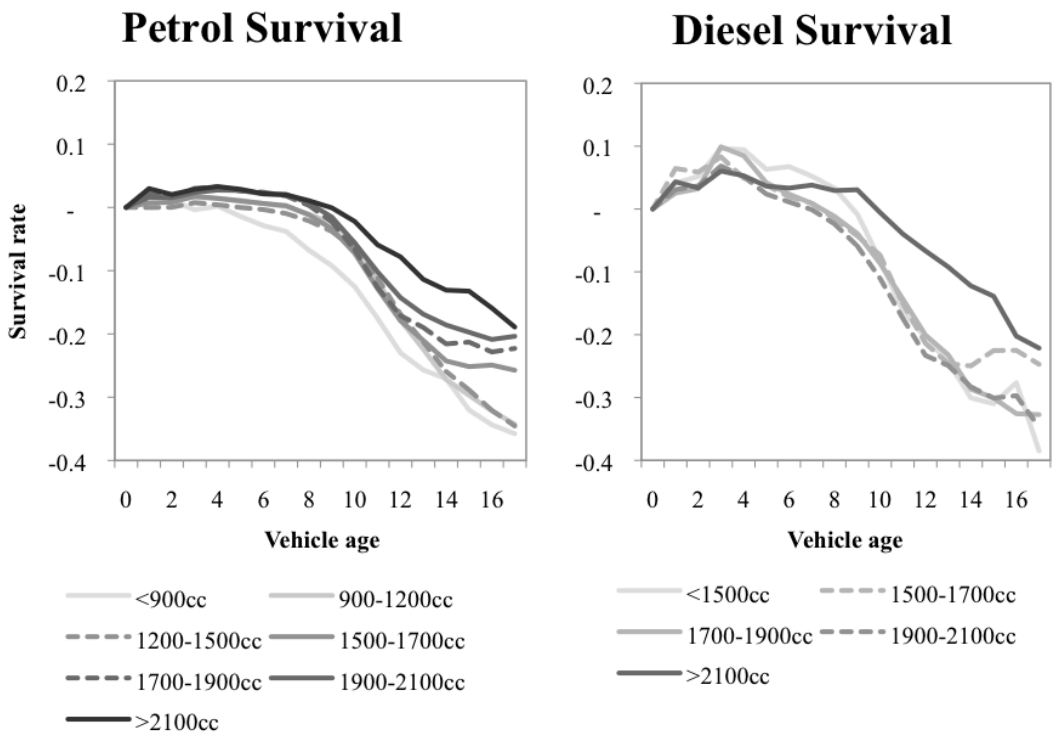


Figure 2.5: Survival rates of different engine bands for petrol and diesel.

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

Table 2.3: Projected baseline stock and fuel shares, 2008-2025.

	2008	2025
Total stock (thousand)	1,917	2,696
Population (thousand)	4,418	5,120
Car saturation (veh/1000 people)	433	526
Petrol car share	0.80	0.56
Diesel car share	0.20	0.44

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.

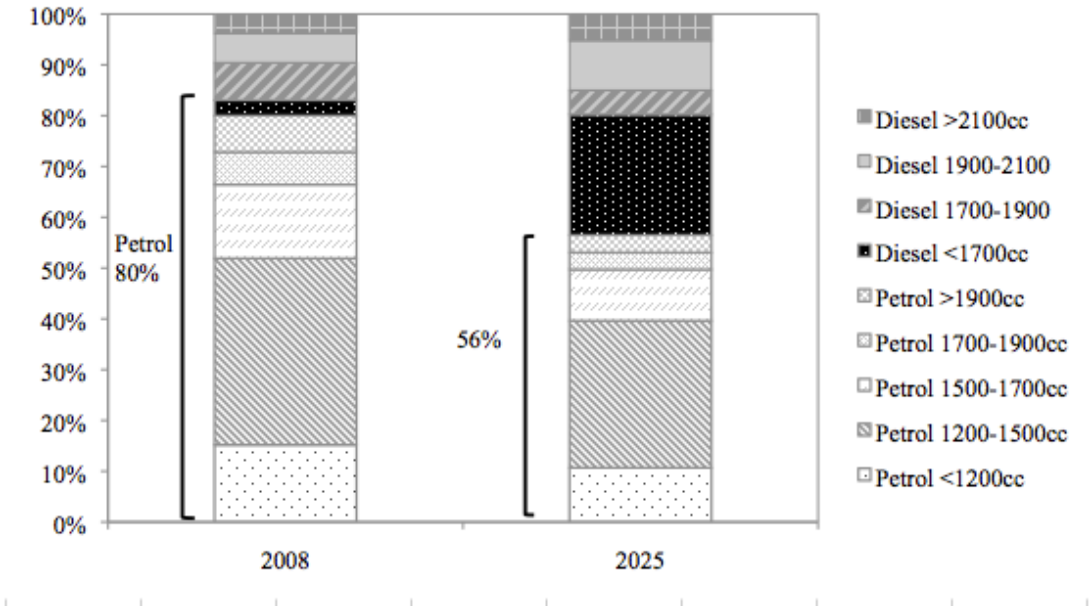


Figure 2.6: Share of stock by technology, 2008 and 2025.

2.2.4 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 & Ó Gallachóir 2011*b*). 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 2.2.2. 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 ($M_{f,t}$), and within each CC band, the third level refers to the mileage of each vintage ($M_{f,t,v}$). 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 in Howley, Dennehy & Ó Gallachóir (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 Equations 2.8–2.10.

$$w_f = \frac{M_{f^*}}{M} \tag{2.8}$$

$$w_{f,t} = \frac{M_{f,t^*}}{M_f} \tag{2.9}$$

$$w_{f,t} = \frac{M_{f,t,v^*}}{M_{f,c}} \tag{2.10}$$

In our calculations, M_{f^*}, M_{c^*} and M_{v^*}, are "base mileages" and represent "petrol", "<900cc" 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 2.4 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 a 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.

Table 2.4: Projected baseline stock and fuel shares, 2008-2025.

	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	7,731	1.00	1,407	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 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 the following equations:

Overall average mileage:

$$AvM^Y = \frac{vkm^Y}{S^Y} \tag{2.11}$$

Level	Base mileage	Other mileages
Fuel type	$M^Y_{f^*} = \frac{AvM^Y \times S^Y}{\sum_{i=\text{fuel types}} w_i \times S^Y_i}$	$M^Y_f = w_f \times M^Y_{f^*}$
CC band	$M^Y_{f,t^*} = \frac{AvM^Y_f \times S^Y_f}{\sum_{i=\text{CC bands}} w_{f,i} \times S^Y_{f,i}}$	$M^Y_{f,t} = w_{f,t} \times M^Y_{f,t^*}$
Vintage	$M^Y_{f,t,v^*} = \frac{AvM^Y_{f,t} \times S^Y_{f,t}}{\sum_{i=\text{vintages}} w_{f,t,i} \times S^Y_{f,t,i}}$	$M^Y_{f,t,v} = w_{f,t,v} \times M^Y_{f,t,v^*}$

In scenario analysis, the weighted activity profiles $w_{f,t,v}$ 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.

2.2.5 Energy intensity

The specific energy consumption (SEC, measured in MJ/km) of cars at the most disaggregated level of the stock model ($SEC_{f,t,v}$) 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 in Van den Brink & 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 in Daly & Ó Gallachóir (2011*b*). SEC is calculated by the equation:

$$SEC_{f,t,v} = e_{f,t,v} \times 1.003^{Y-v} \times ORF_f \tag{2.12}$$

where $e_{f,t,v}$ is new-car SEC, Y is the year of calculation, and $Y - v$ is the age of the car. The stock's disaggregated new-car SEC for cars manufactured between 2000 and 2008 were provided by EPSSU (Howley, Dennehy & Ó Gallachóir 2009) and were 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 2.5 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 the average annual change in new-car intensity between 2000 and 2008, and the engine size profile is determined by the

Table 2.5: The sales share and efficiency of different technology types in 2007 and 2009.

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

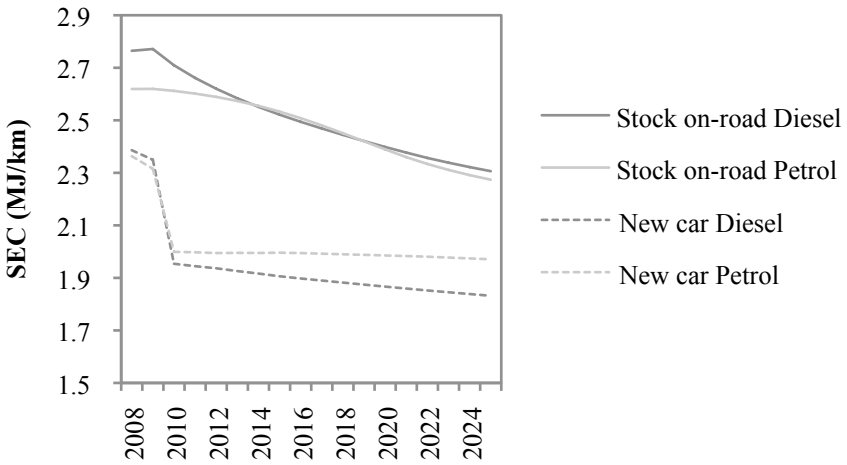


Figure 2.7: On-road stock average and new-car SEC from 2008 to 2025.

process described in Section 2.2.2. Figure 2.7 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 2.3.2.

Figure 2.7 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 Equation 2.12, 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 (Government 2010)), the model forecasts new-car emissions at 130 gCO_2/km in 2015, satisfying EU Regulation 443/2009 (European Commission 2009).

2.3 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.

2.3.1 Energy and trends

Applying Equation 1 to the stock, mileage and efficiency assumptions, we simulate energy demand and CO_2 emissions up to 2025. Figure 2.8 shows stock, activity, energy, intensity and average mileage of the car stock indexed on the year 2000. Table 2.6 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 2.6: The sales share and efficiency of different technology types in 2007 and 2009.

		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%
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%

Table 2.6 shows total energy demand in 2008 and 2025, and the share of energy

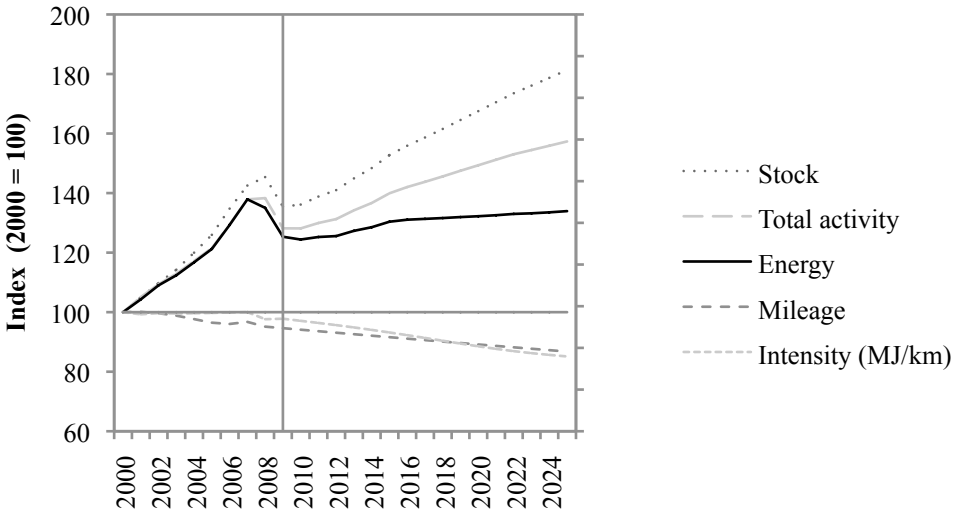


Figure 2.8: Indexed historical and projected car energy, stock, activity and efficiency figures (2000 = 100).

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 2.6 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 & 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 & 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 faster than an increase in activity, which stagnates due to pessimistic economic forecasts. Historically, demand rose because gains in efficiency

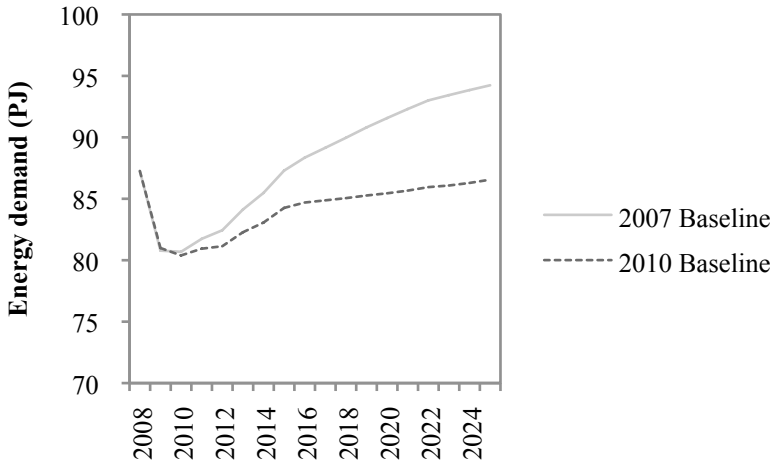


Figure 2.9: 2007 baseline result comparison.

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. Figure 2.9 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.

2.3.2 Emissions and EU targets

Baseline CO_2 emissions are calculated by applying an emissions factor of 65.8g CO_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 CO_2 emissions in Ireland in 2009 totalled 13.1 $MtCO_2$, accounting for 29% of CO_2 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 (Environmental Protection Agency 2011), 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 $MtCO_2$ (Environmental Protection Agency 2011). 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 95g CO_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.

2.3.3 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 as 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 €/litre). 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 2.7 and Figure 2.10 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, Dimitropoulos & Sommerville (2009); a range of long-run rebound effects of 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 2.8. Most notable is the on-road factor, which as a direct multiplier of energy, gives a direct 10% effect. Other than that, income growth and the income activity elasticity are most significant. This shows how sensitive this model is to the macroeconomic assumptions used.

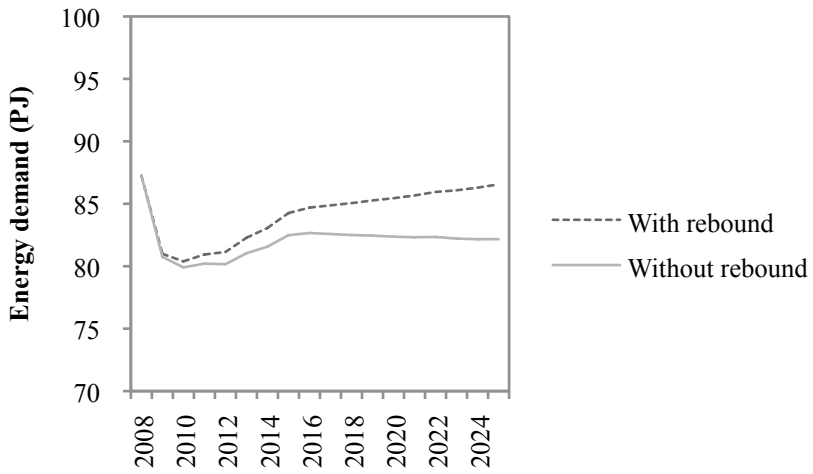


Figure 2.10: Baseline energy demand with and without a rebound effect.

Table 2.7: 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%

Table 2.8: Effect on 2025 energy demand of varying parameters by $\pm$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[3]	0.00%	0.00%
11. Activity vintaging	-0.10%	0.10%

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

[3] 1% added/subtracted from each year of survival profile.

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.

2.4 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, Figure 2.9 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 2.3.2. 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 2.3.3.

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, 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.

Chapter 3

Future Energy and Emissions Policy Scenarios in Ireland for Private Car Transport

Abstract

In this paper we use a technological model of Ireland's future car stock to simulate the impact of a range of policy measures on the baseline trend in energy demand in the period to 2030. The policies and measures modelled comprise meeting deployment targets for electric vehicles and compressed natural gas vehicles, an EU regulation for the improvement of vehicle efficiency, implementation of a national biofuel obligation, as well as several behavioural measures (encouraging modal shifting and reduced travel demand). The impact of the different measures simulated is measured in terms of their contribution to meeting Ireland's ambitious targets for energy savings, for renewable energy penetration and for carbon dioxide (CO_2) emissions reductions. The results point to a possible improvement of 32% in car stock efficiency, the achievement of 7.8% renewable energy share of road and rail transport and a 22% reduction in non-ETS private car CO_2 emissions relative to 2009 levels. A scenario analysis on meeting the EV penetration target shows a significant range of CO_2 emissions reductions depending on the cars (and mileage) displaced and on the electricity generation portfolio.[1]

Keywords: Transport energy modelling; CO_2 emissions; renewable energy

[1]Chapter is in press: Daly, H.E. & Ó Gallachóir, B.P. (2012), 'Future energy and emissions policy scenarios in Ireland for private car transport', *Energy Policy*, DOI:10.1016/j.enpol.2012.08.066

3.1 Introduction

There is a significant and escalating push from within the European Union to improve private car energy efficiency and emissions performance. This is in part due to lower than anticipated recent efficiency gains coupled with increasingly urgent goals for greenhouse gas abatement. In some EU Member States, efficiency savings from technology improvements have been negated by other parallel trends. In Ireland for example, purchasing trends towards larger cars has offset savings (Ó Gallachóir et al. 2009). Moreover, the availability and affordability of efficient and alternatively fuelled vehicles (AFV) have made the sustainability of personal transport through private cars technologically feasible (Johansson 2009, Thomas 2009).

At a Member State level, changes in the private car stock over the period to 2020 can be consistent with meeting goals of energy security and competitiveness, with meeting EU emissions reduction targets and with meeting mandatory minimum shares of renewable energy consumption in transport. In Ireland, private cars account for 14.2% of primary energy demand and are almost entirely fuelled by imported fossil oil (SEAI 2011). Several policy measures specifically targeting the vehicle stock have been put into place, for example a target of 10% stock electrification for 2020, but the pathways for meeting energy and climate targets are as yet unclear, as are the contributions from individual measures towards meeting the overall goals.

Basing potentially expensive, technologically-oriented policy measures on sound, fact-based analysis is very important for governments facing economic and climate constraints. The question of whether "efficient is sufficient" is a critical question, or if mobility management is needed in order to successfully decarbonise passenger transport (Hickman & Banister 2007). Any investment into AFV will require investment into refuelling infrastructure, which will create a technology lock-in situation, making it difficult to switch technology paths in the future. The concept of path dependency explains how the decisions available in the future will be limited by the decisions taken in the present (Ahman & Nilsson 2008). Indeed, the fundamental problem at hand is the lock-in to fossil fuel use and the internal combustion engine.

This paper addresses a number of these issues in a quantitative manner and its purpose is to improve the knowledge-base and modelling capacity underpinning policy decision making in Ireland. Ireland is an interesting case study, having witnessed dramatic levels of growth in private car transport energy demand and related emissions, while also having had some success in implementing policies to address the growth (Rogan et al. 2011). While the focus is on Ireland, the methodology is readily applicable in other countries where similar data are available. We use a technological model of Ireland's future car stock to simulate the impact of a

range of policy measures on the baseline trend in energy demand in the period to 2030. The policies and measures modelled are: meeting deployment targets of electric vehicles (EV) and compressed natural gas vehicles (CNGV); a regulation for the improvement of vehicle efficiency; the implementation of a biofuel obligation, as well as several behavioural measures (encouraging modal shifting and reduced travel demand). The significance of the measures simulated is measured in terms of their contribution to meeting targets for energy savings, renewable energy penetration and carbon dioxide (CO_2) emissions reductions. The paper provides the first robust assessment of the implications of this range of policy measures using a car stock model and considers both the impact of individual measures and the cumulative impact (avoiding double counting).

The structure of the paper is as follows: Section 3.2 provides the context for the scenarios modelled, providing a brief overview of Ireland's policy, transport and climate targets; section 3.3 discusses techno-economic modelling and describes the modelling methodology used in this study, section 3.4 presents the results from the scenarios modelled in this paper; section 3.5 discusses the implication of results for Ireland, the interplay between technology deployment and mobility management, and drawbacks of the methodology as well as suggestions for refinement and future work. Finally, section 3.6 concludes.

3.2 Context

There has been an exceptional increase in transport energy demand in Ireland relative to other EU Member States, both in absolute terms and as a proportion of overall energy consumption. Transport in 2008 consumed 5,612 ktoe (42.8% of overall final energy demand), an increase of 277% on 1990 demand (which at 2,022 ktoe, represented 27.8% of overall final energy demand SEAI (2011)). Figure 3.2 puts these figures in the context of other European counties: In terms of per-capita transport emissions, Ireland was the most carbon intensive country in 2008 and, with the exception of the Czech Republic, showed the greatest 1990-2008 growth, at 220%. While this was in large part due to the growth in freight energy demand (284% growth over the period 1990-2008), private car transport was the highest emitting mode in 2008 (37.5%, Howley, Dennehy & Ó Gallachóir (2009)). It is against this backdrop that Ireland faces challenging targets in transport for energy efficiency, renewable energy and CO_2 emissions reduction.

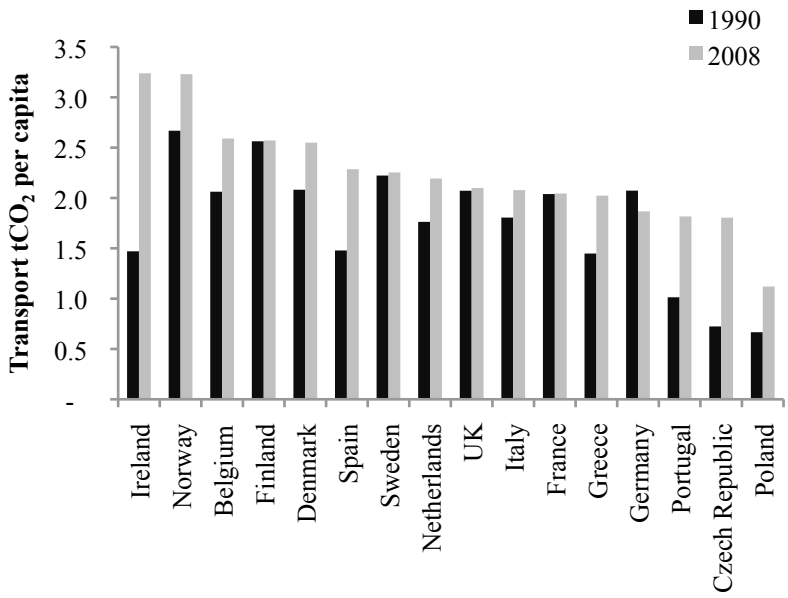


Figure 3.1: European transport emissions per capita in 1990 and 2008 (Total emissions and population data from Eurostat (2012))

3.2.1 Energy and transport related targets for Ireland

Increasing energy efficiency is a key goal of the EU, and is generally recognised as a cost-effective means of reducing dependence on fossil fuels (Enkvist et al. 2007). For passenger transport, increasing efficiency (i.e. reducing the energy demand per passenger kilometre) can be achieved through improving vehicle efficiency, moving passenger kilometres to higher efficiency modes (modal shifting) or increasing vehicle occupancy (Gross et al. 2009). Under the EU Energy Services Directive 2006/32/EC, EU Member States are obliged to publish a National Energy Efficiency Action Plan (NEEAP), outlining measures taken to increase efficiency across the economy. Ireland's 2008 NEEAP contains a number of efficiency measures in transport, including improving the fuel economy of the private car stock via i) a reweighting of tax and ii) implementing the EU Regulation No. 443/2009, an obligation on car manufacturers to reduce new-car specific emissions. Also included are incentivized efficient driving behaviour, EV deployment, encouraging modal shift and e-working (DCENR 2008).

A second EU decision impacting Ireland's energy policy, especially in relation to transport, is a specific target on GHG emissions reduction. The EU has two legislative instruments to reach its target of 20% GHG reduction relative to 1990 levels by 2020, i) imposing a GHG emissions cap and trade system on large point source emitters through Directive 2009/29/EC (the Emissions Trading Scheme), and ii) assigning targets for each Member State for non emissions trading sectors (non-ETS, consisting of transport, residential, services and some industry) through

Decision 406/2009/EC. Ireland is required under this latter "Effort Sharing Decision", to reduce non-ETS emissions by 20% compared to 2005 levels by 2020. The Environmental Protection Agency (EPA) has estimated non-ETS GHG emissions for Ireland in 2005 as 46.9 Mt CO_2eq indicating that the target for 2020 is 37.4 Mt (Environmental Protection Agency 2012*b*). National GHG projections for non-ETS sectors indicate an overshoot of the target of 4.1 - 7.8 MtCO_2eq (Environmental Protection Agency 2012*a*). Ireland's mandated reduction in non-ETS emissions implies a reduction of 1.29% annually in overall emissions over the period 2005-2020: This is the most onerous target facing Irish climate policy.

Private car transport in 2007 accounted for 37.5% of transport CO_2 emissions and 12% of total non-ETS CO_2 emissions (Daly & Ó Gallachóir 2011*b*). CO_2 accounts for the vast majority of GHG emissions in transport. The success of measures in reducing CO_2 emissions from private cars will have a strong bearing on Ireland's ability to meet this binding non-ETS target.

A further binding target for Irish transport relates to renewable energy. First proposed in 2007, the binding target for renewable energy usage in transport (known as RES-T) that each Member State must meet was originally a target for biofuel use in transport (CEC 2007). However, concerns regarding the sustainability of biofuels coupled with the 'food versus fuel' debate led to a change in approach to also allow renewably generated electricity (used in electric vehicles) contribute to meeting the target. The EU Renewable Energy Directive (2009/28/EC) requires that in each Member State, 10% of land-based transport (i.e. excluding marine and aviation) energy by 2020 must come from renewable sources (10% RES-T).

3.2.2 Policies and technology options

Ireland has put in place a number of private car transport policy measures to meet these three targets (energy efficiency, non-ETS GHG emissions and RES-T) arising from EU decisions. The most ambitious technology-related measure is a target that 10% of the vehicle stock be powered by electricity by 2020 (DoEHLG 2008). Studies have shown that vehicle electrification can significantly contribute to reducing specific vehicle emissions (Ahman & Nilsson 2008, Barkenbus 2009, Thiel et al. 2010). While EVs do not emit exhaust fumes like conventional internal combustion engines (ICE), where fuel efficiency and specific emissions depend largely on the vehicle engine, the emissions associated with powering EVs depend on the electricity supplied as well as the time of EV charging (Calnan In review). While it's likely that infrastructure limitations will lead captured fleets, especially public service vehicles (PSV), to convert to alternative fuels before private cars, PSV constitute only 5.4% of road energy demand (SEAI 2011).

According to Hekkert et al. (2005), CO_2 reduction and improved energy efficiency can be achieved by implementing a second alternative fuel chain, compressed natural gas (CNG). There has been growth in the availability and use of CNG vehicles in recent years: In the EU they are used in Italy, Austria, Sweden and Germany, with bi-fuelled vehicles, burning either CNG or gasoline in a standard ICE. In Ireland, the natural gas grid infrastructure already reaches about 40% of the population for home heating and industry, and Thamsiriroj et al. (2011) propose a roadmap for the introduction of bio-CNG as a renewable transport fuel in Ireland by purifying methane from indigenous bio wastes and the grass crop and injecting it into the gas grid. Natural gas accounted for 28% of primary energy and 12% of final energy in 2008 (Howley, Ó Gallachóir & Dennehy 2009). Singh et al. (2010) estimates that a maximum potential of 33% of natural gas in Ireland may be substituted with biomethane from indigenous sustainable sources, such as residues from slurry and slaughter waste together with energy crops, with a practical obtainable level of 7.5% estimated for 2020. The abatement cost of reducing CO_2 emissions by means of CNG depends strongly on the relative price of gas and oil, and the origin of the natural gas (Smokers et al. 2006).

The increased blending of biofuels in petrol and diesel is another legislative route for increasing the amount of biofuels used for transport, replacing a previous measure providing mineral oil tax relief: The 2010 Biofuels Obligation Act requires all oil suppliers in Ireland to ensure that by July 2010, at least 4% by volume (equivalent to approximately 3% in energy terms) of all road transport fuel sold is biofuel. According to data from the energy balance, 92 ktoe of biofuels was consumed in road transport in 2010, out of a total of 2,819 ktoe, a 3.2% share in energy terms, excluding fuel tourism (SEAI 2011).

In addition to these approaches targeting technical and fuel changes, a number of non-technological targets are set out in the Smarter Travel document (Department of Transport 2009), including ambitious plans for modal shifting (moving transport from private cars to public transport), demand reduction, maximising the efficiency of the transport network, reducing reliance on fossil fuels and emissions of CO_2, and improving transport accessibility.

3.2.3 Previous Irish modelling work

Modelling of the Irish energy and transportation systems has been relatively limited. In terms of national energy models, the Economic and Social Research Institute (ESRI) developed an energy model, which is a top-down, sectoral model of energy demand to 2020 that is linked to their HERMES macro-economic model. ESRI also has a top-down environmental model ISuS, which contains a car stock module that has been used to study the impact of government policy on car ownership (Hennessy &

Tol 2011). ESRI's energy model outputs are used by the Sustainable Energy Authority of Ireland (SEAI) to produce national energy forecasts (Clancy et al. 2010). These energy forecasts in turn are used to by the Environmental Protection Agency (EPA) to produce national GHG emissions forecasts (Environmental Protection Agency 2011). Some of the limitations of this approach are outlined in Hull et al. (2009).

The main focus of transport energy modelling work to date has been on private cars. Kelly et al. (2009) and Daly & Ó Gallachóir (2011*b*) used national car test odometer and vehicle registration data to build bottom-up models of car energy demand between 2000 and 2008. Daly & Ó Gallachóir (2011*a*) developed this into a techno-economic simulation model of private car energy and emissions to 2030, studying the impact of trends in engine size, dieselization, mileage and other technical parameters, which forms the basis for the scenarios studied in this paper. The GAINS model has been used for policy analysis in the non-ETS sector for Ireland (Kelly et al. 2011), and contains a car stock model for transport energy demand simulation. Rogan et al. (2011) carried out an ex-post analysis of the impact on CO_2 emissions of changing car taxation in 2008 from an engine sized basis to an emissions performance basis. Jennings et al. (2012) addressed some data gaps and performed a refined Laspeyres decomposition on passenger transport in Ireland over the period 1990–2008.

A number of papers have assessed the 10% EV penetration target: Foley et al. (2010) studied the impact of plug-in hybrid EVs on emissions using an optimising electricity dispatch model, WASP IV, and in particular the importance of charging regimes. Calnan (In review) used the PLEXOS electricity dispatch model to study the effect of alternative electricity generation portfolios in 2025 on EV emissions. Smith (2010) looked at the potential for plug-in HEVs in Ireland, estimating that up to 50% energy and emissions savings could be made. Finn et al. (2012) indicates that demand side management of EV charging cycles could be used to achieve financial savings, increased demand on renewable energy, reduce demand on thermal generation plant, and reduce peak load demand.

3.3 Modelling and scenario analysis

3.3.1 Transport techno-economic modelling

Reviews of energy modelling techniques are found in Swan & Ugursal (2009) and Jebaraj & Iniyan (2006). They identify two distinct approaches to energy modelling: top-down and bottom-up. The top-down approach tends to aggregate end-use technologies and forecast energy efficiency on the basis of historical patterns, while total activity or service demand (for example, residential heating or passenger

kilometres) is modelled using regression on the basis of economic indicators, such as income and population. For example, Acutt (1996) forecasts private car GHG emissions in a number of policy scenarios based on fuel price, taxation and subsidies.

Bottom-up energy-economy models are discussed by Mundaca et al. (2010) in the context of residential energy demand. Simulation models, like the one used in this paper, do not approach scenario development as optimal or rational behaviour in consumers, but rather determine scenarios exogenously and quantify energy demand and supply. Kloess & Muller (2011) use a bottom-up simulation model to study the impact of different tax regimes, energy prices and technological advancement on Austrian passenger car energy and GHG emissions. As in the study presented here, the technological model is combined with a top-down econometric model, where price and income have an influence on the stock size, travel demand and vehicle characteristics. A logit model is also used to simulate the competition between passenger cars and other passenger modes on the basis of costs: In this way, the model allows travellers to react to price increases by changing travel behaviour. A similar approach is taken in this paper to Brand et al. (2012) where several individual measures and one "policy package" scenario are simulated using a technology rich car stock model, the UK Transport Carbon Model. Consumer behaviour and lifecycle emissions are also counted in this methodology. The car stock model used in this paper is comparable to those used in these two studies; the specifics are described by Daly & Ó Gallachóir (2011*a*).

Struben & Sterman (2008) take a different approach to modelling technology diffusion, using consumer preference and word-of-mouth as parameters in the evolution of the car stock. Backcasting is another approach to modelling, where the measures needed in order to reach a given desirable future are explored (Hickman & Banister 2007). For example, Robert & Jonsson (2006) apply this approach to a forecasting model of transport in Stockholm to quantify the impact of travel demand measures on reaching the city's greenhouse gas emissions target for 2030.

3.3.2 Private car energy model

The model used here can be classified as a bottom-up simulation forecasting model of private car transport energy. Energy demand in the model is mainly driven by the technological composition of the car stock, and this is achieved by creating a demographic model of the car stock for each year up to 2030, where the age and technological characteristics of the car stock are disaggregated each year. The methodology and baseline results are described in detail in Daly & Ó Gallachóir (2011*a*). This approach focuses on the on-road fuel economy of the vehicle stock and the emissions intensity of transport fuel, and how trends in these variables effect total fuel consumption and emissions. The fuel economy is calculated from the new-car

energy and emissions test values, grouped according to year of manufacture and engine size band. An 'on-road' factor is then applied to account for the difference in fuel consumption between the test cycle and on-road conditions. For Ireland, this was calculated to be 1.06 for petrol and 1.13 for diesel.

A top-down econometric model forecasts overall travel demand, the size of the car stock and the number and profile of new-car sales, so price and income influence the model, and there is a feedback loop, resulting in higher activity for scenarios with a higher efficiency stock. The econometric model does not include consideration of taxation, which has been modelled separately for Ireland (Hennessy & Tol 2011).

While there are a number of caveats associated with this modelling approach (section 3.5), the authors are confident that this model creates a realistic baseline energy forecast upon which to explore alternative futures. By keeping most parameters consistent across scenarios, it is possible to compare the likely relative impacts of different policy measures.

3.3.3 Scenario modelling

The policy measures simulated in this paper are categorised into i) those improving vehicle efficiency, ii) fuel-switching measures, and iii) behavioural measures. This section describes the scenarios and assumptions made regarding the characteristics of new vehicles and the stock in simulating the policy measures. Assumptions regarding fuel emissions factors and renewable content are described in section 3.3.3.4. The scenario results are quantified in terms of the targets relating to energy efficiency, non-ETS CO_2 emissions reduction and renewable energy penetration.

3.3.3.1 Vehicle efficiency measures

Two scenarios are considered in which the fuel efficiency of the conventional ICE stock is improved through new vehicles entering the stock. Firstly, *New car efficiency* assumes that by 2020, the average specific emissions of the new car stock reach an intensity of 95g CO_2/km. This reflects compliance with a target set forth in EU Regulation (EC) No. 443/2009, which set a legal obligation on car manufacturers relating to the maximum weighted average specific emissions of 130gCO_2/km of new cars sold within EU Member States by 2015, and an indicative target of 95gCO_2/km for 2020. This is target is modelled by simulating increased new-car efficiency in each engine band and also a shift in sales towards cars with lower cylinder capacities (cc), which are more efficient.

Secondly, *High efficiency choice* assumes that there is no change in the sales profile by engine size (cc), but also assumes that consumers choose the most efficient cars

within each band, shown in Table 3.1.

Table 3.1: Highest efficiency vehicles with fuel intensity (litres per 100 km) energy intensity (MJ/km) and specific emissions (gCO_2/km) in each engine cylinder capacity (cc) class for petrol and diesel. Source: VCA (2010).

Fuel type	Engine size band (cc)	Car make with highest efficiency in class	MJ/km	gCO_2/km [2]
Petrol	<900cc	SMART fortwo coupe	1.50	102.0
		Chevrolet Matiz	1.81	123.4
	900-1200cc	Toyota iQ	1.50	102.0
		Suzuki Alto	1.54	104.4
	1200-1500cc	Toyota Prius (hybrid)*	1.50	102.0
		Honda civic (hybrid)*	1.61	109.2
		Fiat 500	1.64	111.5
	1500-1700cc	MINI hatchback	1.88	128.2
	1700-1900cc	Honda Civic	2.23	151.9
	1900-2100cc	BMW 1 Series E81/E82/E87/E88*	2.02	137.6
		Audi A5 Coupe	2.30	156.6
	>2100cc	BMW 3 Series E90/E91/E92/E93*	2.48	168.5
		Vauxhall Vectra MY2008 4 Door Saloon	2.62	178.0
Diesel	<900cc	SMART fortwo cabrio	1.27	86.6
	900-1200cc	No model		
	1200-1500cc	Seat Ibiza	1.43	97.1
	1500-1700cc	Ford Fiesta	1.43	97.1
	1700-1900cc	Audi A3	1.74	118.1
	1900-2100cc	Mercedes-Benz A-Class	1.70	115.5
		BMW 1 Series E81/E82/E87/E88*	1.70	115.5
	>2100cc	Honda Civic	1.97	133.9

3.3.3.2 Fuel switching measures

We consider several fuel switching measures. Firstly, in calculating baseline emissions and renewable energy we include biofuel mixing in petrol and diesel. The baseline scenario incorporates the 2010 Biofuels Obligation Act – a 4% (by volume) mix of bioethanol in petrol and a 4% mix of biodiesel in diesel meet this. The share of biofuel by energy content is calculated using the energy content by volume of each fuel as defined by Annex III of the Renewable Energy Directive and the overall petrol and diesel share as projected in the baseline scenario. For *All scenarios*, this target is increased to 6% by volume (4.8% by energy) by 2020.

Ireland's 10% electric vehicle (EV) target was discussed in section 3.2.2: We model an increasing number of EVs entering the stock to meet this target for 2020, the target date set out by government legislation. We also model a 10% CNG vehicle penetration in a similar manner. In both the *10% EV* and *10% CNGV* scenarios, we assume that the 10% penetration target for the stock (cars, vans, buses and trucks) as

[2] Emissions in gCO_2/km using this methodology are calculated directly from fuel consumption (multiplying SEC by an emission factor in gCO_2/MJ). This correlates very well with test figures but does not match perfectly.

a whole is reached exclusively through private cars. Assuming that the 2008 vehicle mode share holds in the future, this implies a penetration of 11.5% of EVs and CNGVs into the private car stock. This 11.5% share of the private car stock in 2020 equates to 245 thousand vehicles. It is assumed that sales begin in 2012 and accelerate each year to meet this target.

The new EV technology is assumed to have an efficiency of 28 kWh/100km, the equivalent of 1 MJ/km (Thomas 2009), approximately half the energy intensity relative to new cars sold in Ireland in 2010. Initially in the scenario analysis, we assume EVs displace petrol cars (in terms of both numbers and mileage), which is likely given the limited range of EVs. In alternative scenarios we vary this with EVs displacing the stock evenly by technology and displacing diesel only, along with an analysis of the sensitivity of results to the emissions factor of the power generation portfolios and of the timeline of achieving the 10% target.

New CNG vehicles are assumed to displace the sales and mileage of diesel cars and have the same efficiency (MJ/km) as average petrol cars.

3.3.3.3 Behavioural measures

We simulate two behavioural measures outlined in the Smarter Travel policy document, described in section 3.2.2. Firstly, a *Flattened demand* scenario is modelled with the assumption that "the total kilometres travelled by the car fleet in 2020 will not increase significantly from current total car kilometres" (Department of Transport 2009). This is implemented in the model simply by imposing a cap on vehicle kilometres at 2008 levels. This provides an important comparison between the potential benefit from alternative technologies and from demand reduction.

The second measure simulated from the Smarter Travel document is a move towards eco-driving: "We will include a module on efficient driving as part of the rules of the road and national driver test…We will commission research to determine the on-board technology that can be introduced in public vehicles to reinforce eco-driving behaviour." Two aspects are modelled. First is a requirement that all learner drivers must have eco-driving knowledge and ability assessed as part of the test. Smokers et al. (2006) determines that this can achieve a 3% energy saving. It is assumed that the stock of drivers replenishes after 40 years and that training begins in 2013. This is implemented through the on-road factor, which is reduced by 30% by 2053 and linearly interpolated in intermediate years.

A second eco-driving measure modelled is the compulsory installation of gearshift indicators (GSI) on all new cars by 2013. According to Smokers et al. (2006), this give a 1.5% energy saving. This measure is simulated by applying this saving factor to the efficiency of all new cars entering the stock from 2013.

3.3.3.4 Emissions factors and renewable energy content

Overall emissions are calculated in this paper from the results of scenarios for the different fuels and are presented in two ways: Firstly, overall CO_2 emissions to the atmosphere from car transport are counted, including those from the production of electricity and biofuels, taking into account the source of these fuels: the "real-world" emissions of private cars. Sustainability criteria for biofuel qualification specify land-use conditions and emissions savings of at least 60% on fossil fuels to be reached by 2018 (35% from 2009). This assumption is used for emissions associated with biofuels. Secondly, emissions results are presented in accordance with the Effort Sharing Decision for the non-ETS sectors. In this case, the use of EVs involves shifting transport CO_2 emissions from the non-ETS to the Emissions Trading Scheme and emissions associated with EVs are hence excluded from total non-ETS emissions. The use of CNGVs on the other hand does not involve a shift to ETS and hence emissions associated with CNGVs are included in non-ETS emissions. Biofuels are viewed as carbon neutral in emissions accounting and hence emissions associated with combusting biofuels are also excluded from total non-ETS emissions. The emissions associated with biofuel production are attributed as appropriate to industry emissions and may form part of ETS, non-ETS emissions or be imported.

Presenting the emissions results in two ways provides insights into the overall impacts of the scenarios in terms of emissions and separately gives an indication of the relative effectiveness of each measure in contributing towards Ireland's legal obligations for non-ETS GHG emissions reductions.

For "real world" EV emissions, an emissions factor (gCO_2/kWh) is taken from Calnan (In review), which uses an electricity dispatch model to examine the impact of a large number of EVs on the Irish power system under a number of alternative electricity generation portfolios. Emissions factors for the Irish electrical grid with an EV load representing the 10% EV target for 2025 were calculated for a Business-As-Usual (BAU), Coal, Renewable, Flexible and Storage Portfolios and linearly interpolated between 2009 and 2024 based on the 2008 emission factor.

The *10% CNG* scenario assumes that there is a mix of 7.5% of biomethane in the gas grid and that 7.5% of CNG supply to transport is bio-CNG (Singh et al. 2010).

Renewable energy use in private car transport is also presented in two ways: i) as a percentage of total private car energy demand and ii) in terms of its contribution to Ireland's 10% RES-T target, in accordance with the EU Renewable Energy Directive. In the latter instance, we assume that the percentage of non-maritime and aviation transport fuel consumed by private cars remains constant over the time horizon at 61%. In this case also, biofuels produced from residues or lignocellulosic material receive a double credit. Electricity used for EVs from renewable resources is given a

weighting of 2.5, according to the accounting framework of the Renewable Energy Directive.

Table 3.2 contains the emissions factors and renewable energy content assumptions used in the scenario analysis. Biodiesel, bioethanol and bio-CNG (for mixing with CNG) are assumed to reach the minimum emission-related sustainability criterion and achieve a 60% saving on the basis of petrol emissions.

Table 3.2: Emission factors and renewable energy contents of different fuels used in scenario analyses.

Fuel		Emissions (gCO_2/MJ)		Renewable content	
		Real-world	EU-measured	% of energy	Weighted
Biodiesel & bioethanol	60% saving on fossil fuel emissions by 2020	27.4	0	100%	100%
Bio-CNG		27.4	0		
Petrol & diesel	Pure fossil	68.6	68.6	0%	0%
	Biofuel: 4% vol (3.2% energy)	67.3	66.4	3.2%	3.2%
	Biofuel: 6% vol (4.8% energy)	66.6	65.3	4.8%	4.8%
Electricity	2008	161.5	0	11.9%	29.8%
	2020 (BAU)	110.0	0		
	2020 (renewable portfolio)	105.9	0	40%	100%
	2020 (coal portfolio)	119.9	0		
CNG	Pure fossil	63.9	63.9	0%	0%
	7.5% mix of biomethane	61.2	59.1	7.5%	15%

3.4 Results

In this section we present the scenario analysis results. Firstly the energy savings by policy scenario are summarised; the contribution to specific policy targets is then presented, with specific focus on energy efficiency, renewable energy and CO_2 emissions. Finally, a more in-depth analysis of the 10% electric vehicle target is presented.

3.4.1 Energy savings by scenario

Figure 3.2 shows the energy demand simulated for each policy scenario up to 2030. The baseline shows a return to 2008 energy demand by 2028, after the 2008-2011 economic recession, which caused a decrease in stock activity, and the improvements in the stock efficiency since 2008 (Daly & Ó Gallachóir 2011*a*). Between 2010 and 2023, *High efficiency choice* is the scenario with the lowest energy demand. Energy

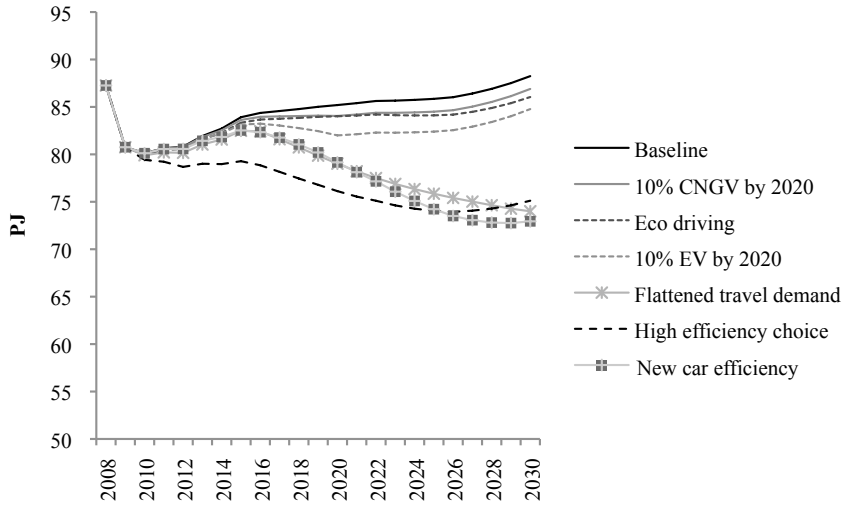


Figure 3.2: Energy demand of individual policy scenarios

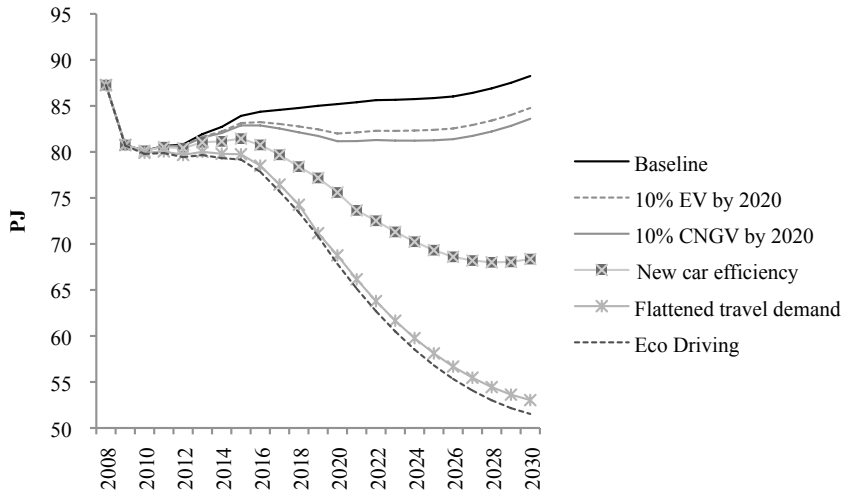


Figure 3.3: Energy demand of cumulative policy scenarios

demand in all scenarios except *Flattened travel demand* shows an increase by 2030, as efficiency measures have all been incorporated gradually into the stock and increased activity dominates again causing energy demand growth.

Figure 3.3 shows the cumulative effect of policy scenarios, with firstly the *10% EV* and *10% CNGV* target scenarios applied to the baseline, then *New car efficiency*, *Flattened travel demand*, and finally *Eco-driving*. *High efficiency choice* is not included as a scenario in these results as it is essentially a sub-scenario of *New car efficiency*, as new vehicles reach 95gCO_2/km by 2020 through this scenario. The advantage of the stock model approach is that this may be done without double counting: For instance, if the overall activity of the stock should be reduced, as in the flattened travel demand scenario, then the quantity of energy saved from efficiency measures is reduced.

Table 3.3 summarises the results for 2030: *Flattened travel demand* and *New car efficiency* show the highest individual energy savings (17.5% and 17.3% respectively), while the cumulative effect of all measures sums to a 43% reduction in energy demand in 2030 relative to the *Baseline*. This is less than the sum of all individual savings (45%, excluding *High efficiency choice*), in the absence of double-counting energy savings.

Table 3.3: Individual and cumulative scenarios savings in 2030 compared with baseline energy.

Scenario	Individual Saving	Cumulative Saving
10% EV penetration by 2020	-3.9%	-3.9%
10% CNG penetration by 2020	-1.5%	-5.3%
New car efficiency	-17.3%	-22.5%
High efficiency choice	-14.9%	n/a
Flattened travel demand	-17.5%	-39.9%
Eco driving	-2.5%	-41.6%

3.4.2 Policy targets

3.4.2.1 Energy efficiency

Figure 3.4 and Table 3.4 shows the stock-average energy intensity in MJ/km simulated to 2030 for each individual technology scenario. This is calculated as the quotient of final energy demand and activity, therefore closely reflects energy demand in Figure 3.2. However, the model responds to higher efficiency scenarios with higher rebounded activity, therefore increase in energy savings (17.3%) are less than increases in efficiency compared with the baseline (24.3%). Baseline efficiency in 2030 improves by 15% on 2008 efficiency due to the step-change in new-car purchasing as a result of the 2008 car tax change, which is a significant improvement on the 2000-2008 trend, where no improvement in efficiency took place. This 0.64% annual efficiency improvement is less than the 1% annual improvement suggested by Zachariadis (2006) for the baseline evolution of the car fleet of EU 15 between 2010 and 2020 because new cars are assumed to improve to a lesser extent in the Irish case.

Table 3.4: Efficiency increases compared with 2030 baseline due to technology measures.

Scenario	Stock Efficiency increase
10% EV penetration by 2020	4.6%
10% CNG penetration by 2020	0.7%
New car efficiency	24.3%
Eco driving	3%
All (cumulative)	31%

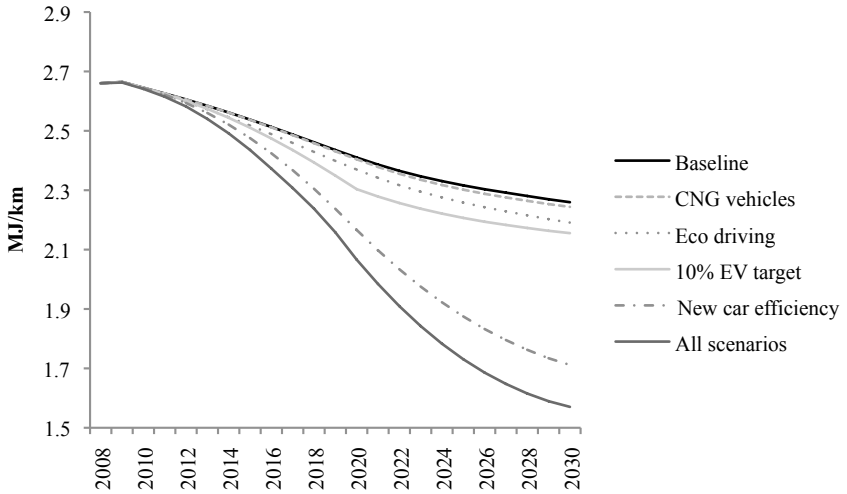


Figure 3.4: Stock energy intensity in MJ/km to 2030.

3.4.2.2 Renewable energy

Figure 3.5 shows the penetration of renewable energy as a result of all scenarios by fuel type. The left axis shows renewable energy as a percentage of private car energy demand in 2020. We also assume a higher penetration of biofuels in the conventional fuel mix from 3.2% to 4.8% (or 4% to 6% in volume terms): For ethanol mixed in petrol, this is a change from an E4 to an E6 mixture, and for diesel also the concentration of biodiesel is increased to 4.8%.

The right axis shows the contribution of all policies to meeting the 2020 RES-T target, assuming that the share of private car energy as a proportion of overall non-aviation and maritime transport demand is the same in 2020 as in 2008, at 61% It shows that with all measures, including the 10% EV target (assuming that 42% of Irish electricity is from renewable sources by 2020) and the 10% CNGV target (assuming that 7.5% of gas in the grid comes from biomethane), Ireland can achieve 7.8% RES-T rather than 10% in 2020 from the policy measures simulated here. This figure includes the weighting of 2.5 allocated to renewable electricity and 2 to biomethane (from ligno-cellulosic grass and from waste) as per the Renewable Energy Directive.

3.4.2.3 CO_2 emissions

Emissions for this analysis are presented in two ways: Firstly, *real-world* CO_2 emitted by private car transport fuels (including emissions from biofuels and electricity), and secondly, non-ETS private car energy-related CO_2 only (described as *nETS-measured* emissions). Figure 3.6 shows total *real-world* private car CO_2 emissions by fuel type for each scenario in 2020, while Table 3.5 shows *real-world* and *nETS-measured* emissions and savings in 2020.

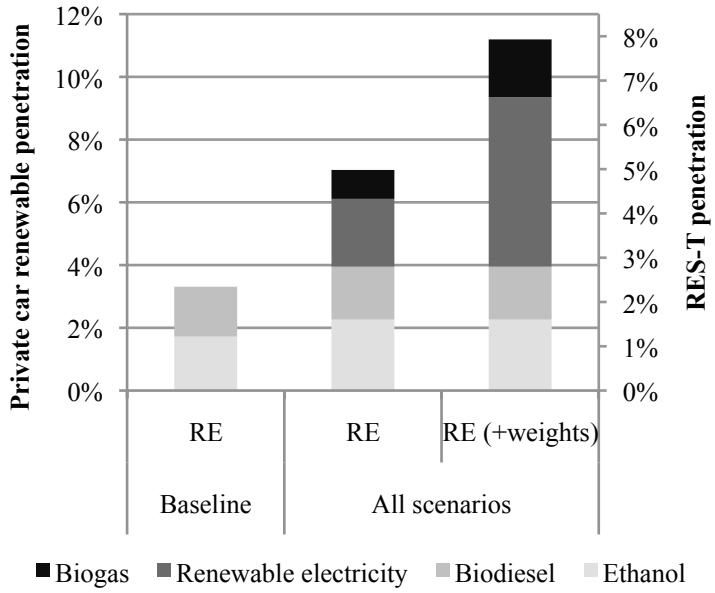


Figure 3.5: Renewable energy penetration in 2020 of private car transport on the left axis and impact on the RES-T target on the right axis.

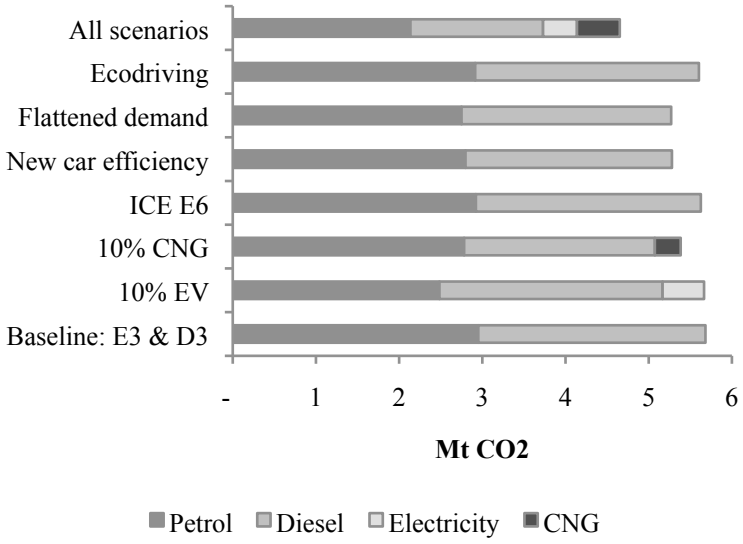


Figure 3.6: *Real world* CO_2 emissions in 2020 from different fuel sources under each scenario.

Table 3.5: Total emissions and emissions savings compared to the baseline in 2020, and emissions as measured by the Effort Sharing Decision for non-ETS emissions.

	Baseline	Individual Scenario						All scenarios
		10% EV	10% CNG	E6/D6 mix	New-cars 95g/km	Flattening demand	Ecodriving	
NETS-measured								
Emissions (Mt CO_2)	5.61	5.10	5.29	5.52	5.21	5.2	5.53	4.09
Saving		-9.1%	-5.3%	-1.7%	-7.1%	-7.3%	-1.4%	-27.1%
Real-world								
Emissions (Mt CO_2)	5.68	5.67	5.38	5.63	5.28	5.27	5.6	4.6
Saving		-0.3%	-5.2%	-1.0%	-7.1%	-7.3%	-1.4%	-19%

There is a difference of 1.2% in baseline emissions in both cases as a result of biofuel blending in petrol and diesel. The measurement difference in the *10% EV* scenarios is striking – 0.3% savings in *real-world* private car emissions, compared with 9.1% *nETS-measured*. This is because all emissions due to electric vehicles are transferred to the emissions trading scheme and therefore are not counted as non-ETS emissions. The saving in energy as a result of higher efficiency EVs in this scenario is almost negated by the higher emissions intensity of electricity compared with petrol and diesel. Sensitivities around this figure are explored in section 3.4.2.4.

No measurement difference occurs in the *New-car efficiency*, *Flattened travel demand* or *Ecodriving* scenarios, as no alternative fuels are involved.

The overall impact of all measures being successful is that non-ETS private car energy-related CO_2 in 2020 are 27% lower than the baseline 2020 projection and 22% lower than emissions in 2011 (5.3 Mt), representing an average annual reduction in emissions of 2.7%. This quite rapid reduction in emissions compares with the 5.2% annual average growth of private car emissions between 1990 and 2007, and a growth of 7.9% in 2007 alone. It is clear therefore, that even with all ambitious measures in place, emissions savings will not go far in reversing the historically high growth. Indeed, excluding the *Flattened travel demand* scenario and allowing travel demand to grow in line with economic growth, annual emissions reductions only reach 1.5%.

Figure 3.7 show how these measures contribute to the overall non-ETS 2020 CO_2 emissions target of 37.1 MtCO_2, a reduction of 20% relative to 2005 emissions. National emissions forecasts (Environmental Protection Agency 2011) point to an overshooting of this target by 7.68 MtCO_2 in a with additional measures scenario. All measures modelled here for private cars, currently accounting for about 12% of non-ETS emissions, can contribute an emissions reduction of 1.52 MtCO_2.

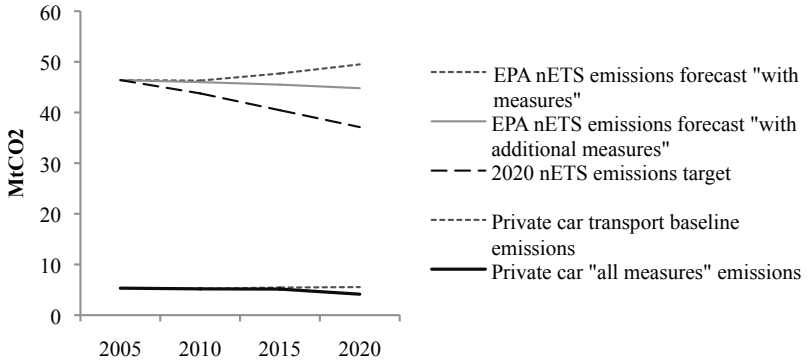


Figure 3.7: Ireland's 2020 non-ETS sector emissions target and EPA projections compared with forecasted savings from private car transport possible from the measures modelled in this study.

3.4.2.4 Sensitivity analysis of electric vehicles

In this final results section we explore the sensitivities around emissions savings from EVs to key input parameters by varying i) the displaced technology and mileage driven by EVs, ii) the timeline of the target, and iii) of the electricity generation portfolio in 2020. The 10% EV target has been a high profile and ambitious target for the Irish government, and many different parameters can affect the outcome in terms of actual emissions savings and contribution to renewable energy targets. This demonstrates that even with a simulation model, there is rarely a single answer when we model meeting a specific target.

This section uses the simulation model to explore the sensitivity of results to:

1. The type of technology displaced by EVs and the mileage of EVs:
    - *EV (avg)* assumes that EVs displace ICE technology evenly across the stock and maintain the average distance driven by the stock (17,109 km/year).
    - *EV (low)* assumes that EVs displace purchases of petrol cars: Given the limited range and power of EVs available, it is likely that lower mileage "city" cars (14,646 km/year), generally running on petrol, lighter and more efficient will be displaced first. These assumptions underpinned the 10% EV measure for which results were presented in the previous section.
    - *EV (high)* provides a counterpoint to the previous scenario, with higher assumed mileage (21,753 km/year on average) of diesel car sales displaced by EV sales.
2. Timeline of the target: There are concerns as to whether the penetration of EVs can grow so quickly in 9 years to meet the 10% target and also whether the costs (investment into infrastructure and tax incentives) are worth the environmental benefits (The Irish Academy of Engineering 2011), so we

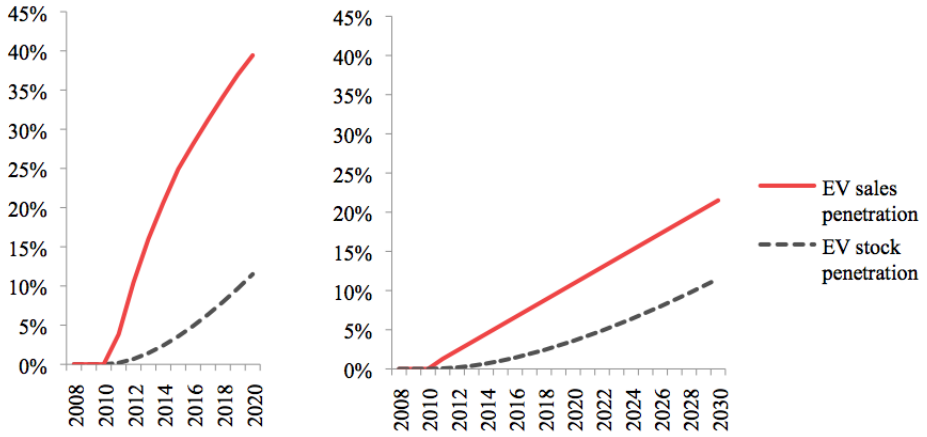


Figure 3.8: Sales penetration of EVs required to meet a 10% EVs in the stock by 2020 and 2030 respectively.

simulate a scenario, *EV (avg-2030)*, based on the parameters from *EV (avg)*, where the 10% EV target is not met until 2030. This may reflect a market where EVs are adapted more slowly without government subsidy. Figure 3.8 shows the EV proportion car sales needed in order to reach the target by 2020 and 2030: Up to a 40% penetration would be required to meet the target by 2020, compared to 25% to meet the target by 2030.

3. The electricity generation portfolio in 2020: A business-as-usual (BAU) weighted average electricity emissions factor (g/kWh or g/MJ)) is used in the EV scenario in the previous section derived by Calnan (In review) to calculate the emissions associated with the electricity required to charge EVs. The lowest and highest factors derived in the study, from coal and renewable generation portfolios respectively, are applied to the EV (avg) stock simulation to give an indication of the range of emissions possible from varying the electricity generation portfolio. Table 3.6 gives these factors for 2008, 2020 and 2025.

Table 3.6: Total emissions and emissions savings compared to the baseline in 2020, and emissions as measured by the Effort Sharing Decision for non-ETS emissions.

Scenario	Electricity emission factor (gCO_2/MJ)		
	2008	2020	2025
BAU	162	110	89
Renewable portfolio		106	83
Coal portfolio		120	103

Table 3.7 gives results for these EV scenarios in terms of emissions savings compared with the baseline, and stock emissions in gCO_2/km, for the real-world and nETS measured accounting frameworks. The greatest real-world emissions savings come from the *EV (high)* scenario in 2020 (1.4%) and *EV (avg – renewable portfolio)* and *EV*

(high) in 2030 (3.4%). The latter scenario also gives the highest non-ETS emissions in 2020 and 2030, as in this scenario more vehicle kilometres are displaced by EVs. It is interesting that in 2020, *EV (avg – coal portfolio)* gives no real-world emissions savings due to the higher emissions intensity of electricity in this scenario. Indeed, applying the coal portfolio emissions to the *EV (low)* scenario gives an increase in emissions of 0.5% in 2020 compared with the baseline.

Table 3.7: Total emissions and emissions savings compared to the baseline in 2020, and emissions as measured by the Effort Sharing Decision for non-ETS emissions.

	Real-world emissions				Non-ETS emissions			
	Emission Savings		Emissions (gCO_2/km)		Emission Savings		Emissions (gCO_2/km)	
	2020	2030	2020	2030	2020	2030	2020	2030
Baseline			160.5	150.7	0.0%	0.0%	158.4	148.7
EV (avg)	0.9%	2.9%	156.2	144.1	10.7%	10.1%	138.9	131.6
EV (high)	1.4%	3.4%	154.6	143.1	13.7%	11.5%	133.6	129.3
EV (low)	0.3%	2.3%	157.3	145.1	9.1%	8.8%	141.6	133.8
EV (avg-2030)	0.3%	3.0%	159.1	143.6	3.3%	11.3%	152.2	129.6
EV (avg - renewable portfolio)	1.2%	3.4%	155.6	143.4				
EV (avg - coal portfolio)	0.0%	1.8%	157.6	145.8	As *EV (avg)*			

3.5 Discussion

3.5.1 Climate mitigation targets

In Ireland, non-ETS emissions must be reduced by 1.29% annually between 2009 and 2020 in order to reach the 20% reduction target. Private car emissions, currently representing 12% of non-ETS emissions, as modelled can achieve reductions of 2.8% per annum if all technological and behavioural measures simulated in this paper are fully implemented and successful: This includes an end to the growth in private car travel and a 10% penetration of EVs and of CNGVs by 2020. Assuming that travel demand continues to be coupled with GDP and the economy recovers and returns to growth as projected, an annual reduction of 1.5% is possible from vehicle efficiency-related measures alone. It is evident from Figure 3.3 that efficiency measures can cause a step-reduction in emissions, but growth is resumed once the growth in travel demand overtakes efficiency-related savings. This indicates that unless travel demand is managed effectively, efficiency measures need to be continually deepened after 2020. Figure 3.7 highlights the challenges Ireland faces in reducing non-ETS emissions: The target is projected to be overshot by 12.58 $MtCO_2$ under a "with measures" scenario, while savings from private cars from all measures modelled in this paper amount to 1.52 $MtCO_2$.

Private car transport is sensitive to fuel price volatility, given its almost entire reliance on imported oil. The EU 10% RES-T target should reduce the impacts of price risk and lead to higher energy security. The scarcity of oil in the future is a de facto assumption behind analysis in the 2011 EU White Paper on Transport (European Commission 2011). This paper calculates a scenario where almost 80% of this target is met through renewable energy in private cars, assuming 10% vehicle stock electrification and 42% renewable penetration in electricity, along with biogas used in CNGV and biofuel blending in petrol and diesel cars.

3.5.2 Technologies, fuels and mobility management

The EU is at a crossroads in relation to vehicle technology: The Transport White Paper emphasise the need for an integrated approach of member states to vehicle technology, to prevent incompatibilities and inconsistencies in, for example, EV charging infrastructure (European Commission 2011). Scenarios for EVs, a topic of close study in this paper, show that the impact of the 10% target on RES-T and on emissions abatement in 2020 varies significantly depending on the electricity generation portfolio, the ICE sales displaced by EVs and the timeline of achieving the 10% EV penetration: Emissions savings in a coal portfolio scenario are nil, and a scenario where EVs displace petrol cars gives almost half the savings of EVs displacing diesel cars. Studies have also shown that differing EV charging profiles has a big effect on efficiency (Foley et al. 2010). To this end, a 10% EV target is itself a very ambitious measure, but without complementary supports to ensure, for example, controlled charging and a less carbon intensive electricity system, the benefits are likely to be minimal given the substantial investment cost. While non-ETS-measured emissions savings are high, this is due to all displaced emissions being shifted into the emissions trading scheme. Caution should be exercised in making technology goals considering that any such target would require large capital investment to break out of the technology lock-in the car stock is subject to with petrol and diesel ICE vehicles (Ahman & Nilsson 2008), and that there is as yet no harmonised EU approach to alternative vehicle infrastructure.

The paper also contains a CNGV scenario showing that real-world emissions reductions from a 10% private car CNGV target (coupled with a 7.5% penetration of natural gas with biomethane) are 5.2% in 2020, compared with 0.3% emissions reduction due in the EV scenario. In terms of non-ETS emissions however, this changes to 5.6% emissions reduction for the CNGV scenario, and 9.1% for the EV scenario. While natural gas has lower greenhouse gas emissions per unit of energy than petrol and diesel, some fleet trials have seen CNGV performing worse than diesel vehicles they were replacing, due to the energy efficiency of compression-ignition engines (Green Truck Partnership 2012). It would be important

to combine any measure to encourage CNGVs with a plan for injecting biomethane to the natural gas grid in order to achieve the full emissions reductions as indicated. Options for introducing CNG to freight vehicles and to captured fleets could complement this target.

In the long run, pursuing targets for both EVs and CNGVs would be complementary: EVs covering short-distance travel demand (half of vehicle kilometres are from trips less than 30km) while CNGVs suits longer distance travel. CNGVs might also be a good hedging strategy if battery technology does not progress as well as expected.

Emissions results emerging from the *Flattened travel demand* scenario gives an interesting insight into the debate as to whether "efficient is sufficient" in the context of passenger travel technology. Each other scenario consists of an increase in stock efficiency or energy decarbonisation through technology advancement or fuel switching, and causes a decrease in emissions for a certain time, before a return to growth. Halting vehicle kilometre growth is the only scenario showing a continued decline in emissions, year-on-year, even compared with a scenario where all technology measures are in place.

Reducing travel demand can be a valuable hedging strategy given the risk of depending on uncertain technology development. The EU, however, is resistant to curbing mobility, stating in the White Paper on Transport that it is "not an option" as a means of achieving sustainable transport, based on the view that the availability and growth of transport as vital for the internal market and for the quality of life of citizens. If mobility is not to be curbed, then the only options for significant GHG reductions lie with either moving mobility to more energy efficiency and higher occupancy modes (public transport) or else moving towards highly efficient private car technologies. This paper has investigated the potential of the latter option, but the range of savings from measures is very broad, depending on implementation, as seen in the EV analysis.

The question of whether mobility management is necessary for reducing passenger transport emissions in a way which is consistent with EU climate targets is discussed by Johansson (2009), who concludes that it is theoretically possible to have a very mobile society in which transport does not negatively contribute to the climate, but there are limits to the use of low-cost fuels and technologies. He argues that with high fuel prices, however, renewable energy sources can be economically viable, but that the success of alternative and sustainable fuel sources is highly dependent on societal commitment to supporting new infrastructure, especially during a phase-in period where costs are still high. The case for curbing vehicle travel is also highlighted in the number of other externalities associated with traffic, namely congestion, noise and air pollution, space demand and road traffic deaths and injuries.

3.5.3 Efficiency measures

Efficiency measures affecting the new car fleet have very good long-term potential for reducing private car emissions: Improvements in vehicle technology and EU Regulation 443/2009 on performance standards for new passenger cars pave the way for a significantly more efficient car stock. The significant step-change in new-car specific emissions as a result of rebalancing the car tax regime in 2008, bringing Ireland close to meeting the goal of 130 gCO_2/km by 2015, shows how successful policy can be in bringing about improved energy efficiency.

In order to bring about further increases in private car fleet energy efficiency, Ireland's National Energy Efficiency Action Plan (DCENR 2008) sets the target of meeting the EU's target of an average specific emissions level of 95 gCO_2/km for new cars in 2020. This target is assumed to be met in SEAI's Baseline and NEEAP forecast scenarios (Clancy et al. 2010) and consequently is implicit in the EPA's With Measures scenario. However, the EU target is an obligation on vehicle manufacturers, not on countries, and applies to sales across the whole of Europe and so won't necessarily be met in individual countries without legislation. In this respect, Ireland has not made any legislative move towards meeting the 95 g/km target for 2020.

Results from the car stock model show that achieving this target about in Ireland can bring about significant emissions reductions, up to 0.4 $MtCO_2$ by 2020. This measure also can be designed to be revenue neutral through a rebalancing of tax bands. The rates would need to be carefully selected and monitored/evaluated up to 2020 to ensure there is a continuing incentive to reduce new car emissions and that it achieves revenue neutrality. The 2008 tax change failed in this respect as it was more successful and easier to achieve than anticipated (Rogan et al. 2011).

3.5.4 Caveats, limitations and recommended future work

Future energy demand depends on many complex parameters, some with higher uncertainty than others. Consequently, long term modelling is uncertain and what is more important here is not the absolute future projections of energy use in the different scenarios, but the scales of change associated with each scenario. The parameters modelled depend on the aspects of the energy system under question: In order to model the rebounding of activity and shifting in car sales patterns, price does feed into this model, but the main focus is on technological parameters, so there is a limit to the effect price has on the model. For example, the sales costs of different car types is not accounted for: Subsidies and other incentives are most likely to be needed to reach a 10% EV target, for example, but the device for achieving a goal like this is not modelled here.

Similarly, resource availability is related to price: Peak oil, the cost of lithium for EV batteries and the production of biofuels are all issues which will determine government targets and the cost of running different technologies in the future, but which are not covered here. The technical potential of renewables to reduce CO_2 is discussed by Johansson (2009).

In this model, private car vehicle kilometre travel is determined as a function of income, fuel price and simple government targets. In reality, this is a derived demand for passenger mobility and so is influenced much more widely: The transportation network, incorporating aspects of vehicle speed, geography, settlement patterns, trip choice and public transport availability and convenience, is the subject of extensive modelling (Nargurney 2000). Furthermore, by not incorporating other transport modes in this model, displaced emissions from private cars to public transport modes in the *Flattened travel demand* scenario are not calculated. The development of a transport network model, integrating mode choice, cost, energy demand and a bottom-up car stock model for Ireland is recommended in order that a wider range of policy measures is modelled.

3.6 Conclusion

From a planning perspective, ambitious goals for renewable energy growth and GHG emissions reductions exist for Ireland, but it is as yet unclear how precisely these targets will be achieved at a sectoral level and what the impact of individual policy measures will be. This paper approaches this issue focussing on private car transport, responsible for 13.5% of Ireland's energy demand, and the technological options available for mitigating emissions. The results show a wide variety of possible impacts which vary significantly according to the implementation of measures.

This paper finds that substantial energy and emissions savings can be made from policy measures in private car transport, but only when the level of car activity is controlled or new technologies and decarbonised fuels are continually introduced. If private car travel continues to grow in line with income, savings achievable from even very ambitious technological targets for 2020 will give insufficient emissions reductions, given the level of ambition in Ireland's non-ETS GHG emissions reduction target.

In an economic climate constrained by both resources available and legislative and regulatory obligations, it is prudent for governments to use evidence-based approaches to making energy and transport policy. This study has focussed on achieving Ireland's obligatory EU targets for 2020, but developing a more sustainable transport system is justified beyond meeting international commitments: A scenario

of oil supply shocks would be devastating to the Irish economy with the current transport system.

Recommendations arising from this study include firstly, a continued focus on demand-side measures along with technological improvements, secondly that strong consideration be given to a CNGV target, thirdly that a legislative target for new-car efficiency for 2020 is introduced, and finally, that care is taken to ensure EVs are rolled out in a way as to maximise their mitigation potential.

Part II

Passenger Transport Within Energy Models

Chapter 4

Modelling transport energy demand within LEAP-Ireland

4.1 Background[1]

Bottom-up energy demand modelling and a greater degree of sectoral disaggregation was identified by SEAI in the 2009 forecasting report as an potential area for improving Ireland's research base for informed policymaking (Walker et al. 2009). Energy forecasts in Ireland were aggregated and based on top-down macroeconomic assumptions, which had the potential for being incompatible with bottom-up energy savings estimates for particular measures. The advantage of building a disaggregated model of future Irish energy demand is that particular policies are modelled explicitly for their impact on energy service demand, technologies and fuel supply, and so several policies and measures can be grouped into future scenarios with consistent assumptions and avoiding double counting.

The tool identified for building a bottom-up baseline energy demand projection for each sector was the 'Long Range Energy Alternatives Planning (LEAP) System'[2]. LEAP is a widely used software tool for energy policy analysis and climate change mitigation assessment. The focus is on building scenarios for how energy is consumed and produced in a given region under a range of alternative assumptions.

[1]Chapter is based on extracts from publications leading from a project commissioned from the Sustainable Energy Authority of Ireland:
(i) Daly, H.E., Dineen, D., Rogan, F., Cahill, C. (2011) 'Bottom-Up Energy Demand Modelling - LEAP Ireland.' In *Energy Forecasts for Ireland to 2020, 2010 Report*, Sustainable Energy Authority of Ireland, Dublin
(ii) Cahill, C.J., Daly, H.E., Rogan, F, Dineen, D. & Ó Gallachóir, B.P. (2011), 'Functional Design Specification for LEAP Energy Demand Model for Ireland', submitted to the Sustainable Energy Authority of Ireland.
(iii) Rogan, F, Cahill, C.J., Daly, H.E., Deane, J.P., Dineen, D., Heaps, C. & Ó Gallachóir, B.P., (2012), 'LEAPs and Bounds – A Hybrid Energy Demand and Constraint Optimization Model of the Irish Energy System'. In preparation.

LEAP has flexible data structures, and so can be adapted depending on data availability and can be as rich in technological detail as required.

The University College Cork Energy Policy and Modelling Group has built a LEAP model for Ireland and produced a bottom-up energy forecast for the transport, residential and industrial sectors for SEAI's 2010 forecast report (Clancy et al. 2010), covering the transport, industry and residential sectors. The model has beed extended to include the services sector, some transport modes (passenger aviation and light duty freight) and the new programming feature OSeMOSYS is used to represent supply side electricity. The paper is the first to our knowledge that combines such detailed and varied sectoral representations with a cost-minimising optimisation approach for modelling the electricity sector within LEAP. For future demand projections we combine two packages of energy efficiency measures into scenarios termed *Energy Efficiency* and *Energy Efficiency+* and compare the results with a reference scenario.

This chapter is structured as follows: Section 4.2 contains a brief description of the Ireland LEAP model as a whole, introduces the three scenarios generated and gives results. Section 4.3 then describes in detail the modelling behind the transport sector. Section 4.4 presents results from transport, focussing on the electric vehicle (EV) target. Section 4.5 concludes.

4.2 Ireland LEAP model

The Ireland LEAP model has contributed to the Sustainable Energy Authority of Ireland's 2010 Energy Forecast Report (Clancy et al. 2010) and has been developed into a full energy demand and supply model by UCC's Energy Policy and Modelling Group (Rogan et al. 2012). This section summarises the collaborative project and paper.

The Ireland LEAP model contains five sectors – transport (as described below), residential, services, industry and agriculture. Each sector contains sub-sectors and is modelled according to data availability and the policies under question. The tree structure for all energy demand sectors is shown in Figure . The residential sector is represented using an archetypal dwelling type housing model. For each of these dwelling archetypes, the space-heating energy consumption (main and secondary) and water-heating energy consumption (main and supplementary) is calculated using an engineering heat flow model. The residential model is used to analyse the effect of historical and future building regulations and future building retrofit programmes on energy demand (Dineen et al. 2012, Dineen & Ó Gallachóir 2010).

[2] http://www.energycommunity.org/

The industrial sector is split into the participants of the EU Emissions Trading Scheme (ETS) and non-ETS industries, and energy demand is further split into 13 sub-sectors and ten fuel types. The modelling structure is a top-down approach, linking activity in each sub-sector to Gross Value Added (GVA) projections for different sections of the economy. Scenarios relating to energy efficiency, GVA, ETS and non-ETS shares and fuel shares are generated with this approach. The services sector is modelled using a simple top-down approach based on the national energy forecasts (Clancy et al. 2010) because data is limited.

Energy supply in the model is split into energy resources and electricity generation. Each fuel requirement is included in the model and fuel costs are taken from the IEA World Energy Outlook and adjusted for transport costs to Ireland. Electricity supply uses the new Open Source Energy Modeling System (OSeMOSYS), a linear optimisation module which ran with both daily and hourly time slices to match electricity supply with demand. It also determines which power plants are to be dispatched and which new capacity is to be built.

The scenario modelling period is 2009-2020. We model three scenarios, representing a reference scenario, which assumes that current energy demand patterns continue into the future, and two portfolios of policies scenarios: an energy efficiency scenario and an energy efficiency+ scenario.

- Reference scenario: Expected energy consumption in the business-as-usual, scenario, which excludes the impact of any future government targets or energy efficiency policies. It is not intended to be realistic, its main purpose is to enable quantification of the impact of the energy efficiency scenario and energy efficiency+ scenario.
- Energy Efficiency scenario (EE): Expected cumulative impact of all the sector-specific scenarios on energy consumption for a selection of current or proposed energy efficiency policies at probable implementation rates. Many of the energy efficiency policies in this scenario are in Ireland's National Energy Efficiency Action Plan (NEEAP).
- Energy Efficiency+ scenario (EE+): Expected impact on energy consumption of a selection of energy efficiency policies beyond their assumed rate of implementation; also includes exploratory scenarios for which no polices currently exist.

Table 4.1 contains a description of scenarios by sector while Figure 4.2 shows results by scenario and Table 4.2 gives the TFC for all sectors, sub-sectors and scenarios(Rogan et al. 2012).

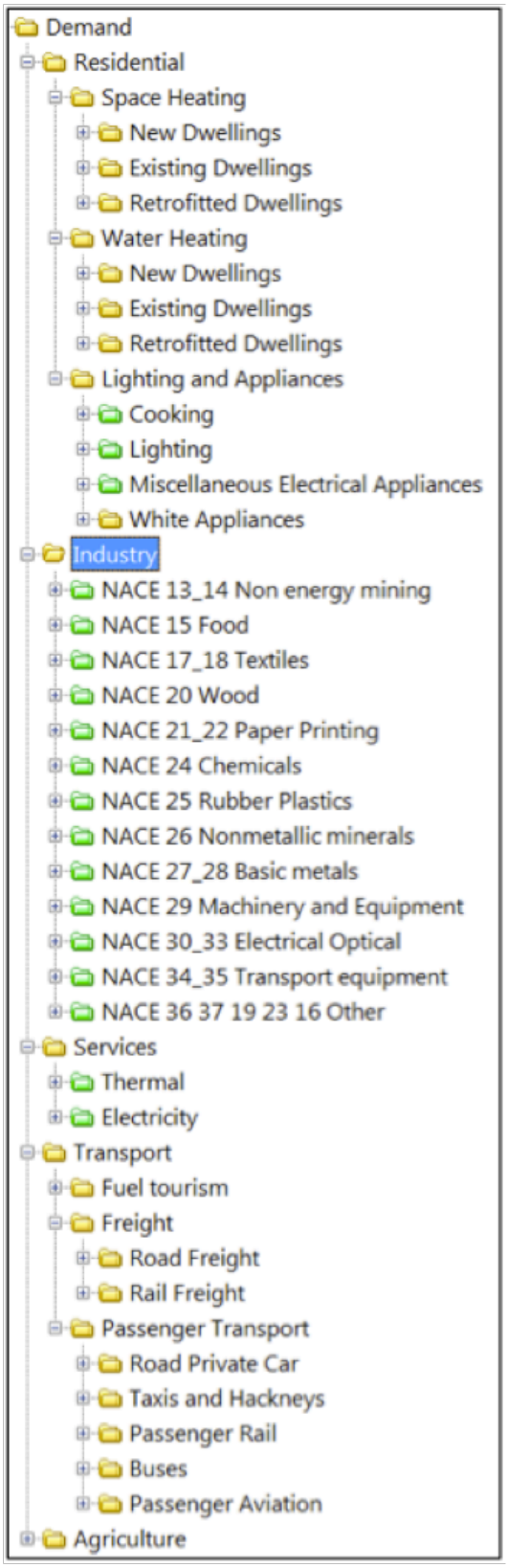


Figure 4.1: Tree structure for all energy demand sectors (Rogan et al. 2012)

Table 4.1: Scenarios by sector, sub-sector and policy (Rogan et al. 2012)

Scenario	Sector	Sub-Sector	Policy
Reference	All	All	business-as-usual
EE	Transport	Private Cars	electric vehicles
		Private Cars	private car demand
		Private Cars	efficient driving
	Residential	New Dwellings	building regulations 2010
		New Dwellings	building regulations 2013
		All Dwellings	CFL lighting
		Existing Dwellings	retrofit_average
EE+	Transport	Private Cars	high efficiency vehicles
		Private Cars	electric vehicles_best
		Private Cars/Trains/Buses	modal shift
		Private Cars	private car occupancy
	Residential	Existing Dwellings	retrofit_best
	Industry	All NACE categories	GVA change
		All NACE categories	efficiency change

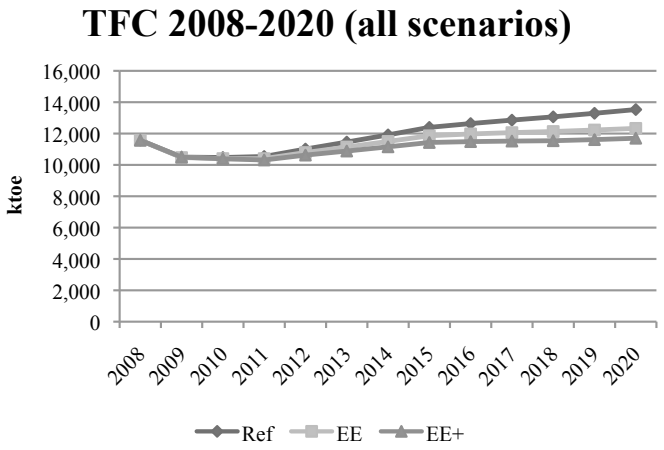


Figure 4.2: Total final energy consumption (ktoe) from Ireland LEAP model between 2008 and 2020 for three scenarios (Rogan et al. 2012)

4.3 Transport modelling methodology

A detailed passenger transport energy model in LEAP focusses on measuring the impacts from energy efficiency policies on future energy demand. A baseline scenario, assuming past trends continue into the future, is a reference case on which savings from different scenarios are measured. The bottom-up nature of the baseline model readily allows scenario analysis which measure improvements due to technological efficiency. Energy savings from the 10% electric vehicle (EV) target, from the 2008 car tax change and from the EU target for new-car efficiency have been quantified using LEAP. This model has also been developed with the capacity to measure savings from modal shifting and efficient driving and the impact of increased biofuels penetration.

Table 4.2: TFC for all sectors and sub-sectors for base year (2008) and all scenarios (2020) (units: ktoe) (Rogan et al. 2012)

Sector	Sub-Sector	Base Year	Reference	EE	EE+
Transport	Fuel Tourism	421	295	295	295
	Freight	929	951	951	951
	Road Private Car	1,921	2,106	1,327	1,218
	Taxis & Hackneys	53	71	67	65
	Passenger Rail	50	100	102	101
	Buses	113	230	217	223
	Passenger Aviation	486	996	996	996
	Subtotal	3,975	4,750	3,954	3,848
Residential	Space Heating	2,006	2,127	1,790	1,535
	Water Heating	704	756	715	677
	Lighting	91	62	36	36
	Cooking	110	138	138	138
	Appliances	389	619	619	619
	Subtotal	3,300	3,702	3,297	3,005
Industry	All NACE Categories	2,517	3,256	3,256	3,025
Services	All Sub-Sectors	1,782	1,822	1,822	1,822
	Total	11,573	13,530	12,330	11,701

This section focuses on the modelling of the baseline scenario for passenger cars, buses, passenger rail and aviation, and presents the results of three scenarios relating to the 10% EV target, employing a range of assumptions surrounding the technology of EVs introduced and the types of cars they displace. The EV target is chosen here as an example to illustrate how LEAP operates and the type of outputs it provides. The model has the capacity to model a range of other policy measures as already mentioned

4.3.1 Passenger cars

External to LEAP, a private car stock model was developed by Daly & Ó Gallachóir (2011*a*); this is incorporated into the Ireland LEAP model using the Transport Analysis demand mode and is extended to include taxis and hackneys. The LEAP passenger car sector disaggregates the Irish car stock into a demographic and technological model, explicitly incorporating the vehicle efficiency and mileage profile of cars across engine types (according to cylinder capacity, cc) and vintages. The overall annual mileage of the car stock (in vehicle kilometres, vkm) and annual car sales is modelled based on a top-down econometric model incorporating the year-on-year percentage change in national income (Bergin et al. 2010) and fuel price (Capros et al. 2008); income and price elasticities with respect to sales and activity are taken from a study of car energy demand (Johansson & Schipper 1997).

Details and sources for vehicle retirement rates, mileage profile, specific fuel consumption are described by Daly & Ó Gallachóir (2011*a*). Energy demand for each year is calculated as the product of stock, distance travelled and specific energy

consumption in each technology and age category. The bottom-up, technology rich methodology for passenger cars is enabled by the availability of good data for car registrations, activity and efficiency and it readily allows scenario analysis that measures improvements due to technological efficiency, overall travel reduction, modal shift, switch to biofuels and efficient driving.

4.3.2 Public passenger transport

Passenger rail is divided according to five main services: DART and LUAS (both urban light rail systems), Dublin suburban, mainline services, and international travel (between Dublin and Belfast). Based on the average annual growth for overall passenger rail travel (in passenger kilometres, pkm) between 2000 and 2008 (Central Statistics Office 2008), a annual growth rate of 6% is applied for the model time horizon (2009-2020). A final energy intensity of 1.06 MJ/pkm is calculated as the quotient of overall energy demand (Howley, Ó Gallachóir & Dennehy 2009) and overall rail travel in pkm, and is kept constant over the model time horizon.

Bus travel is disaggregated into Dublin suburban, Ireland intercity, school buses, touring coaches and other scheduled services (mostly town and city routes). Energy demand data for each of these modes is available from fuel excise duty relief receipts; vehicle kilometre data is available for Dublin Bus and Bus Èireann (Central Statistics Office 2008) and these are used to calculate fuel intensity values of 10.8 MJ/vkm for inter-urban routes and 19.9 MJ/vkm for urban routes. We apply a 6% annual average growth rate for overall bus travel, reflecting the rise between 2000 and 2008, and energy intensity values are kept constant over the future modelling horizon.

4.3.3 Aviation

A forecast for domestic and international aviation energy demand is taken from Dineen (2009). In this report, a projection for international aviation passenger numbers is based on an econometric origin-destination model of tourism destination choice, and domestic aviation activity is based on current regional travel and population projections. In our model, energy demand is calculated using the weighted average fuel demand per passenger and weighted average flight distance to each region.

4.3.4 Freight transport

Freight transport demand is divided into road freight and rail freight. Road freight is further divided into light goods vehicles (LGV) and heavy goods vehicles (HGV).

HGV energy demand forecasts are based on a study by Whyte et al. (2012), which takes a commodity-based approach to projecting tonne-kilometre (tkm) demand based on projections for sectors of the economy (Bergin et al. 2010). Specific energy consumption in MJ/tkm for each vehicle class, based on unladen weight, was based on a Finnish study.

Poor data exists for LGV in Ireland, so a simple top-down activity-based model is implemented. National GDP forecasts are used as the explanatory variable driving LGV activity (in vehicle kilometres, vkm) with an elasticity of 1. An average efficiency for LGV in 2008 of 3.03 MJ/vkm is calculated based on 2008 activity data and total LGV energy demand from the Energy Balance (SEAI 2011).

Rail freight energy demand is modelled similarly to LGV demand, except tonne-kilometres are assumed to remain at 2008 levels (Central Statistics Office 2008); an energy intensity value of 0.7 MJ/tkm based on a UK Climate Change Working Group report (McKinnon & Piecyk 2009) is used.

4.4 Electric vehicle scenarios

The baseline scenario for passenger cars cars comprises a forecast of energy demand where growth in car sales is tied to an assumed recovery of the economy, and the technology profile of new cars remains as it was in 2009. The total car stock rises from 1.91 million cars in 2008 to 2.02 million cars in 2020, and fleet activity rises from 29.6 billion vehicle kilometres (bvkm) to 33.2 bvkm in 2020. Baseline private-car energy consumption grows in this scenario from 1,920 ktoe in 2008 to 2,116 ktoe in 2020, a rise of 10%. This is as a result of growth in the larger cc bands in the 2000s.

Three EV scenarios are developed to demonstrate the potential impact on energy demand of a 10% EV target for 2020. The scenarios are developed by varying the sales technology profile. Three EV scenarios give a range of outcomes from an upper-bound 'best case' to less successful scenarios with fewer energy savings. The three EV scenarios are summarised as:

- The most optimistic scenario, EV_bestcase, assumes that high-efficiency (0.58 MJ/km) and high-mileage EVs will displace the less efficient (2.51 MJ/km) and higher-mileage (20,148 kms/year) cc bands above 1,500 cc.
- EV_average assumes that new EVs (0.72 MJ/km) will displace average internal combustion engine sales and mileage (efficiency 2.25 MJ/km and 16,032 kms/year).
- EV_low gives a scenario in which EVs have lower mileage than the stock and displace the smaller petrol engines, which are generally used as city and second

family cars for shorter trips (0.95 MJ/km EVs displacing 2.21 MJ/km cars travelling 13,000 kms/year).

Figure 4.3 shows the new-car and stock-average fuel efficiency for each of the four scenarios. Efficiency is measured in terms of energy, MJ/km, as diesel has a higher energy content than petrol and the growing share of the former would show greater efficiency improvements if measured in terms of fuel volume. Figure 6 shows the energy consumption in each of the four scenarios, with the best-case EV scenario giving energy savings of 8.7% for 2020 compared to the baseline scenario, with the efficiency gained displacing the rise in car travel. EV_low and EV_average give savings of 2.5% and 6.5% respectively.

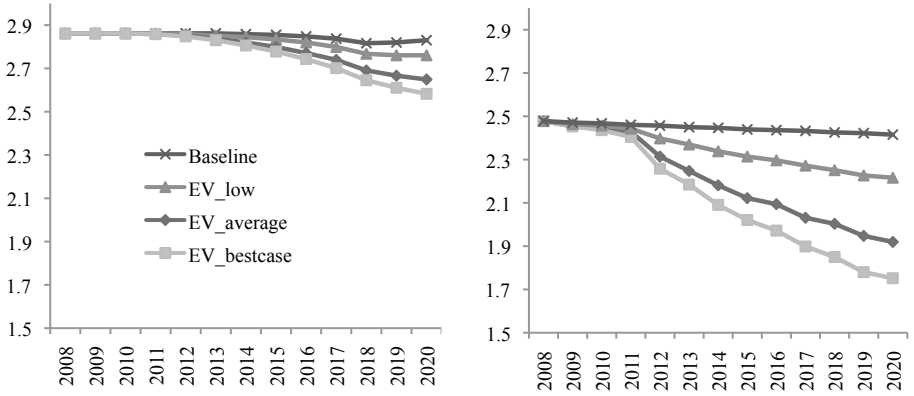


Figure 4.3: New-car and stock-average fleet efficiency in MJ/km for LEAP reference and EV scenarios

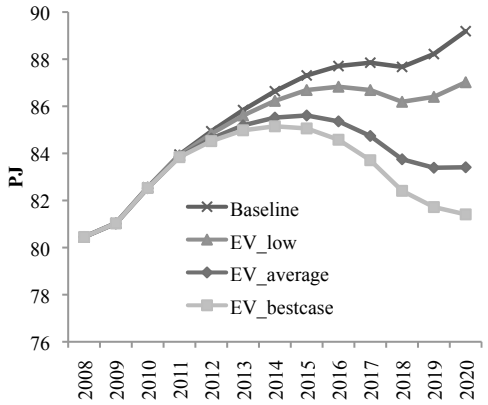


Figure 4.4: Total final energy consumption (PJ) from private cars under a baseline and three EV scenarios

4.5 Conclusion

This model has demonstrated the capabilities and flexibilities of LEAP: It incorporates a wide range of modelling techniques that are sector specific and published models in their own right which have been used to evaluate different energy efficiency policies. This model ties them together and the bottom-up nature allows policy scenarios to be combined into aggregated portfolios of measures, as was shown for the EE and EE+ scenarios. The potential role for LEAP in Ireland as an energy planning tool has been acknowledged in Ireland's national energy forecasts: "The long-term vision is to use LEAP-Ireland as a planning tool for assessing the future impacts of possible energy efficiency policies and measures, complementing and providing an alternative perspective to ongoing macro-economic modelling" (Clancy et al. 2010).

Chapter 5

Private car energy demand: Comparing two techno-economic approaches for Ireland

This paper compares two approaches to projecting private car energy demand using two techno-economic models developed for Ireland. A car stock model (CSM) uses historic sales, activity and scrappage rates to iteratively simulate the structure of the car fleet and vehicle activity for each year up to 2050. Imposed technologically-oriented scenarios, such as Ireland's 10% electric vehicle target, can determine the impact of emerging technologies or policy measures on baseline energy demand and contribution towards climate targets. In contrast, the Irish TIMES model is an energy optimisation framework for the Irish energy system which identifies the least cost technology mix to satisfy a specified energy service demand, subject to renewable and emissions constraints. Both models have been developed independently. We describes the results of both in terms of energy service demand, technology selection and final energy demand, and compares the underlying theoretical frameworks which give rise to different results. The models are complementary, and the outputs of each can inform the inputs of the other. We describe a way of soft-linking the models and give results. [1]

5.1 Introduction

The case for energy policy modelling is strong in Ireland, which faces stringent climate change targets from the EU which are likely to be strengthened by a domestic

[1]This chapter is based on a workshop paper, Daly, H.E., Gargiulo, M, & Ó Gallachóir, B.P., (2011). 'An integrated energy systems and stock modelling approach for modelling future private car energy demand.' *International Energy Agency ETSAP meeting*, July 9th 2011, Stanford, USA.

climate change bill. Arising from EU Decision 406/2009/EC, non-emissions trading sector (non-ETS) CO_2 emissions, compromising the services, transport, residential and small industry sectors, are required to be reduced by 20% on 2005 levels by 2020. The 20% reduction imposed on Ireland is the strictest of all EU member states along with Denmark and Luxembourg, because the burden of emission reductions was distributed in 2008 according to each country's relative wealth, when Ireland had a relatively high GDP. Since then Ireland entered into an economic recession, where GDP has declined by 12% in the three years 2008-2010 (Barrett et al. 2011). The cost of reducing carbon emissions is therefore now more pressing for a government that has cut spending and increased taxation. Furthermore, the Irish government has published a climate change bill, which extends carbon emissions targets to a 40 per cent cut relative to 1990 levels by 2030 and 80 per cent relative to 1990 levels by 2050.[2]

Private car transport is a particular sector for focus for carbon reductions in Ireland, with transport representing 30% of non-ETS emissions in 2008 and cars being the most significant mode. Little has been achieved to reduce the footprint of cars, whose energy demand has grown by 37% between 2000 and 2008 and not decoupled from economic growth as in other sectors. In 2009, renewable energy in road and rail transport (RES-T) was 1.5%; EU Directive 2009/28/EC sets a mandatory target of 10% by 2020, which won't be met without the introduction of alternatively fuelled vehicles. The EU has also set an upper limit for the average emissions (gCO_2/km) of new passenger cars of 130g/km by 2015 (European Commission 2009), and transport energy has also been the focus of recent domestic policies, the most significant being a target that 10% of Irish road vehicles are to be electrified by 2020. Biofuel blending in non-aviation and marine transport fuels is also a focus (Government 2010).

The need to quantify the cost towards reaching these targets has been highlighted in public debate; these particular regulations and targets have given a need for effective policy modelling, particularly in the area of transport. Two models have been created for this end; a car stock-based bottom-up demographic forecasting model which compares the results of differing technological scenarios, and a whole energy systems model, of which private cars are a part, which cost-optimises the technology mix up to 2050 given different climate constraints.

In Section 5.2, the two modelling paradigms are compared through an analysis of their respective assumptions, equations, inputs and outputs. Section 5.3 describes the integration the models through 'soft linking' model outputs and inputs, and how both models are used to give insights into Ireland's future with respect to climate targets and specific technology-orientated measures.

[2]The Irish Climate Change Bill, 2011, was abandoned before passing through legislation because of a change in government in April 2011.

5.2 Two modelling frameworks

Energy systems modelling can have an instrumental role in setting climate and energy targets, the formulation and planning of specific policies, and the ex-ante evaluation of policies for efficiency and cost effectiveness: Strachan et al. (2009) describes a MARKAL-Macro energy-economic model which was used to inform the development of the UK's 2050 carbon dioxide reduction target of 60%. Energy models can also be used for visioning the future by describing the technological and structural changes needed in order to reach a visionary target, for example through backcasting (Hickman & Banister 2007). Mundaca et al. (2010) reviews and classifies bottom-up energy-economy models using the residential sector as an example, and concludes that while such models have gained wide acceptance for informing policy instruments, there is limited literature on their development, use and evaluation.

Two such techno-economic energy models of the Irish energy system are the subject of this research. Both are bottom-up, in that technological detail is an important component (Jebaraj & Iniyan 2006).We firstly examine the transport module in the Irish TIMES model (Ó Gallachóir et al. 2012). The second model in question is a car stock model (CSM), which builds a technological model of private car energy demand by disaggregating the car stock, activity and on-road efficiency by the technology and demographic profile of the fleet (Daly & Ó Gallachóir 2011*b*).

5.2.1 Private cars in Irish TIMES

TIMES (The Integrated MARKAL-EFOM System) is an economic model generator which estimates energy dynamics over a long time period. The Irish-TIMES model has been created to represent the entire energy system; the user inputs the energy service demand of each sector (ESD, freight tonne-kms, lighting or heating, for example), provides the capacities and costs of available technologies, and TIMES selects technologies to serve the demand such that the system is the least cost under a range of climate constraints. TIMES can be used to study one sector in detail. For example, Gul et al. (2009) uses MARKAL to examine the global prospective for alternative transport fuels. TIMES as a modelling tool is a type of hybrid model, combining the technological richness of a bottom-up model while still representing the macro-economy.

Private cars are one component of the Irish TIMES model. The energy service demand, passenger kilometres (pkm) are forecast econometrically using GNP macro forecasts and elasticities. Pkm is divided into long journeys and short journeys, as technology types can fill long and short journeys at different rates, due to limited range of, for example, battery electric cars. Calibrated to 2005 data, "current"

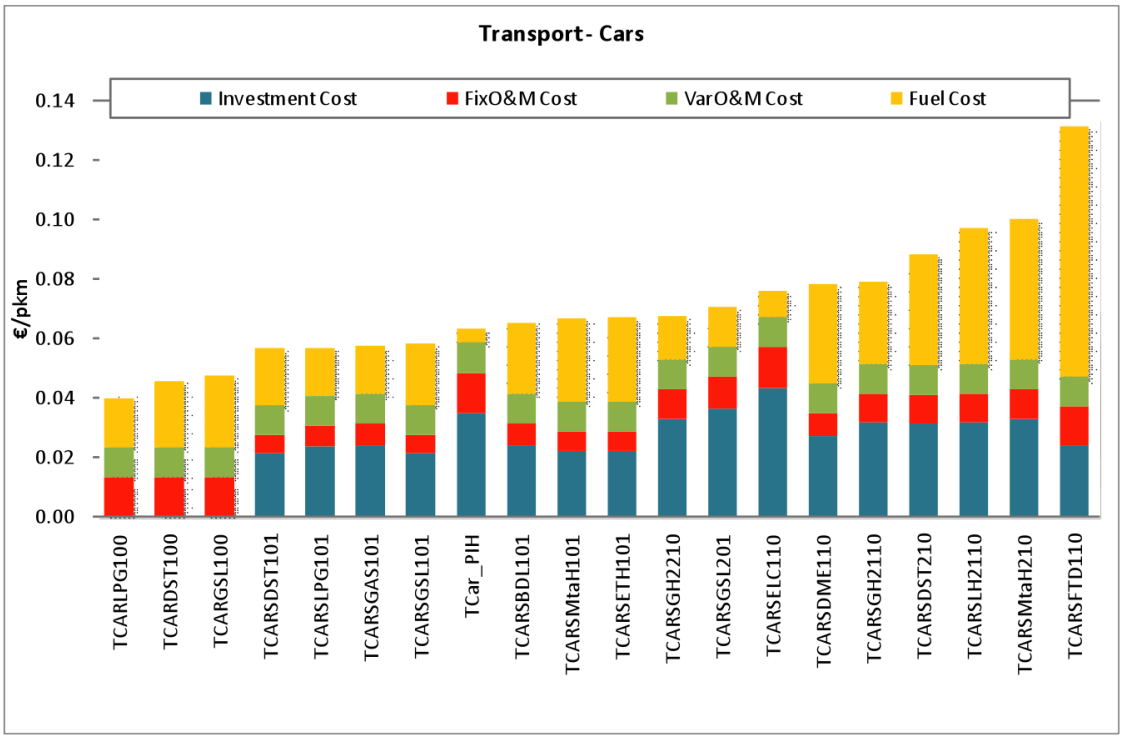


Figure 5.1: Costs of private car technologies in the Irish TIMES model, in €/km.

technologies in the system are used and expire at a rate of 10% per year, and are replaced by new technologies to fill the ESD. Using the available technologies to the model – petrol, diesel, LPG, E85 ethanol, biodiesel, battery electric, CNG, hydrogen, biogas – and each technology's respective investment, operations and fuel costs and annual capacity (kilometres driven), the technology mix is optimised over a given time frame to minimise the total system cost. Scenarios are run to simulate policy targets by constraining climate variables: Renewable energy as a percentage of final energy consumption, greenhouse gas emissions, and energy security.

5.2.2 Car stock model

The CSM forecasting methodology is an energy simulation model whose power largely lies in describing the future structure of energy demand given exogenously determined vehicle sales scenarios. For example, future aspirational targets are assumed met, such as a cap on new-car tailpipe emissions, without describing the economic developments needed in order to reach that target In the stock model, cars are disaggregated into technological categories: firstly by fuel type (petrol, diesel, hybrid electric, battery electric, CNG etc) and further by engine type (0-900cc, 15-20 kWh battery etc), and finally by vintage. Historic data for the number of cars registered in each subcategory in Ireland was made available, analysis of odometer readings from the National Car Test gave disaggregated mileages, and official car test

results provided new-car specific energy consumption and emissions. Daly & Ó Gallachóir (2011*a*) describes the data sources and bottom-up energy calculation methodology for modelling historic Irish private car energy demand used in this model.

The historic energy model is then simulated into the future. In this simulation model, the demographic features of each technology type – sales according to national GNP growth and car retirement rates – are used to iteratively simulate the stock in each category for each year T in the forecasting time horizon. Irish drivers tend to import second-hand cars from the UK, and this rate is incorporated into the scrappage factor, which is in fact greater than 1 for younger cars. Total sales are forecasted econometrically using elasticities and GNP forecasts. Secondly, total stock mileage is calculated independently to the composition of the stock, and is determined using GNP and fuel price forecasts and elasticities. The patterns of annual mileage by vintage and technology category are replicated. Finally, new car efficiency and the distribution of new car sales over technology types depends on exogenously determined scenarios.

The model does not predict the structure of new car sales, but uses scenarios to predict the impact of different vehicle technology sales scenarios on the on-road fleet efficiency, taking into account the stock and distance driven of vehicles across vintages and technologies. This is a very useful tool for demonstrating the relative consequences of different technology targets, for example, targets for electric vehicles versus for biofuel vehicles, or the impact of incentives for more fuel efficient vehicles.

5.2.3 Comparison of methodologies

The differences in the stock modelling and energy systems approaches are quite complementary and allow scope for integration, work which is ongoing. A study by Kannan & Strachan (2009) compares the residential modelling approaches and results of the UK MARKAL model and several stock approaches. Table 5.1 contrasts the CSM and TIMES methodologies for modelling private car demand. The power of the stock simulation model is in calculation and description: it can give good insight into the future dynamics of the fleet with regard to the drivers of energy consumption; it is a descriptive model. In contrast, the TIMES approach is prescriptive: it selects technology to best achieve certain goals. For the CSM, while macro variables drive travel demand and car sales, there is no interaction with power generation or other sectors, and no trade-offs with emissions saving technologies in other sectors, and exogenous emissions factors are used. Technology and sales assumptions are imposed on the model, and the effects in terms of contribution towards targets is inferred. In contrast, climate targets are imposed on the whole energy system in TIMES, and the model outputs the optimum technology to meet the demands and

climate targets at least cost.

Table 5.1: Broad analytical comparison of the two modelling frameworks

	CSM	Private Car in Irish TIMES
Baseline inputs	Base year stock, scrappage profiles, mileage and aged efficiency by technology and vintage; GNP forecast and sales and activity elasticities	Available technologies, capacities and associated costs; future passenger kms.
Costs	Technology cost not included	Capital, OM, fuel costs defined for each technology
Scenario inputs	Sales by technology types; new car efficiencies; fuel mix	System-wide climate constraints
Purpose	Evaluates specific technology measures Forecasting pkm	Informs cost effective technology measures given climate targets Least cost technology mix for each scenario; Marginal cost of CO_2
Targets	Implications of policies for targets may be inferred from results	Targets imposed on model
Model	Car stock demographic model Forecasts passenger kms	Linear optimisation Pkms determined exogenously
Level of disaggregation	High: 17 vintaged technology types. Each technology type has an associated efficiency, mileage and scrappage pattern.	7 vehicle technologies, no vintaging. Mileage or scrappage not disaggregated. Distance travelled divided by "long" and "short" distance.

We propose to develop both models by integrating them in two ways: Firstly, using the technology selection in TIMES as a baseline input for the sales profile in the CSM, which is currently static at 2009 levels. Secondly, using the CSM vehicle activity output to model the private car mode in TIMES in more detail: Because of vintaging and disaggregating mileage by technology, the stock model produces the stock average on-road efficiency (SEC) more accurately.

5.2.4 Comparison of model outputs

Figure 5.2 shows private car energy demand, vkms and fleet efficiency results from the reference scenarios of the CSM and from TIMES, as well as from an 80% CO_2 emissions cap for 2050 in TIMES. It is clear that the derivation of vehicle activity causes significant divergence in the models, with 2050 TIMES vkms 55% greater than the CSM. The static baseline technology assumption in the CSM in the fleet efficiency, which becomes flat as current cars are retired out of the model. Energy intensity decreases in the TIMES reference scenario, dramatically in the CO_2 reduction scenario, where the model selects plug-in hybrid electric vehicles in order to

decarbonise the system. Notably, vkms are the same in TIMES for both scenarios, as behavioural change or elastic demand is not modelled.

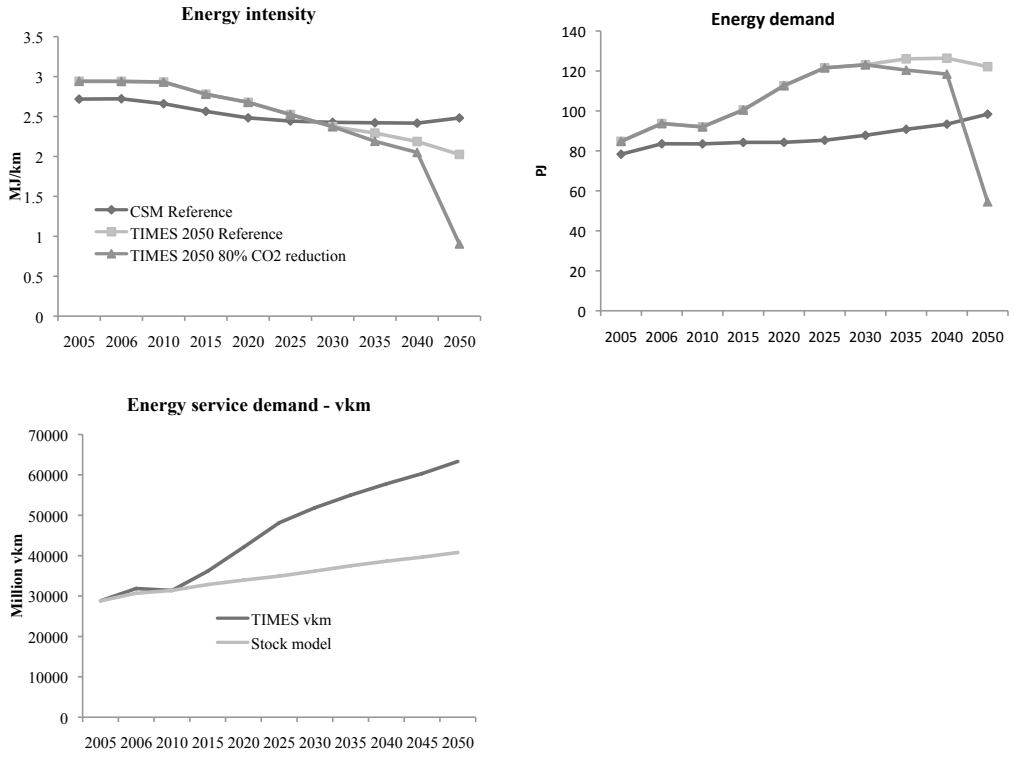


Figure 5.2: Comparison of the characteristics from the Car Stock Model and private cars in TIMES under a reference scenario and a CO_2 constraint scenario.

Figure 5.3 shows projections of travel and freight demand for each mode to 2050, indexed on 2005 levels.

Figure 5.4 shows the technologies selected by TIMES in the reference and CO_2 reduction scenarios by vehicle activity. Diesel dominates both scenarios by 2030, and plug-in hybrid electric vehicles are selected in the constrained scenario, increasing the efficiency of the stock as shown in Figure 5.2. In contrast, the profile of vehicle activity generated in the CSM reference scenario reflects the 2009 sales profile which is simulated into the future.

5.3 Soft linking models

The econometric assumptions underpinning the models are the major source of difference in results, and the first step in integrating the approaches is to bring these assumptions in line. The comparisons above highlight the difficulty in comparing different models with differing objectives and methodologies.

The aim of this study is to improve each model by using outputs of each to inform

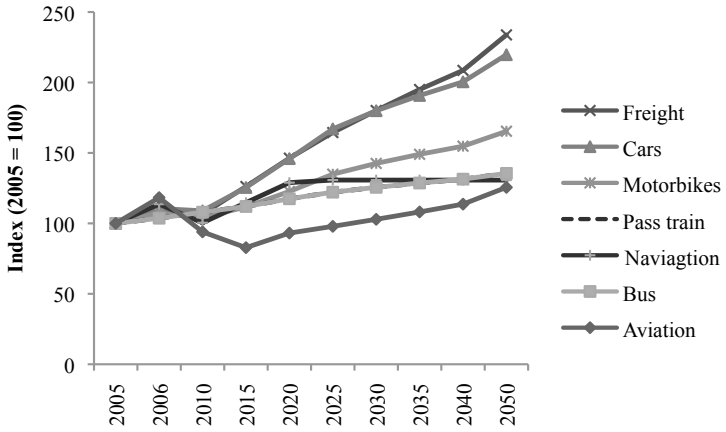


Figure 5.3: Projections of travel demand in Irish TIMES for each passenger mode (pkm), for freight (tkm) and for aviation and navigation (PJ) indexed on 2005.

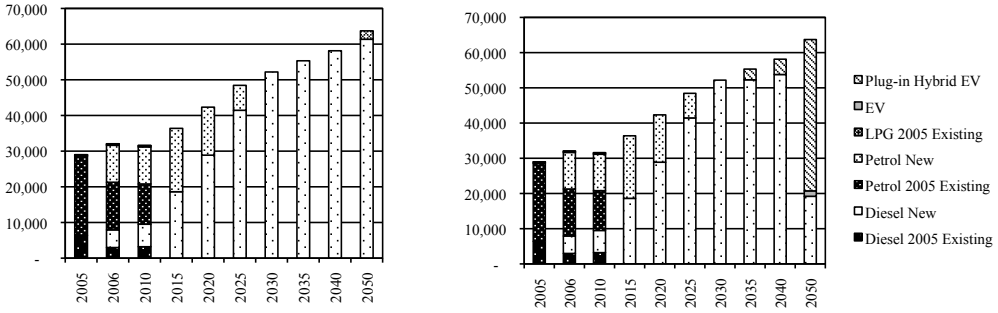


Figure 5.4: TIMES private car technology capacity in vehicle kilometres, Reference and CO_2 Constraint scenarios

inputs of the other. Firstly, we develop the TIMES energy systems modelling approach by using the stock model to supply elastic energy service demand. This has been done with the Irish TIMES Phase 2 stage of calibrating demand assumptions. This brings the model demands in line.

Secondly, the technology selection results from TIMES scenarios are simulated using the car stock model. This has two advantages: The car stock model gives a more detailed picture of private car energy demand, because the stock is highly disaggregated and travel demands reflect technology type. Furthermore, this strategy allows scenarios from TIMES to be compared with a wider range of scenarios generated in Chapter 3.

5.4 Conclusion

We have included results from both modelling approaches in order to highlight firstly the purposes of the respective models, and secondly to highlight the

complementary nature of the models. The stock modelling approach gives a detailed picture of the evolution of the car fleet under different sales scenarios, while the TIMES model gives a cost-optimal technology mix under system-wide climate constraints. The assumptions of both models have been brought into line so that results are comparible and replicable. Work is ongoing to extend TIMES analysis to the RES-T target, and we propose to encorporate modal shift into the transport sector.

This approach is not limited to private car transport; stock modelling approaches are common in transport in general and the residential sector (Mundaca et al. 2010).

Both models are techno-focused: neither accounts for driver behaviour and so softer travel measures – ride sharing, public transport initiatives, for example – are generally not, and therefore are in danger of being overlooked in policy decision making should purely technology models be considered. Furthermore, technology costs and availability are uncertain over such a long 40-year time span, as is the economic outlook.

Chapter 6

Modelling Modal Choice Behaviour in a TIMES Energy System Model

Abstract

Achieving ambitious climate change mitigation targets clearly requires a focus on transport that should include changes in travel behaviour in addition to increased vehicle efficiency and low-carbon fuels. Most available energy/economy/environment/engineering (E4) modelling tools focus however on technology and fuel switching and tend to poorly incorporate travel behaviour. Travel demand for each mode is typically fixed, so switching between modes is not featured. This paper describes a novel methodology for incorporating competition between private cars, buses and trains in a least-cost linear optimisation E4 model, called TIMES. This is achieved by imposing a constraint on overall travel time in the system, which represents the empirically observed fixed travel time budget of individuals, and introducing a cost for infrastructural investments, which reduces the travel time of public transport. Two case studies from California and Ireland are developed using a simple TIMES model, and results are generated to 2030 for a reference scenario, an investments scenario and a CO_2 emissions reduction scenario. The results show the significance of modal shifting in the CO_2 mitigation scenario.[1]

Keywords Modal choice; travel behaviour; energy systems modelling; climate mitigation

[1]This chapter is based on a submitted journal paper: Daly, H.E., Ramea, K., Chiodi, A., Yeh, S., Gargiluo, M. & Ó Gallachóir, B.P. (2012) 'Modelling modal choice behaviour within a linear energy system model.' *Submitted to Energy on September 30th 2012.*

6.1 Introduction

6.1.1 Background

Transportation contributes to 23% of energy-related CO_2 emissions globally. With increasing demands especially for light-duty vehicles, freight, and aviation, global transport CO_2 emissions are expected to double by 2050 (IEA 2010*b*). Reducing greenhouse gas emissions from the transport sector will require complementary policies in improving the efficiency of vehicles, introducing low-carbon fuels and advanced vehicles technologies, and better travel demand management (Schafer & Heywood 2009). Most of the growth in demand for cars will come from developing countries, as car travel in developed countries essentially saturated, and is projected to remain flat in the next few decades. On the other hand, public transport and aviation already play an important role in many developed (especially Europe) and developing countries, and are expected to play an even greater role in the future, given the need to drastically reduce on-road transportation emissions in order to meet stringent climate targets (Fulton et al. 2009, IEA 2010*a*).

However, while most of the integrated assessment (IA) models that governments rely on for developing climate mitigation policies have been able to project portfolios of advanced fuels and vehicle technologies given climate goals, most of these models are ill suited to examine potential travel demand changes and travel mode shifts given climate policies and changes in fuel prices, and most importantly the necessary investments needed to reduce vehicle travel, increase public transport shares, and non-vehicle infrastructure given climate goals (Schafer 2012). Most IA models use scenarios describing future travel modal shifts without explicitly linking demand changes to drivers (e.g. fuel price changes) or infrastructure and technology investment decisions. This is evident in Figure 6.1 and other studies (Fulton et al. 2009, IEA 2010*b*).

A recent seminal paper by Schafer (2012) provides a critical review of the (lack of) modelling of behavioural changes in transportation in energy/economy/environment/engineering (E4) models, compares common methodologies employed in IA models, their shortcomings and gives recommendations for future improvement. This paper states that "Overall, introducing behavioural change in transportation into E3 models is feasible and intellectually rewarding. However, when pursuing holistic approaches to mitigating energy use and emissions, it is indispensable." Our paper explores some of the recommended methodologies and applies them for the first time in the bottom-up optimisation modelling framework using the TIMES model and implements this in two case studies based on the Californian TIMES model and the Irish TIMES model.

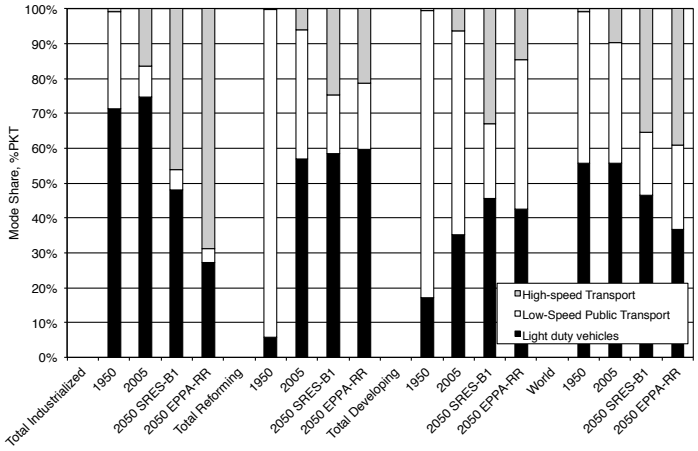


Figure 6.1: Relative share of transport modes in the three meta-regions and the world, in history (1950 and 2005) and in projections (2050) based on various scenarios. SRES-B1: Special Report on Emissions Scenarios – SRES, rapid economic growth and advanced technology scenario. EPPA-RR: MIT Emissions Prediction and Policy Analysis (EPPA) CGE model. Source: Schafer & Heywood (2009)

This paper describes the TIMES modelling framework and reviews the role of transport in energy models and key underlying concepts of travel behaviours in Section 6.1.2, introduces the concept of travel time budgets in Section 6.1.3, describes the methodology in Section 6.2, introduces and compares the case studies in Section 6.3, presents results in Section 6.4 and concludes in Sections 6.5 and 6.6.

6.1.2 Transport modelling and energy systems models

Transport modelling is a very well established discipline used widely by decision-makers for planning infrastructure such as airports, roads and railways, for cost-benefit analyses, and environmental impact assessments. Transport planning models typically simulate travel trips by origin and destination, trip purpose, mode of travel and household demographies. Multinomial logit (MNL) modelling is often used to compute mode choice for trips between each origin and destination (de Dios Ortúzar & Willumsen 2001). This methodology functions the utility associated with alternative modes and includes the variables that describe the attributes of alternatives, which influence the utility of all members of the population, and variables which influence people's preferences, or choices, among alternatives.

For example, the travel time, comfort, reliability and walking distance associated with alternative modes are valued differently by different groups of people. MNL models then reflect the characteristics of the transport system and of the decision makers. MNL models have the following mathematical formulation:

$$P(i) = \frac{e^{V_i}}{\sum_{j \in J} e^{V_j}}$$

where $P(i)$ is the probability of alternative i being chosen, V_i is the utility associated with alternative i, and $j \in J$ is the set of all alternatives (Koppelman & Bhat 2006). This results in a monotonically increasing probability in alternative i being chosen as the utility of i increases, and a decreasing probability with the increase in utility associate with other alternatives. The value of time can be included in the utility equation, which is associated with increasing income, and so an increase in national per-capita income can lead to a move towards faster modes.

Behaviour is generally a strong element of transport models, as well as detail of the transport network. There is generally very little or no treatment of energy demand in transport planning models: They can be suitable for projecting travel (and hence energy) demand, but not for analysing trade-offs in climate mitigation policymaking.

On the other hand, E4 models explicitly look at the energy system to examine issues ranging from macroeconomic interactions to looking at pathways to meeting climate mitigation scenarios. The TIMES model, used to implement the approach described here, is a bottom-up energy systems model developed by the Energy Technology Systems Analysis Programme (ETSAP), an IEA Implementing Agreement (Ó Gallachóir et al. 2012). Energy systems models like TIMES are generally partial equilibrium linear optimisation models, with very rich technological detail of the entire energy system, from fuel production and imports to energy conversion and demand technologies. The total system cost is minimised over a time horizon subject to user-defined constraints, such as maximum system-wide CO_2 emissions and technical constraints. Demands are generally exogenously projected, and can be derived from other models. A facility for elastic demand is available in TIMES, where end-use can be a function of price or income. The full technical documentation of the TIMES model is available in Loulou et al. (2005).

TIMES is typically very detailed in technologies, fuels and system-wide interactions. A common use of TIMES/MARKAL models is developing least-cost pathways for meeting long-term climate targets (Strachan et al. 2009, Ó Gallachóir et al. 2012), but the nature of the model restricts these pathways to showing only fuel and technology options. Travel demand (measured in terms of passenger kilometres travelled, or PKT) for each mode is individually inputted into the model over the time horizon, and technologies within that model compete to meet the demand at least cost, subject to system-wide constraints.

Figure 6.2, for example, shows passenger transport energy demand by mode from an Irish TIMES scenario which meets a 20% decrease in non-emissions traded emissions

(based on 2005) by 2020. Demand for each transport mode is based on forecasts generated by the ESRI HERMES macroeconomic model (Bergin et al. 2010) and technologies to provide the service demand are selected on the basis of least cost in order to satisfy the demands, subject to constraints. Figure 6.2 shows that some fuel switching occurs in transport in the climate mitigation scenario for 2020, with some efficiency improvements in freight. However, as demand in each mode is fixed, mitigation pathways cannot feature shifting from low efficiency modes (private cars) to higher efficiency modes (public transport).

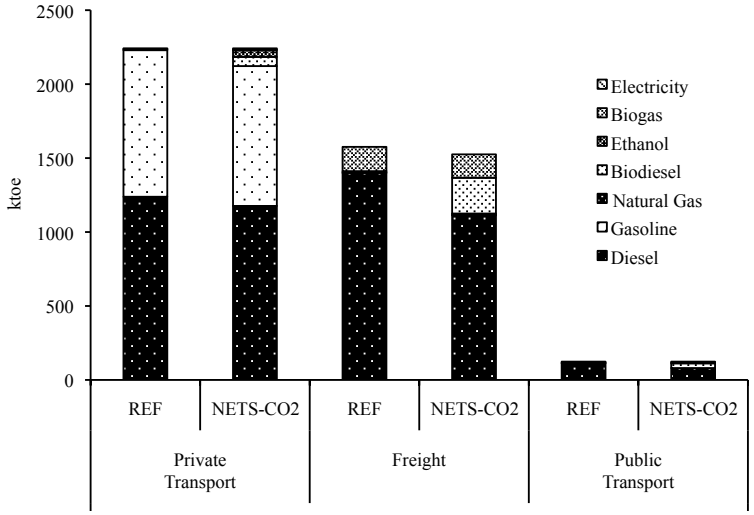


Figure 6.2: Irish TIMES output: Transport energy demand by mode in 2020 under a reference and climate mitigation scenario.

This deficiency in representing travel behaviour is common in technology-rich linear optimisation models. Schafer (2012) describes how transport is represented in a range of E4 models, many of which also poorly represent behaviour.

Several energy models have included a mode choice module using different modal choice methodologies: For example, the Global Change Assessment Model (GCAM), developed at the Pacific Northwest National Laboratory, is a general equilibrium model that solves for prices, supply and demand for all markets (Kyle & Kim 2012). Mode choice in this model is endogenous and responds to fuel price, wage rate and the cost of transport services. This uses a MNL approach to determine mode choice.

The Canadian Integrated Modelling System (CIMS) also includes a logit sub-model for mode and fuel choice (Horne et al. 2005). A third hybrid model with transport behaviour is IMACLIM-R (IMpact Assessment of CLIMate policies-Recursive version), developed at CIRED, which maximises a utility function subject to travel budget constraints. Infrastructure is endogenous: a decrease in supply leads to congestion and lower speeds, which feeds back into the model.

In terms of applying these methods to linear optimisation tools like TIMES, however,

the logit model contains non-linear probability functions and so is not compatible with the linear optimisation approach of TIMES.

Another way of modelling modal shift is to use cross price elasticities between different modes. The cross-price elasticity describes the changes in the demand of one mode when the price of the other mode increases. This method requires estimates of both own-price elasticity (which is already available in the TIMES model) and mode choice elasticity. So, for example, when gasoline price increase, consumers can either reduce driving, or switch to buses, or both. This implementation, however, will require code changes to the TIMES model and is therefore a long-term solution. This paper explores the options of modelling modal choice within the existing linear optimisation paradigm.

6.1.3 Travel time budget

An important attribute of the passenger transport sectors of the hybrid energy models such as GCAM, where modal choice is simulated, is that travel time is modelled. Representing travel time explicitly is at the core of our approach. We use the conception of a fixed travel time budget to constrain overall travel time in the model: Empirical research has shown that averaged over a country or region, people spend a fixed amount of time travelling per day. Studies suggest that region-wide average personal travel time is constant and is estimated as 1.1 hours per person per day (Schafer & Heywood 2009). This "travel time budget" as such is a stable characteristic and is considered a constant in our model. Figure 6.3 shows data on daily travel time from the UK National Travel Survey between 1970 and 2010, demonstrating the stable TTB (Metz 2010). Section 6.3.4 describes how we translate a daily personal travel budget of 1.1 hours into travel time spent in motorised modes (car, bus and train).

Other studies have used the notion of a travel time budget to simulate travel demand and modal split: Schafer & Victor (2000) uses a fixed travel time and money budget to forecast future global mobility, assuming a constant shift towards faster travel modes. Metz (2010) comes to a different conclusion, observing that daily travel demand is saturating in Britain, while the daily travel time budget has been constant, because of the diminishing marginal utility of the value of the extra choice associated with more mobility. Girod et al. (2012) also uses fixed travel time and money budgets to simulate travel demand and modal share. The fixed travel time has implications for travel demand and speed: Studies have shown evidence that reducing travel time of journeys through increasing capacity and improving infrastructure induces increased travel demand (Noland & Lem 2002).

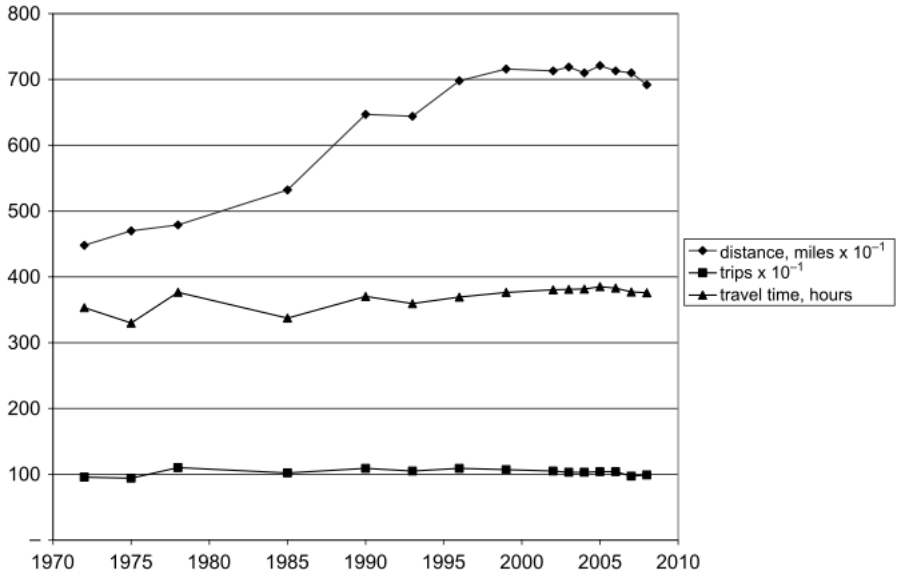


Figure 6.3: Travel time (hours per person per year), distance (miles pppy) and journeys (pppy) (Metz 2010)

6.2 Methodology

This section describes the basic model structure of the methodology and its implementation in a simple illustrative TIMES model. In this model, different transport modes compete on the basis of fuel and capital costs to deliver overall travel demand, while a constraint on overall travel time in the system, representing the travel time budget (TTB) of individuals, ensures that faster and more expensive modes can also compete. We introduce a new variable, travel time investment (TTI), a proxy for investments to reduce the time associated with travel. This model is then tested under a reference scenario (to 2030), an investment scenario and a CO_2 emissions reduction scenario.

6.2.1 Model

Motorised travel demand is represented by passenger kilometres travelled (PKT), which is the sum of demands of car (CKT), bus (BKT) and train (TKT). PKT for a technology is given by the vehicle kilometres travelled (VKT) multiplied by the load factor (LF, or occupancy of the vehicle). PKT is divided into long and short distance demand (PKT_L and PKT_S) in order to capture the characteristics of the different technologies servicing the different demands: High-speed train and buses can service long distance travel, while city buses and electric trams can service short distance; cars serve both. Furthermore, the speed of technologies serving long and short distance differs significantly: For example, for longer distance rail trips, the required waiting time is absorbed by the speed of the overall journey, compared with shorter

trips where it is more significant.

The model is based on a least-cost linear programming approach. It determines $PKT_{t,d}$, the travel demand d for long and short distance of each of the technologies (t) such that the overall system cost is minimised. The cost of technology activity, $c_{t,d}$ is the cost in €/PKT of travel in each technology producing long or short distance travel demand d, given by the sum of the fuel, investment and operation and maintenance (OM) costs in €/PKT. OM costs include insurance costs and wear and tear, but exclude fuel.

The model is constrained to meet annual short- and long-distance travel demand, which are modelled exogenously and can be based on the output of transport models, for example. The projection of PKT is outlined in Section 6.3.4 and we assume a constant split of short and long distance demand in the future.

The concept of a travel time budget (TTB in million hours, Mh) is introduced to the model to represent the empirically observed fixed travel time per-capita in the real world, as described in Section 6.1.3. This enables competition between different transport modes based on travel time in addition to cost. Without this the model will be likely to switch modes immediately to the cheaper but slower and more time-costly public transit modes, which does not reflect observed travel behaviour.

Ideally, speed and infrastructure would be endogenous to the model, so that the model could chose to invest in infrastructure, decreasing travel time. We introduce a variable TTI (travel time investment in €/h) which is a proxy to endogenise this relationship.

The model determines $PKT_{t,d}$ and $tti_{t,d}$ subject to:

Minimise total cost:

$$C = \sum_{t,d} PKT_{t,d} \times c_{t,d} \tag{6.1}$$

where $PKT_{t,d}$ is the travel demand of technology t for long or short distance travel demand d, and $c_{t,d}$ is the sum of fuel, investment, OM and TTI cost in €/PKT:

$$c_{t,d} = f_{t,d} + i_{t,d} + om_{t,d} + tc_{t,d} \tag{6.2}$$

where fuel cost $f_{t,d}$ is a product of the price per unit of energy of fuel (€/MJ) and the energy intensity of the technology (MJ/vkm), divided by the load factor (passengers per vehicle):

$$f_{t,d} = \frac{F \times int_{t,d}}{LF} \tag{6.3}$$

and the cost of travel time investment $tc_{t,d}$ depends on vehicle speed:

$$tc_{t,d} = \frac{tti_{t,d} \times \tau}{s_{t,d}} \tag{6.4}$$

where τ is the TTI cost in €/hour and $s_{t,d}$ is the speed in kilometres per hour of technology t.

The model is subject to two main constraints, firstly, that technologies meet the exogenously defined travel demand:

$$\sum_{t} PKT_{t,d} = PKT_d \tag{6.5}$$

for long and short distance demand d, and secondly, that the total yearly travel time of the system minus the travel time investment (a proxy for a reduction in the travel time of modes) does not exceed the yearly travel time budget (TTB):

$$\sum_{t,d} \frac{PKT_{t,d}}{s_{t,d}} - tti_{t,d} \leq TTB \tag{6.6}$$

The methodology for projecting PKT_d and TTB is described in Section 6.3.4.

We may also constrain the model to meet a CO_2 target X:

$$\sum_{t,d} PKT_{t,d} \times e_{t,d} \leq X \tag{6.7}$$

where $e_{t,d}$ is the emissions in gCO_2/PKT of each technology, which is given by the fuel emissions factor, technology efficiency and mode load factor.

6.2.2 Implementation in TIMES

In TIMES models, the transport sector typically comprises a stock of technologies in competition that contribute to meeting each exogenously defined modal travel demand (in PKT). Figure 6.4 shows an example of this approach in the form of a Reference Energy System (RES) extracted from current Irish TIMES passenger transport sector (Ó Gallachóir et al. 2012). An equivalent structure characterises the CA-TIMES model (McCollum et al. 2012).

Within the new Reference Energy System, as shown in Figure 6.5, we introduce just two travel demand commodities: long distance demand (TLDD) and short distance demand (TSDD) expressed in PKT/year. In order to produce energy service demands all technologies such cars, trains and buses have two inputs: the fuel input and the time input. Here the time input describes the travel time from origin to

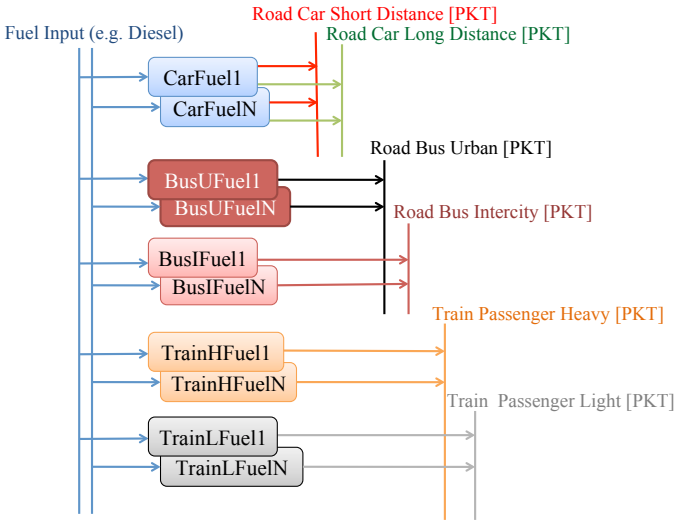


Figure 6.4: Reference Energy System for Irish TIMES passenger travel sector. Technologies can compete within modes but not between modes.

destination, which is dependent on the modal speed, waiting and transfer time. This depends on technology, infrastructure, reliability, congestion, accessibility, etc.

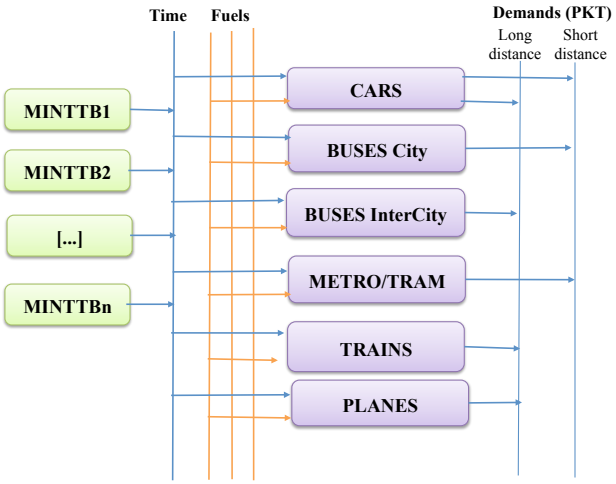


Figure 6.5: Proposed Reference Energy System.

6.3 Case studies: Ireland and California

6.3.1 Data for California

Passenger cars are predominantly used as the preferred mode of transport in California. Public transit, that includes all the commuter trains and buses in the state, comprises about 10% of the total demand (California Dept. of Transportation 2002). The short distance PKT demands are captured from the trips within the metropolitan areas in the state, with population greater than 1 million. Table 6.1 lists the data

sources for the attributes used in this model.

Table 6.1: Data Sources for the California Modal Share model.

Attribute	Source
Person trips by mode and average trip distances per person in each region in CA	2009 National Household Travel Survey, 2010 California Household Travel Survey
Travel time for public transit (including waiting time and transfer time)	National Highway Institute of Federal Highway Administration, U.S. Bureau of Transportation Statistics
California population estimates	U.S. Census Bureau
Load factors and availability factors for transit modes	National Transit Database of Federal Transit Administration

6.3.2 Data for Ireland

For the Irish model, short distance travel demand is defined to be trips of 30 kilometres or less. Total annual travel demand and the base-year modal split of demand by car, bus and train for short and long demand were derived from microdata from Ireland's Central Statistics Office Pilot National Travel Survey (CSO 2011) conducted in 2009. This used a travel diary methodology to survey travel characteristics, including distance, mode, time and trip purpose, for a cross section of the population. Total annual travel demand in PKT for this modelling exercise was calculated using the average daily distance (by car, bus or train) per person for this survey. The speed of each mode for long and short distance demand was calculated as the weighted average quotient of trip distance and trip time.

In order to calculate load factors for cars and buses, vehicle kilometres travelled (VKT) were used: Total private car VKT for 2008 was derived from national car test odometer readings (Daly & Ó Gallachóir 2011*b*); bus VKT were sourced from the Central Statistics Office, and VKT for Dublin's light rail system (Dart and Luas) was used for short distance demand (Central Statistics Office 2008).

The physical characteristics of the transport technologies (efficiency and costs) was taken from the Irish TIMES model (Ó Gallachóir et al. 2012).

6.3.3 Characterisation and comparison of case studies

This section describes and compares the transport technological characteristics for Ireland and California.

Figures 6.7 and 6.6 describe the investment and operation and maintenance, (OM) costs per PKT used in the model: Cars have a higher investment cost than either public transport modes in both regions, and investment cost is higher than OM costs for all modes. Interestingly, there is a significant difference between Ireland and California in OM costs for cars.

Figures 6.8 and 6.9 describe the time and fuel efficiency of all modes. Time efficiency is the inverse of speed. It is evident why there is a low share of bus and train travel in both regions – bus travel, particularly, takes much more time than car travel, over twice as much time in California than cars for long distance trips, for example. Time efficiency is taken from travel surveys, where trips were actually taken. This means that only the possible and the available trips are captured, and so does not capture the limited supply of, for example, long distance train stations, which can only cover a limited number of trips (usually city-to-city trips). No data was found for short distance train travel time for California, so the same figure as for Ireland was used.

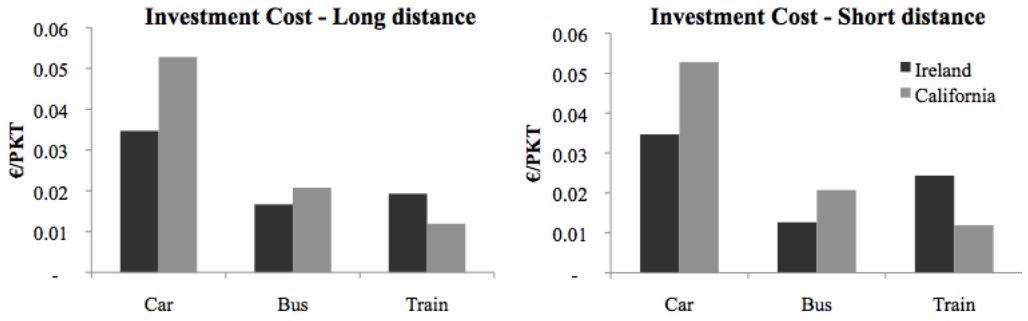


Figure 6.6: Investment costs (€/PKT) for three transport technologies

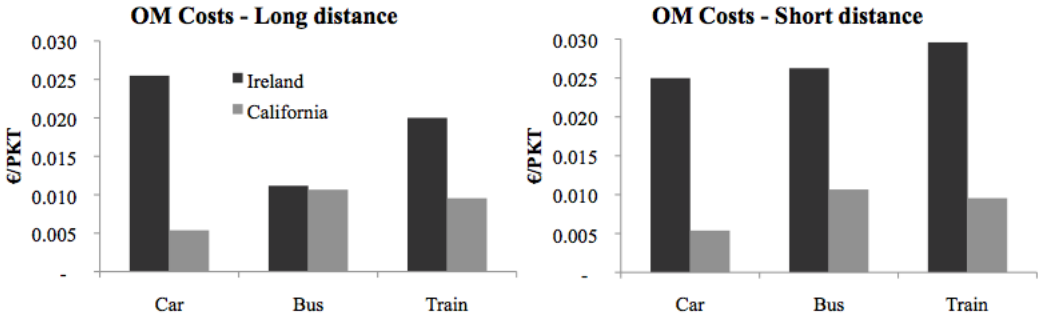


Figure 6.7: Operation and Maintenance (OM) costs in €/PKT

Energy intensity is an important variable because it determines the fuel price and emissions. Figure 6.9 shows that for Ireland, buses are more fuel efficient than cars and trains are more fuel efficient than both other modes. Californian long-distance trains are less efficient than buses, but all public transport modes are more efficient than cars. Finally, long distance travel is more fuel efficient because there tends to be less stop-start driving styles outside of cities and towns.

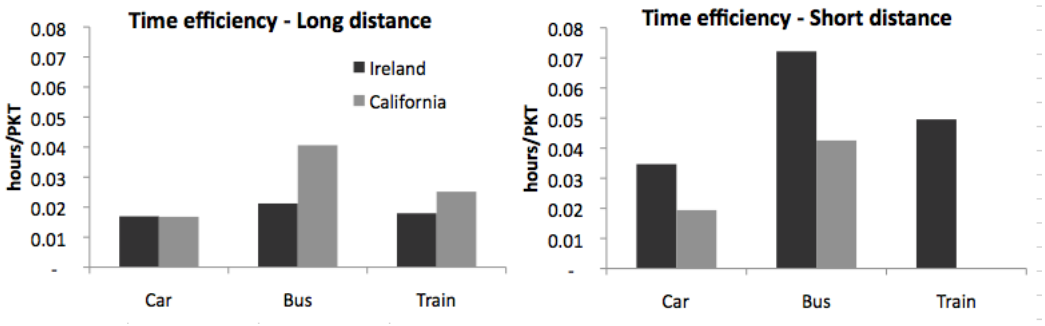


Figure 6.8: Time efficiency (inverse of travel speed) in hours/PKT

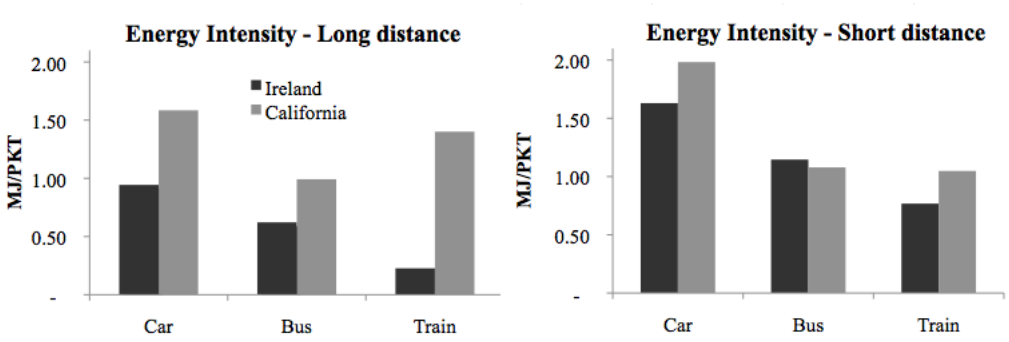


Figure 6.9: Energy intensity per passenger kilometre (MJ/PKT)

Table 6.2 compares the base-year mode share for Ireland and California. Car travel dominates both regions, accounting for 98% of travel (PKT) in California and 91% of travel in Ireland. Ireland's share of public transport is low, at 9%, but higher than the 2% found for California.

Table 6.2: 2009 mode share (PKT) for Ireland and California.

	Ireland	California
Bus share	5.2%	1.9%
Car share	91.2%	97.9%
Train share	3.6%	0.2%

The average speed of motorised travel in Ireland is 37 km/hour, compared with 50 km/hour in California.

Table 6.3 describes the load factor for each mode of transport for long and short distance demand in Ireland and California. This variable is important for determining technology characteristics: Higher occupancy leads to lower cost and higher time and fuel efficiency.

6.3.4 Travel demand and travel time forecast

Typical TIMES models project passenger travel or vehicle kilometre demand for each transport mode individually (CKT, BKT and TKT). In contrast, our methodology

Table 6.3: Transport mode load factors for long and short distance travel demand.

	Ireland		California	
	Long	Short	Long	Short
Car	1.76	1.76	1.53	1.53
Bus	17.37	17.37	20	16
Train	165.92	51.38	162.25	49.40

requires a projection for overall passenger travel demand (PKT) and for total motorised travel time (TTB_{mot}), annually for each region up to 2030.

PKT is projected on the basis of population and income forecasts: Per capita travel demand is assumed to grow at the same rate as per capita income. Irish population in the future is from the ESRI demographic model and income (GDP/capita) is from the ERSI long term macroeconomic forecasts (Bergin et al. 2010). Californian population projections come from the State of California Department of Finance (State of California 2012) and GDP growth projections are based on national forecasts, as no long term economic forecast exists for the state (EIA 2008). A travel demand growth elasticity of 1 is used, which was used by Girod et al. (2012) and falls within the range of long-term income elasticities for car VKT, 0.12 to 1.47, found in a review of elasticities of road traffic (Goodwin et al. 2004). Per-capita PKT in California is projected to grow from 18,803 kilometres in 2009 to 26,209 kilometres in 2030, while Irish per-capita PKT is projected to grow from 12,305 kilometres in 2009 to 19,829 kilometres in 2030.

The calculation of overall annual travel time in the model, *TTB*, requires the average amount of daily travel time allocated to motorised modes. While the total daily travel time budget is considered a constant at 1.1 hours/person/day, the model requires the time spent in cars, buses and trains. This value tends to be lower for developing countries, where more time is spent travelling on foot or on bicycles. The Schafer-Victor model of world mobility (SV model) refers to this value as TTB_{mot} and models this number against annual average PKT for 11 global regions (Schafer & Victor 2000). For Ireland, the 2009 value for TTB_{mot} is calculated from the 2009 National Travel Survey (Central Statistics Office 2011) as 0.91 hours/person/day. For California, personal travel time is calculated as the sum of travel time in each mode, which is derived from the average passenger kilometres per person per day for each mode, from the Nationwide Household Travel Survey (U.S. Department of Transportation, Bureau of Transportation Statistics 2003) and the average speed of trips of each mode (CUTR 1998) – TTB_{mot} is calculated to be 1.02 hours/person/day.

The SV model investigated the relationship between motorised travel time and personal mobility in different regions, and found a strong positive correlation. TTB_{mot} is modelled using the following formulae:

$$TTB_{mot} = a + \frac{b}{(TV - c)^d} \tag{6.8}$$

where TV is traffic volume, in PKT/person/year,

$$a = -\frac{b}{(-c)^d} \tag{6.9}$$

$$b = \frac{1.1}{\frac{1}{(240000-c)^d} - \frac{1}{(-c)^d}} \tag{6.10}$$

Schafer & Victor (2000) describes the rationale behind these equations. We use the value for d used in the SV model, $d = 20$, and calculate c for Ireland and California separately, based on the 2009 TV for each region. c was found to be -134,082 and -134,287 for Ireland and California respectively, very close matches, compared with -176,083 calculated as the best fit for 11 global regions in the SV model. Figure 6.10 shows TTB_{mot} as a function of TV modelled in this way, as calculated for Ireland and California, and as modelled using the SV model.

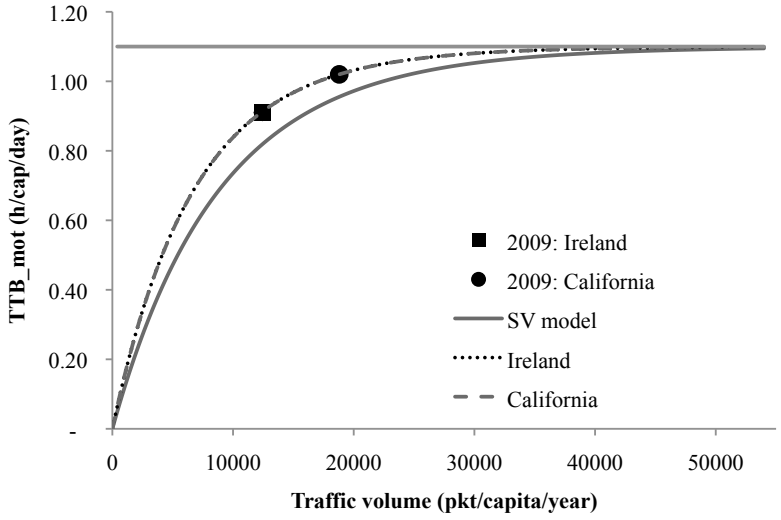


Figure 6.10: Model of TTB_{mob} for Ireland and California, compared with SV model

This function is used to project TTB_{mot} for both regions up to 2030 based on PKT/capita projections. For California, TTB_{mot} in hours/capita/day is projected to rise to 1.07 in 2030 compared with 1.02 in 2009, and for Ireland is is projected to rise to 1.03 in 2030, from 0.91 in 2009. This results in total system travel time (TTB) of 17,391 Mh (million hours) per year in 2030 for California and 1,983 Mh for Ireland.

6.4 Results

The modal-share model is run for several scenarios for each region. Table 6.4 gives the descriptions of all the scenarios of this modelling exercise.

Table 6.4: Description of scenarios in the modal-share model.

Scenarios	Description
S0: Reference	Imposes no TTB constraint. Allows competition between modes based on technology and fuel costs only
S1: Introducing TTB	Uses constant TTB per capita over the time horizon. Competition between modes is based on time in addition to cost
S2: TTB + TTI	Different levels of TTI are modelled as a proxy for investments to reduce travel time
S3: TTI + CO_2 constraint	This scenario includes a 20% CO_2 emissions reduction by 2020 to the above scenario

6.4.1 S0: Reference

This reference scenario represents the outcome of standard TIMES model structure. The model is first run without the limit on travel time budget, which implies the passenger has no bound on travel time. The model chooses freely between modes on the basis of technology and fuel costs. As shown in Figure 6.11 once the existing car capacity retires, the model chooses new bus technology for both regions, which is the slower and cheaper mode of transport according to our assumptions.

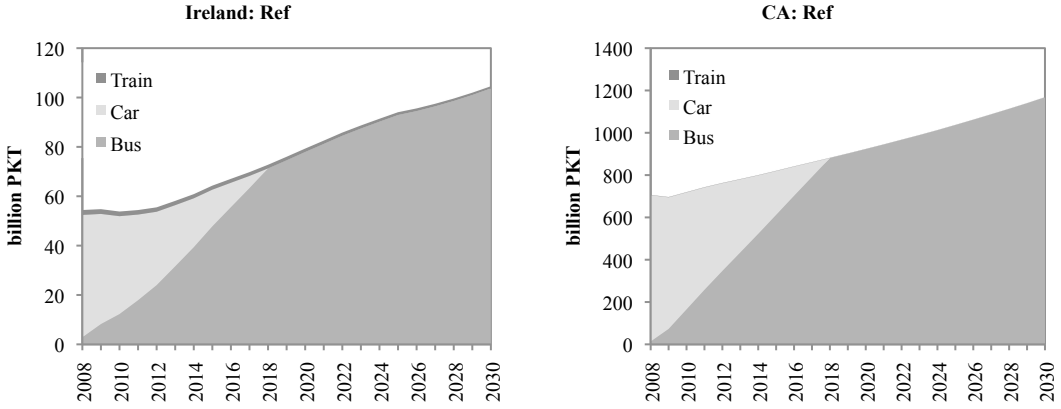


Figure 6.11: Modal share results for S0, the standard TIMES/MARKAL formulation

6.4.2 S1: Introducing TTB

A constant travel time budget is introduced into the model based on projected annual passenger kilometres travelled (PKT) and travel time budget (TTB). In both regions, PKT grows faster than TTB, therefore pushing the model to choose faster modes of travel within the given time budget. The models quickly become unfeasible as cars, the fastest mode, are already saturating travel demand and and the model has no faster mode to switch to. Results for this scenario are shown in Figure 6.12.

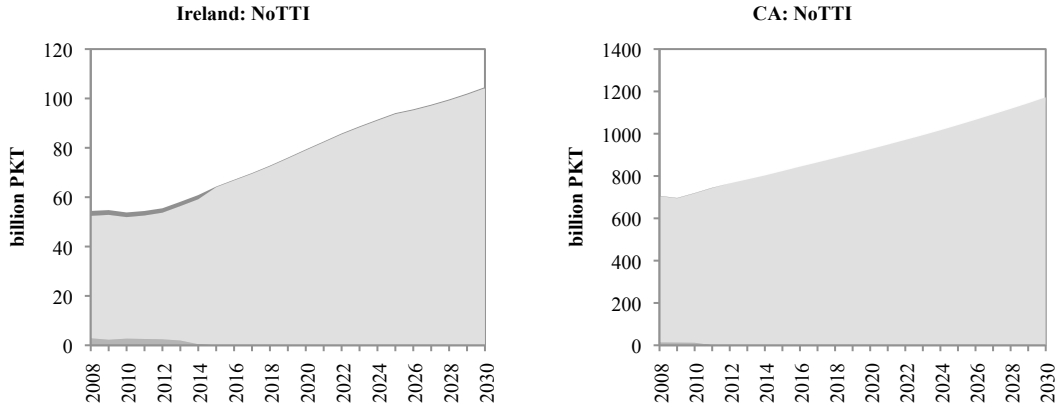


Figure 6.12: Modal share results for S1, TTB + TTI

6.4.3 S2: TTB + TTI

Travel Time Investment (TTI) is introduced in this scenario, allowing the model to invest in increasing the overall travel time budget. This variable acts as a proxy for the investment required to encourage modal shifting, for example through improving public transport speeds. The cost of TTI impacts significantly on results: For low costs, the model for both regions invests heavily in slower public transport, because the mode's investment, fuel and OM costs are sufficiently low that investment in TTI is cost effective. At low TTI cost, the model for both regions also chooses a level of rail transport, which has a higher cost but greater speed than bus transport. When TTI cost is sufficiently high, shown in the results here, the model invests in new private cars exclusively in Ireland, while using the installed capacity of buses and trains, and invests in some new bus technology in California as well as mainly private cars. At very high TTI costs, the model chooses exclusively private cars in meeting travel demands, and the current capacity of bus and rail is not used. Figure 6.13 shows results for TTI cost at €7/hour.

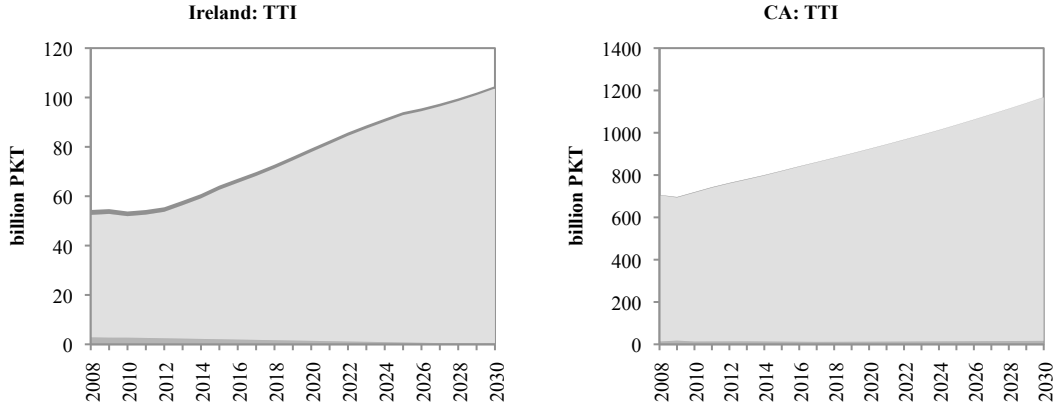


Figure 6.13: Modal share results for S2

6.4.4 S3: TTI + CO_2 constraint

This scenario introduces a 20% CO_2 emissions reduction constraint, relative to S2 emissions. The constraint is applied to 2030 emissions from S2 and linearly interpolated from 2010. In this scenario, there is a tradeoff between speed and emissions: the slower public transport modes are invested in both regions so that the emissions constraint is met, but a minimal amount of TTI is invested in. New rail is invested in in this scenario for both regions for short distance travel, with new capacity for long distance buses also featuring. At a very high TTI cost, rail is chosen exclusively over busses, as the slower speeds consumes more TTI and makes buses more costly than trains. Thus, the modal share in a CO_2 constraint scenario is sensitive to the price of TTI. Figure 6.14 shows results for a TTI cost of €7/hour.

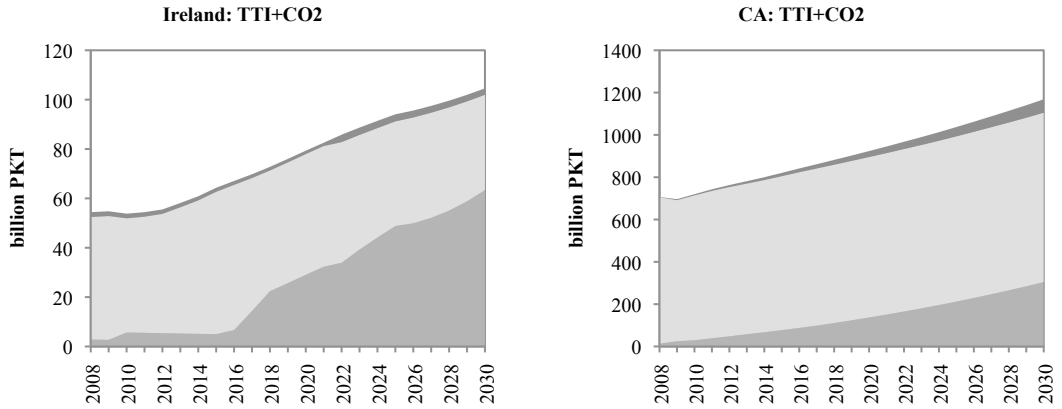


Figure 6.14: Modal share results for S3

6.5 Discussion and future work

The results presented in the previous section show how this methodology portrays the competition between transport modes in a least-cost linear framework. In particular, results show a higher penetration of efficient, public transport modes when a CO_2 constraint is imposed. In this case, there is a tradeoff in the model between the cost of investing in higher TTI, and so reducing the travel time associated with these modes to make them more attractive to passengers, and an emissions constraint. The reference scenario shows why a TTB constraint and a TTI cost is necessary to the model: Without imposing a restriction on travel time, the model would choose the most efficient and cheapest mode, which are buses in both Ireland and California. This reflects the real-world drawback of public transport, namely, the associated additional time and inconvenience, and the cost required of government to make efficient transport modes more acceptable to the public.

It also highlights a key drawback of the linear optimisation modelling paradigm, which lacks a good representation of behavioural aspects of travel and misrepresents results unless subjective constraints are used.

While this model illustrates the methodology and demonstrates its functionality, a number of developments are required to use the model to its full potential. Firstly, the strength of linear optimisation is its capability for computing a huge number of equations and constraints: Typical TIMES models contain thousands of technologies and technical constraints. This prototype model can be integrated into a full energy systems model and used to show the tradeoffs between energy planning and decarbonisation at multiple levels of the energy system, such as low carbon vehicles or low carbon fuel pathways.

Secondly, the model uses a highly stylised TTI variable to represent investment potentials to reduce travel time through investments in public infrastructure, such as more bus/rail routes. This is done by by relaxing the TTB constraint with new investments in TTI and the model results appear to be sensitive to this variable. Thus, the important next step is the calibration of the TTI variable. The cost of TTI is critical to the choice of modes: At low TTI costs, the model only favours low-cost public transport, which is an unrealistic result. The TTI cost must be calibrated for the region in question to ensure the results are reflect a realistic baseline. In a carbon constrained scenario, the cost of mitigation depends on TTI cost, so in a full TIMES model, the level of modal shifting would depend on the TTI cost, speed of technologies and the relative costs of other carbon mitigation technologies. Future refinements of this model could specify TTI by mode and use a cost curve to reflect costs of different measures and infrastructural improvements.

Load factors in the model are exogenously determined, whereas measures for

increasing the occupancy of all modes are used to increase transport efficiency. To make this attribute endogenous, so that the model could invest in programmes to increase the loading of cars, for example with dedicated "ride-sharing" lanes, or of buses and trains by improved scheduling, for example, would require a cost curve, which was not found in this study.

A final desirable improvement to this model is to endogenise transport infrastructure and speed, where the model would specifically invest in roads, railway lines, bus lanes and airports and modal speed would be related to the capacity of built infrastructure. Travel demand is influenced by infrastructure and accessibility/speed: With a fixed daily travel time budget, access to modes with higher speeds enables a passenger to travel longer distances. It would be desirable to reflect this in the PKT forecast.

Modelling TTB and TTI and characterising travel speed have a number of advantages over modelling modal choice using MNL equations or cross price elasticities: Firstly, only aggregate data is needed for this methodology. Travel speed and a TTI cost curve are the only additional parameters needed for the model, while other models require calibration of elasticities and preference variables. As was demonstrated for Ireland and California, the model structure can be adjusted to accommodate different levels of data availability. For example, long and short distance travel was defined differently for each region. Furthermore, linear equations allow modal shifting to be fully endogenous to the objective function, so that modal shifting competes as a decarbonisation measure.

6.6 Conclusion

Many parameters influence modal choice. Some, such as the cost of fuel for a car or price of public transport or the travel time of different modes are objective and easily modelled. Other parameters - social status and comfort, for example - are not so easily quantifiable, and so are more difficult to incorporate into a model. Price alone is not the main consideration for passengers, making modal choice particularly complicated for cost-optimisation models such as TIMES. Developers of these models often overcome this difficulty by imposing constraints: In the case of passenger transport, this is manifested in exogenous projections of passenger kilometre demand for each mode individually. The overlooks that energy demand in passenger transport is a derived demand for mobility, and not private car travel, and consequently, investment into public transport and influencing travel behaviour as a strategy for decarbonisation is overlooked by energy systems models, whose outputs typically focus on technological solutions. Policy makers rely on outputs from energy systems models to formulate least-cost strategies for meeting CO_2 targets, and

influencing behaviour has an important role in meeting these goals.

This model makes a first step towards incorporating competition between modes in linear optimisation energy models. Novelly, it uses a methodology based on the empirically observed, stable and global daily travel time budget (TTB) to realistically represent the modal choice in a reference case, and introduces a new parameter, travel time investment (TTI), which is a proxy cost for investment into public transport, representing the cost to decision-makers of reducing the barrier to more public transport use. While TTB has been used in other energy models, this is the first time known to the authors this parameter has been used to represent modal choice in a linear optimisation model, which has the advantage of being technologically rich and comprehensively covering the whole energy system.

This prototype model requires further work to be fully useful, in particular, an extension of the TTI parameter to distinguish investment costs for each mode, and the inclusion of the methodology into a full energy systems model. However, the approach presented here is a significant step towards incorporating behaviour into energy systems models.

Acknowledgements

This research was supported by a grant from the IEA ETSAP.

Part III

Additional Contributions to Transport Modelling and Policy Analysis in Ireland

Chapter 7

Co-benefits? Not always. Quantifying the negative effect of a CO_2-reducing car taxation policy on NOx emissions

Abstract

With the current focus of policy action on climate change mitigation, it is important to investigate possible negative side effects of climate change policies on air pollutants. A 34% increase in CO_2 emissions from private cars in Ireland over the period 2000-2008 prompted a change in private car taxation in 2008 to incentivise the purchase of lower CO_2 emitting cars. The impact has been successful and the measure has accelerated the dieselisation of the car fleet. This however, raises an important question, namely how does the dieselisation of the car fleet affect NOx emissions? This paper combines two models to address this question, a car stock model to generate activity data (future composition and activity of Ireland's car stock) and the COPERT model to quantify the NOx emissions generated in the period 2008 – 2020. Previous analysis shows that the CO_2 taxation policy measure is anticipated to deliver a 7% reduction in private car related CO_2 emissions in 2020 compared with a baseline pre-tax scenario. The results here show that private-car NOx emissions will be 28% higher in 2020, when compared with a pre-tax scenario.[1]

Keywords: air pollution, bottom-up approaches; CO_2 reductions; energy models; policy evaluation; transport policy

[1]Chapter submitted for publication as: Leinert et al. (2012), 'Co-benefits? Not always. Quantifying the negative effect of a CO_2-reducing car taxation policy on NOx emissions', *Transportation Research Part A: Policy and Practice* Submitted on July 26th, 2012.

7.1 Introduciton

The European Union has set an ambitious target to reduce greenhouse gas (GHG) emissions to 20% below 1990 levels by the year 2020 as part of the EU climate and energy package (CEC 2007). Two of the policy instruments established to deliver this are EU Directive 2009/29/EC (ETS Directive) (European Union 2009*b*), which imposes a 21% reduction in GHG emissions by 2020, relative to 2005 levels on large point source emitters through an emissions trading scheme (ETS) and EU Decision 406/2009/EC (the Effort Sharing Decision, or ESD) (European Union 2009*a*) establishing individual Member State targets to deliver an EU-wide 10% GHG emissions reduction target (relative to 2005 levels) for non-ETS sectors. The Irish target for the non-ETS sector is a reduction of 20%. In addition, the EU has a strategy to improve air quality that focuses on tackling pollutants responsible for acidification, eutrophication and ground-level ozone pollution. EU Directive 2001/81/EC (NEC Directive). The European Union (2001) established national emissions ceilings or upper limits for four pollutants for the year 2010 which will be revised to incorporate recently joined Member States and to set targets for 2020 and beyond. A revision of the Gothenburg protocol, also setting emission ceilings on air pollutants, was agreed in May 2012. It is likely that the revised NEC directive will adopt these changes.

This paper focuses on how policy measures designed to limit GHG emissions may have unintended impacts on efforts to limit air pollutants. The analysis takes one EU Member State, Ireland, as a case study, which can readily be implemented in other countries, subject to data availability. Ireland is an interesting case study as it witnessed significant growth (26%) in GHG emissions between 1990 to 2005 (Environmental Protection Agency 2012*b*), in contrast with the EU wide trend (an 8% reduction (European Environment Agency 2010)) and now faces the challenge of reducing its greenhouse gas emissions in the non-ETS sector under the Effort Sharing Decision (ESD) to 20% below 2005 levels by the year 2020.

In addition, Ireland has a relatively high share of GHG emissions in the agriculture sector (30% in 2010 compared with <9% in the EU). Non-ETS emissions in Ireland are dominated by agriculture and transport, which collectively account for over two thirds of Ireland's non-ETS emissions in 2010 (42.5% agriculture, 26.4% transport) (Environmental Protection Agency 2012*b*). The mitigation opportunities in agriculture are limited and in addition, Ireland is currently implementing a strategy to increase agricultural activity as set out in Food Harvest 2020 (Department of Agriculture Food and the Marine 2011). The net impact of this is that GHG emissions from agriculture are anticipated to be 0.8% above 2005 levels by 2020, pointing to a need for increased reductions in other sectors, to meet the overall 20% reduction target in the non-ETS sector.

Under the EU NEC Directive, Ireland was required to reduce national NOx emissions to 65 ktonnes by 2010. Ireland's total NOx emissions were 75.7 ktonnes in 2010, exceeding the Directive target by 16.4%. Adjusted for fuel tourism, NOx emissions in 2010 were 72.6 ktonnes in 2010, an exceedance of 11.7%. The current NEC ceilings for Ireland (including the 65 ktonnes limit for NOx) continue to apply for future years beyond 2010. A revision of the Gothenburg Protocol was agreed in May 2012. Its limit values are likely to be also adopted in the revised NEC directive. This leaves the Irish NOx emission limit at just under 65 ktonnes. Therefore, the challenge in reducing NOx emissions remains.

With the current focus of policy action dominated by climate change, compared with air pollution, it is important to investigate possible negative side effects of climate change policies on air pollutant levels. This paper assesses the impacts of a climate focused policy measure introduced in 2008 that was designed to reduce non-ETS GHG emissions in transport. The policy was aimed at incentivising the purchase of lower CO_2 emitting passenger cars. Separate analysis has detailed the context for this policy measure in terms of CO_2 emissions (Ó Gallachóir et al. 2009) and demonstrated its early success in changing purchasing trends, the most noticeable effect being a switch to diesel cars (Rogan et al. 2011).

Switching to diesel cars raises an important question: what impact will this successful CO_2 mitigation policy have on Ireland's efforts to reduce NOx emissions? This paper combines two models to address this question, namely a car stock model (Daly & Ó Gallachóir 2011*a*) to generate activity data (future composition and activity of Ireland's car stock) and the COPERT model (Gkatzoflias et al. 2012) to quantify NOx emissions generated from passenger cars in the period 2008 – 2020. Three scenarios are generated: (i) a pre-tax baseline scenario which is used to simulate the future trend in NOx emissions in the absence of the change in car tax, (ii) a post-tax scenario simulating the impact of the car tax on purchasing trends and resultant NOx emissions and (iii) a post-tax rebound scenario which includes an increase in activity (mileage) as a rebound effect to the financial savings associated with efficiency improvements.

Several studies have assessed historical NOx trends. Vestreng et al. (2009) examined the trends of NOx emissions in Europe with a focus on road transport. The study indicated that the Euro standards have been effective in controlling NOx emissions from private cars, but that progress is hampered by slow vehicle turnover, loopholes in the type-approval testing and an increase in diesel consumption. Additionally a number of papers have focussed on NOx emission trends in individual countries including Belgium (Logghe et al. 2006), Ireland (Kelly et al. 2009), China (Han & Hayashi 2008) and India (Bose 1998).

Furthermore, there are several in-depth reports on projecting NOx emissions in

individual countries. Anderl et al. (2011) projects road emissions in Austria using the GLOBEMI model, which uses the input parameters of car stock according to propulsion system, engine cc, and the emission factors according to the same parameters. The GEORG model calculates energy demand using a more disaggregate stock model as the one used in this study, where the age distribution of the stock is taken into account. Policy scenarios are undertaken for GHG emissions only, in Anderl et al. (2011). Nielsen et al. (2012) projects Danish NOx emissions. Official Danish forecasts of activity and the COPERT model were used to project transport emissions, with a stock model similar to that used here, with the year of registration deciding the relevant Euro standard, and assuming emissions over time in line with standards.

There are also a number of papers on the co-benefits of policies targeting GHG emissions that have a positive impact on NOX emissions (Mao et al. 2012, Takeshita 2012). However there are very few papers in the literature that model the unintended impacts that climate policy measures can have on air pollutants and this paper contributes to addressing this knowledge gap. Denny & O'Malley (2006) assessed the impacts of increased wind power on the operation of conventional electricity generation plants and the resulting emissions of carbon dioxide, sulphur dioxide, and NOx. They found that in some cases, while CO_2 emissions decreased, national total NOx emissions increased with increasing wind generation. The US Environmental Protection Agency (2002) shows that an increased penetration of biodiesel can increase NOx emissions; similarly, the impact of a switch towards battery electric vehicles may increase electricity-related air pollutant emissions.

Section 7.2 provides the context for the paper, drawing on trends since 1990 in CO_2 emissions and NOx in transport in Ireland. Section 7.3 provides an overview of the methodology used and how the car stock model and COPERT model were used in this analysis. Section 7.4 presents the results of the paper, i.e. the modelled future NOx emissions for the different scenarios. Section 7.5 discusses the results and draws some conclusions.

7.2 Context

7.2.1 CO_2 emissions

Ireland's GHG emissions peaked in 2001 at 27% above 1990 levels and declined to 11.2% on 1990 levels in 2010 to 61.3 Mt CO_2. The most significant growth was in energy-related CO_2 emissions that grew by 32.3% over this period (26.9% when adjusted for fuel tourism[2], i.e. removing the emissions associated with fuel purchased inside but used outside of the Republic of Ireland). The breakdown of energy-related

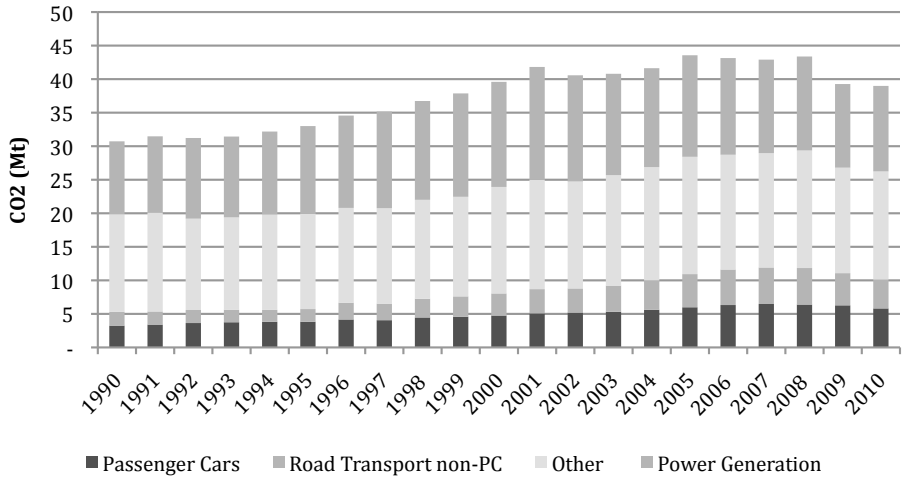


Figure 7.1: Trend in energy-related CO_2 emissions in Ireland by sector 1990 – 2010, adjusted for fuel tourism

CO_2 emissions is shown in Figure 7.1, showing the split between energy use in transport, power generation, and others. The addition of new and efficient combined cycle gas turbine power plants in the energy transformation sector since 2002 helped to offset continuous growth in other energy-related sectors over the period.

The sector exhibiting the largest growth in energy-related CO_2 emissions is transport, which more than doubled between 1990 and its peak in 2007. This steep increase was prompted by economic growth rates of 6.5% per annum in the same period (Howley, Dennehy & Ó Gallachóir 2009). This paper focuses on private car transport, which accounted for 45.6% of total transport energy (excluding fuel tourism) in 2010 (Howley, Ó Gallachóir & Dennehy 2009). There were technological efficiency improvements in private cars in this period, but car purchasing trends in Ireland offset these gains resulting in no net improvement of the energy efficiency of the car fleet (Ó Gallachóir et al. 2009). This prompted the change in private car taxation in 2008 which is the focus of this paper. The impacts of the economic recession are also evident in Figure 7.1, leading to a 14.7% (adjusted for fuel tourism) reduction in CO_2 emissions in transport between 2007 and 2010. This change in taxation is just one of a suite of policy measures designed to reduce CO_2 emissions in private car transport (Daly & Ó Gallachóir 2012).

[2]Fuel tourism refers to transport fuels purchased in one jurisdiction and consumed in another, generally associated with price differences (i.e. fuel bought in the Republic and consumed in Northern Ireland). In 2007, it is estimated that fuel tourism accounted for approximately 11% of Ireland's transport energy.

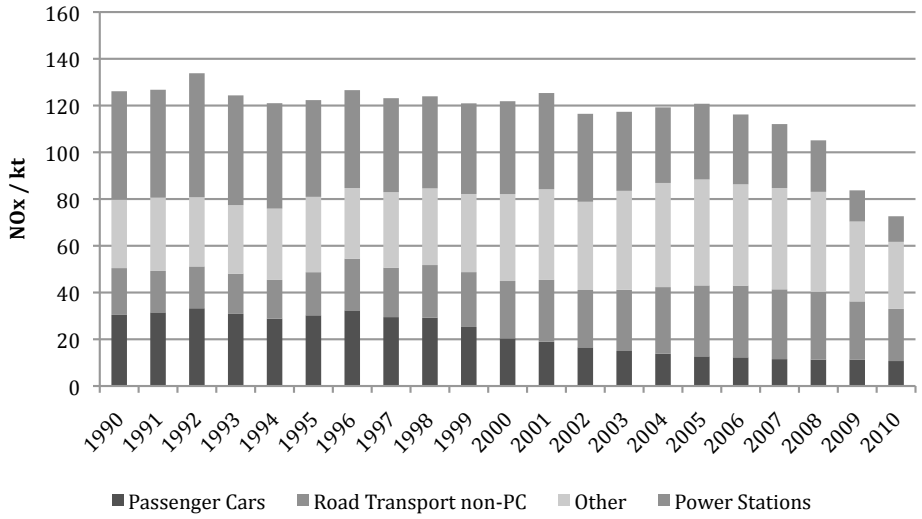


Figure 7.2: Trend in energy-related NOx emissions in Ireland by sector 1990 – 2010, adjusted for fuel tourism

7.2.2 NOx emissions

Figure 7.2 shows the overall trend in NOx emissions (also adjusted for fuel tourism) over the period 1990-2010. The trend is markedly different from the trend in CO_2 emissions, with NOx emissions peaking in 1992 and reductions evident in advance of the economic recession, most significantly in the power sector and in car transport.

NOx emissions due to road transport (adjusted for fuel tourism) amounted to 50.5 kt in 1990, peaked at 54.5 kt in 1996, and reduced to 33.0 kt by 2010. Passenger cars accounted for 30.4 kt in 1990, and 10.7 kt in 2010, with a continuous decline since 1996. This decline is a result of effective policies, i.e. more stringent emission standards (Euro) leading to a decrease in specific NOx emissions (g/km). The impact of improved emission standards is partly offset by increasing car numbers and mileage.

7.2.3 Specific CO_2 and NOx emissions and private car activity

Over the period 2000-2008 there was a rise in passenger car activity (measured in terms of vehicle kilometres, vkm) of 34% (101% in diesel activity), as shown in Table 7.1. There was also a 46% increase in the size of the car fleet (120% increase in the diesel stock) and together these factors prompted a 34% rise in CO_2 emissions.

Regarding emissions, the weighted average specific NOx emissions factor(in g/km) for the private car fleet in Ireland declined over this period, as shown in Table 7.1 and illustrated in Figure 7.3. This was achieved due to the introduction of successively stringent EU emissions standards from 1992 onwards that limit specific emissions

Table 7.1: Trends in private car activity, NOx emissions and intensity and CO_2 emissions and intensity (EPA data)

	Passenger car activity	NOx emissions		CO_2 emissions	
	Million vkm	Total (kt)	Intensity (g/km)	Total (kt)	Intensity (g/km)
2000	26,860	20.4	0.76	4,756	177
2001	28,642	18.9	0.66	5,073	177
2002	29,282	16.5	0.56	5,200	178
2003	30,018	15.0	0.50	5,316	177
2004	31,698	13.9	0.44	5,621	177
2005	33,534	12.7	0.38	5,989	179
2006	35,269	12.3	0.35	6,321	179
2007	36,020	11.5	0.32	6,478	180
2008	36,124	11.3	0.31	6,395	177
2009	35,563	11.3	0.32	6,277	176
2010	33,296	10.7	0.32	5,818	175

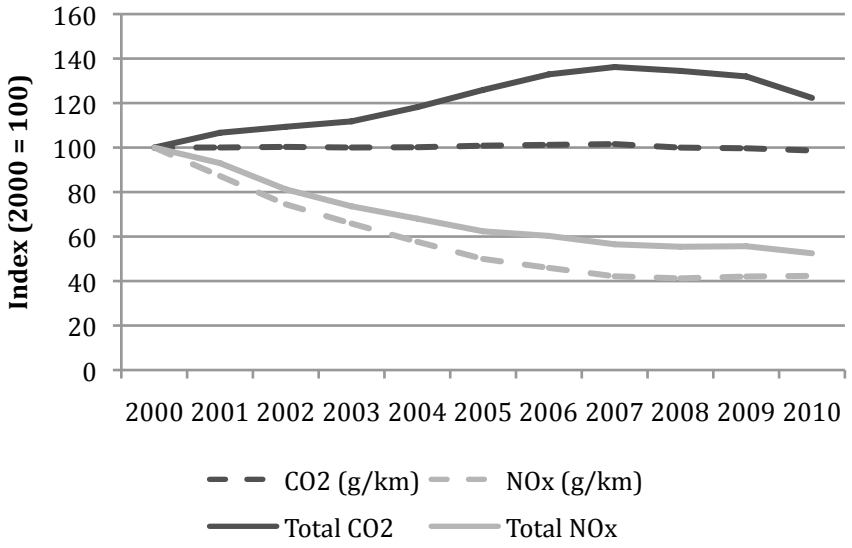


Figure 7.3: Index of passenger car CO_2 and NOx trends, total emissions and emissions intensity

(including NOx) for new petrol and diesel passenger cars. The current standard in place (Euro 5) limits specific NOX emissions to 0.18 g/km for new diesel cars and 0.06 g/km for new petrol cars. The impact has been a 59% reduction in specific NOx emissions for Ireland's passenger car fleet over the period 2000 – 2008. At the same time however, the total activity (in terms of vkm travelled) has increased. The decline in specific emissions was thus offset by this increase in activity, leading to an overall 45% decrease in NOx emissions from passenger cars between 2000 and 2008.

A very different trend is evident in the case of CO_2 emissions. Weighted average specific emissions remained constant, and the increase in activity led to an overall 34% increase in CO_2 emissions from passenger cars.

7.2.4 Change in private car taxation and dieselisation of the fleet

The change in private car taxation policy in Ireland was prompted by the lack of improvement in energy efficiency and CO_2 emissions performance in the car fleet over the period 2000 – 2008 (as illustrated in Figure 7.3). The rebalancing of both vehicle registration tax (VRT) and annual motor tax (AMT) was designed to influence car purchasing patterns by linking VRT and AMT to the vehicle's specific CO_2 emissions values. This change was enacted through the Finance Act 2008 and took effect from July 1st 2008. Table 7.2 summarises the VRT rates and bands prior to July 1 2008 and Table 7.3 shows the rates since the change took effect. The VRT rates are expressed as fixed percentages of the Open Market Selling Price (OMSP, i.e. the expected retail price, including all taxes) of the new car (Revenue Commissioners 2012).

Table 7.2: Vehicle Registration Tax Rates in Ireland prior to July 1st 2008

Old Bands	Engine Size (cc)	VRT (% of OMSP)
A	< 1,400	22.50%
B	1,400 - 1,900	25%
C	> 1,900	30%

Table 7.3: New Vehicle Registration Tax and Annual Motor Tax in Ireland since July 1st 2008

New Bands	CO_2 Emissions (gCO_2/km)	VRT	Motor Tax
A	0 – 120g	14%	€100
B	> 120g/km –140g/km	16%	€150
C	> 140g/km – 155g/km	20%	€290
D	> 155g/km – 170g/km	24%	€430
E	> 170g/km – 190g/km	28%	€600
F	> 190g/km – 225g/km	32%	€1,000
G	> 225g/km	36%	€2,000

The old VRT rates vary between 22.5% and 30% of the OMSP and there are three broad categories of engine size. Comparing Table 7.2 with Table 7.3, the new VRT rates vary more widely, both in terms of range (14% – 36%) and in terms of the number of bands (seven compared with three previously). As shown by the range applied across the bands, the signal to encourage purchase of more fuel efficient, lower-CO_2 emitting cars is strong. A car with a market value of €30,000, for example, will have a VRT rate of €4,200 if it is in Band A, compared with a VRT rate of €10,800 if in Band G.

Rogan et al. (2011) show that the changes in VRT and AMT led to a 13% decrease in the average specific CO_2 emissions for new cars over the first year after the tax change was introduced. This reduction in specific CO_2 emissions was caused not by a reduction in engine size, but rather by the dieselisation of car sales: As shown in Figure 7.4 there was an evident gradual shift in new private car sales towards diesel since 2000 and this trend was accelerated with the changes in private car taxation,

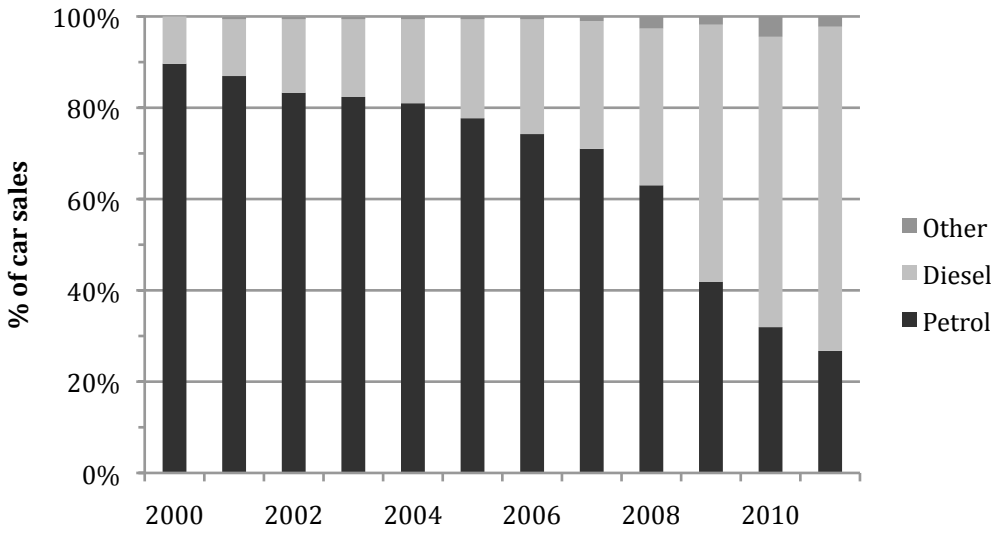


Figure 7.4: Share of private car sales according to fuel type, 2000 – 2011 (Source: SEAI)

doubling from 27% in 2007 to 57% in 2009. Note that the total numbers of car sales in 2008 were down by 19%, and in 2009 were less than half of those in 2007 due to the economic recession in Ireland. The shift towards diesel cars has further continued, accounting for 73% of new private car sales in 2011.

Daly & Ó Gallachóir (2011*a*) simulate the future impacts of this taxation measure in the period to 2025 and project that the share of diesel cars in the total stock of private cars increases from 20% in 2008 to 44% in 2025. The results show that this change results in a CO_2 saving of 7% in 2020, relative to a scenario that excludes the measure.

7.3 Methodology

In this paper future NOx emissions for the Irish car fleet over the period 2009 – 2020 for three different scenarios are modelled:

- PRE, a pre-tax-baseline scenario, which assumes the future sales share of petrol and diesel vehicles will be the same as in 2007, the year before introduction of the new tax system
- POST, a post-tax scenario where the sales share of petrol and diesel cars is assumed to be the same as in 2009, the year after the introduction of the new tax system. Total mileage is the same as in the pre-tax-baseline scenario.
- REB, a post-tax-rebound scenario, which assumes the same petrol and diesel sales share as the post-tax scenario for new cars, but with an increased mileage due to a rebound effect on activity

In this paper the underlying projected activity data for the car fleet and mileage in Ireland are taken from a car stock model and activity model developed by Daly & Ó Gallachóir (2011*a*). The activity data is then adapted to feed into the COPERT model, in order to calculate associated NOx emissions. Specific NOx emission factors (in g/km) are separately calculated using the COPERT model to allow a direct comparison of relative NOx emissions between diesel and petrol cars in Ireland.

7.3.1 Future fleet/mileage

Daly & Ó Gallachóir (2011*a*)[3]provide a detailed description of the methodology underpinning the car stock model for Ireland that is used here to generate the activity data underpinning the three different scenarios. The model simulates the composition of the car stock and of activity according to the type of technology (fuel and engine type) and vehicle vintage and builds on previous work focusing on the historical car stock and activity (Daly & Ó Gallachóir 2011*b*). Disaggregating the stock by technologies and vintages allows the simulation of the diffusion of different technologies through the car stock, necessary, for example, for representing electric vehicles diffusing through the stock, or older cars retiring as a result of a scrappage scheme. Vintage also effects activity: new cars tend to be driven greater distances then older cars, and due to purchasing trends can have much different engine technology profiles and therefore emissions profiles.

National economic forecasts and fuel price forecasts are used to calculate the baseline overall activity in vehicle kilometres (vkm), and the stock model uses historic scrappage rates and new-car sales for each engine type to calculate the stock profile in each projected year. Table 7.4 shows the car stock and share of petrol and diesel cars in 2008 and 2020 for the three tax scenarios. The share of diesel cars in the stock rises from 20% in 2008 to 23.8% in the PRE scenario due to the increased share of diesel in new-car purchases between 2000 and 2008, and rises to 39% in the POST scenario, due to the switch towards diesel sales as a result of the car taxation change in 2008. Figure 7.5 shows the new car and fleet efficiencies of the PRE, POST and REB scenarios.

Table 7.4: Summary of car stock in 2008 and 2020

	2008	2020		
		PRE	POST	REB
Stock ('000s vehicles)	1,917	2,132	2,132	2,200
Petrol share	80.0%	76.2%	61.0%	60.7%
Diesel share	20.0%	23.8%	39.0%	39.3%

Mileage trends by vintage and technology are applied to give the activity profile, and new-car specific energy consumption figures are used to calculate annual private car

[3]Chapter 3 of this thesis

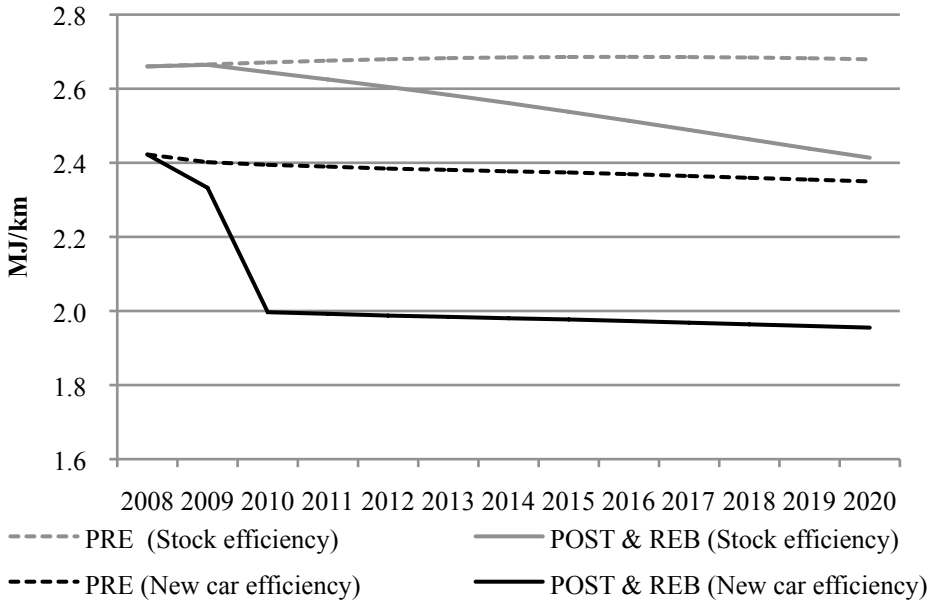


Figure 7.5: New-car and overall stock efficiency in pre-tax and post-tax (and REB) scenarios

energy demand. Activity is responsive to fuel cost in €/km, and therefore responds to both fuel price at the pump and to a change in the efficiency of the fleet in a rebound effect: Figure 7.6 shows the activity for petrol and diesel vehicles for the three scenarios for 2008 and 2020. Because of Ireland's economic recession, vehicle activity falls after 2008 and recovers to 2008 levels by 2015. The share of diesel activity in the POST and REB scenarios increases from 28% in 2008 to 30% in the PRE scenario and 47% in the POST and REB scenarios in 2020. In the REB scenario, overall activity in 2020 is 4% higher than in the PRE or POST scenarios which takes into account the impact that the tax change had on the efficiency of new cars and therefore the cost of driving. The tax change led to a 16% increase in new-car efficiency between 2007 and 2010 (Rogan et al. 2011), which leads to a projected 10% long-term improvement in the fleet efficiency between 2008 and 2020.

7.3.2 NOx emissions for future fleet/mileage using the COPERT model

In order to calculate the NOx emissions for the three different scenarios, the road transport emission model COPERT4v8.1 is used (Gkatzoflias et al. 2012). COPERT 4 is a software tool used world-wide to calculate air pollutant and greenhouse gas emissions from road transport. The European Commission's Joint Research Centre manages the scientific development of the model. COPERT has been developed for official road transport emission inventory preparation in EEA member countries. The COPERT 4 methodology is part of the EMEP/EEA air pollutant emission inventory guidebook for the calculation of air pollutant emissions and is consistent with the

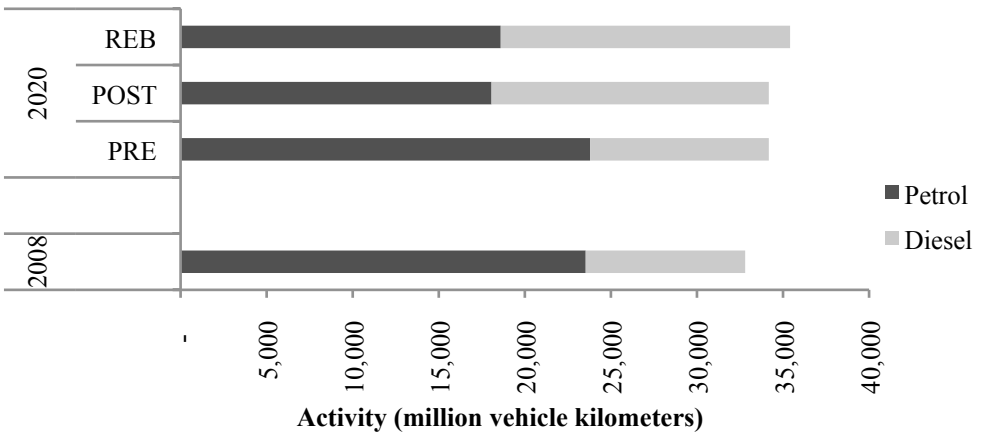


Figure 7.6: Fleet activity of petrol and diesel vehicles in million vehicle kilometres in 2008 and the three tax scenarios

2006 IPCC Guidelines for the calculation of greenhouse gas emissions. COPERT is used by most of the EU27 countries for reporting of air pollutant emissions from road transport.

For NOx emissions, COPERT uses a detailed methodology, based on specific emission factors. Both hot and cold emissions are taken into account in the approach.

The COPERT model assumes that future Euro standards deliver reduced NOx emission factors as anticipated. There are no real world measurements on Euro 5 and Euro 6 passenger cars available as yet.

COPERT calculates NOX emissions based on the fleet and mileage characteristics. The fleet is broken down by technology (Euro standard) and three engine size classes for petrol (<1.4 l, 1.4 – 2.0 l, >2.0 l) and two engine size classes for diesel (<2.0 l, >2.0 l).

The car stock model yields the mileage as well as the fleet broken down by engine size and technology. Engine size bands derived from the car stock model do not exactly match the bands required as input for the COPERT model. The vehicle numbers from the car stock model in the different engine size bands are therefore redistributed to yield numbers for the COPERT bands as shown in Table 7.5.

The COPERT model is then used to calculate total NOx emissions for each engine size, technology and fuel type. COPERT input classes are shown in Table 7.6. Other input data to the COPERT model are the speed on urban/rural/highway roads, and the percentage of the mileage driven on urban/rural/highway roads. The values used are consistent with those in Ireland's national air pollution emission inventory calculations.

Table 7.5: Engine size bands in car stock model and COPERT input

Stock model output	Copert input	
	Petrol	Diesel
<900	<1400	<2000
900 – 1200		
1200 – 1500		
1500 – 1700	1400 – 2000	
1700 – 1900		
1900 – 2100	>2000	>2000
>2100		

Table 7.6: COPERT input classes

Fuel type	Petrol, diesel
Technology	Pre-Euro, Euro1, Euro2, Euro3, Euro4, Euro5, Euro6
Engine size	Diesel <2l, >2l; Petrol <1.4l, 1.4-2.0l, >2.0l
Speeds	Urban 30 km/h, rural 60 km/h, highway 100 km/h
Shares	Urban 30%, rural 50%, highway 20%

7.3.3 Comparison of relative NOx emissions from diesel and petrol cars

For a direct comparison between diesel and petrol cars, implied NOx emission factors (in g/km) were calculated, using COPERT. For these calculations, the fleet number or mileage does not have an effect, because emission factors are calculated on a per km basis. Environmental variables (such as average speed, split between urban/rural/highway etc.) are consistent with those used in the national air pollutant inventory estimates (Environmental Protection Agency 2012*b*).

7.4 Results

7.4.1 Future fleet/mileage

The underlying activity data for the car fleet and mileage in Ireland is taken from the car stock model and activity model as previously outlined. The activity data describes the future car fleet, in the period to 2020, classified by fuel type (diesel, petrol), by engine size, and by vintage (i.e. year of first registration) of the vehicle. The vintage of the vehicle is used to determine the technology (Euro standard) that applies to the vehicle.

Figure 7.7 shows total mileage for passenger cars for the PRE scenario (pre-tax-baseline) with a decline in mileage for older vehicles (i.e. Euro 1, 2, 3) and an increase in mileage for new vehicles (i.e. Euro 4, 5, 6).

The activity contribution of newer cars (Euro 4, 5, 6) increases from 29.3% in 2008 to

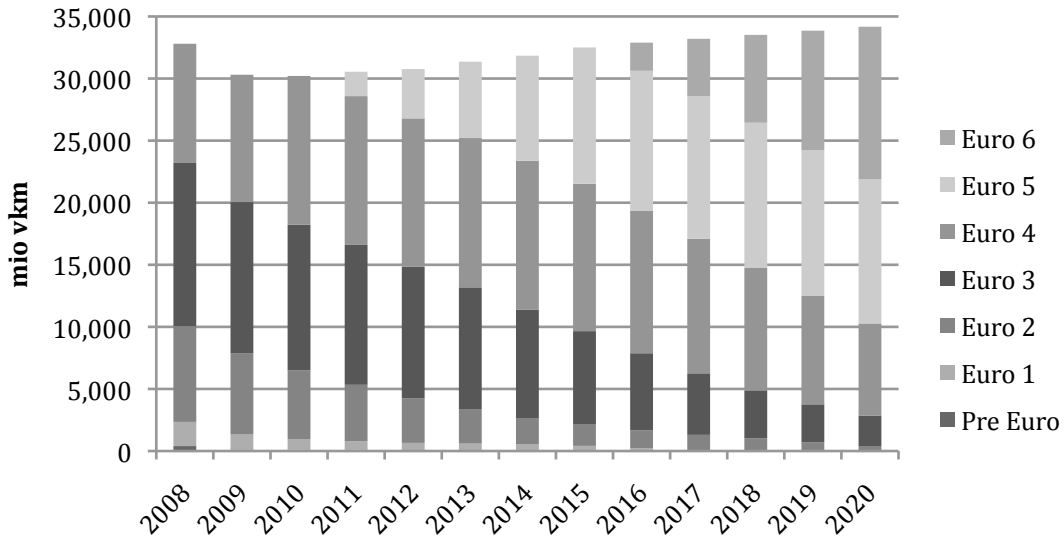


Figure 7.7: Total mileage by technology (Euro standard), for the PRE scenario (pre-tax-baseline)

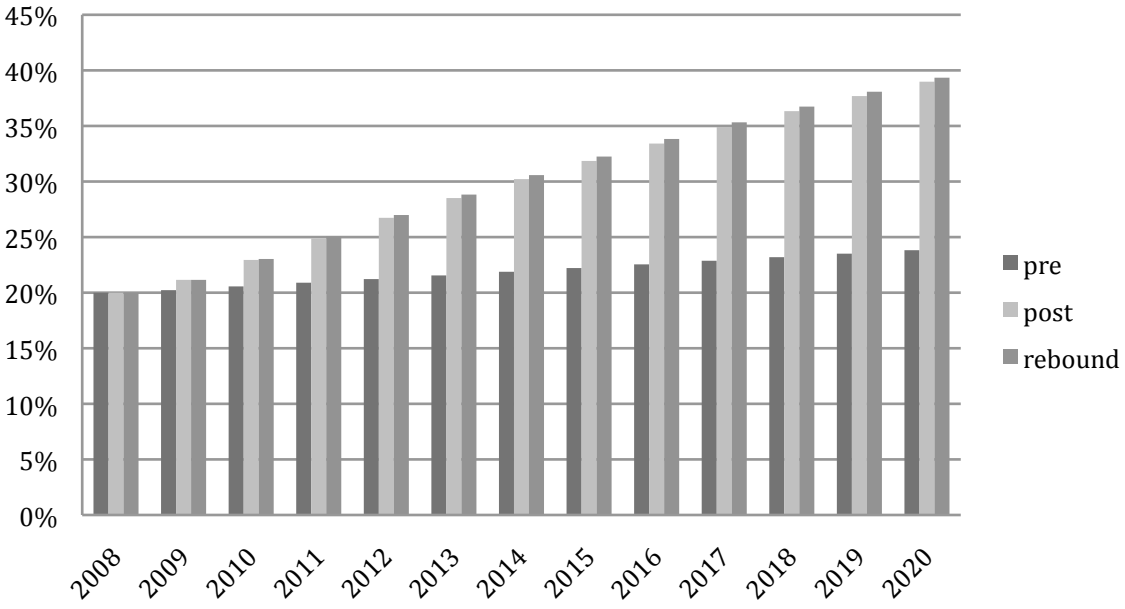


Figure 7.8: Diesel cars as fraction of total car fleet, for three scenarios

91.6% in 2020, due to replacement of older with more modern cars. This will result in a decline in NOx emissions from the car fleet.

Figure 7.8 shows the increase in diesel cars as a fraction of the total car fleet, for the different scenarios. In the PRE scenario (pre-tax-baseline), the diesel fraction increases from 20% in 2008 to 23.8% in 2020. In the POST scenario (post-tax), the fraction of diesel cars increases to 39.0%, and in the REB scenario (post-tax-rebound) it increases to 39.3%.

Table 7.7 summarises the proportion of diesel cars in 2020, in terms of vehicle stock, total vkm, and energy demand (fuel use), for the three different scenarios. It also shows the absolute numbers for diesel cars, vkm, and energy, and the change for 2020 compared to 2008.

Table 7.7: Diesel cars, vkm, energy: absolute numbers and change 2020 vs 2008

		2008	2020			Change 2020 vs 2008		
Absolute			PRE	POST	REB	PRE	POST	REB
Stock		383,421	507,789	830,963	865,624	32.4%	116.7%	125.8%
vkm	million	9,266	10,385	16,111	16,812	12.1%	73.9%	81.4%
Energy	TJ	23,198	26,052	39,406	41,113	12.3%	69.9%	77.2%
Diesel fraction								
Stock		20.0%	23.8%	39.0%	39.3%			
vkm		28.2%	30.4%	47.1%	47.5%			
Energy		27.1%	28.4%	44.6%	44.9%			

In the PRE scenario, the number of diesel cars increases by 32.4% between 2008 and 2020. Total mileage by diesel cars increases by 12.1% over the same period, and energy demand by 12.3%. In the POST scenario, the number of diesel cars increases by 116.7%, and in the REB scenario by 125.8%.

In the PRE scenario, the proportion of diesel cars increases from 20.0% in 2008 to 23.8% in 2020, whereas the mileage of diesel cars increases from 28.2% to 30.4% of total mileage by 2020. In the POST scenario, the proportion of diesel vehicles increases to 39.0% in 2020, and diesel mileage to 47.1% of total mileage. In the REB scenario the values are slightly higher.

Thus, even in the absence of the changes in taxation, a slight shift to diesel cars is expected. With the change in taxation, the shift to diesel is enhanced.

7.4.2 Relative emission factors for diesel and petrol cars

NOx emission factors in g/km for petrol and diesel cars are shown in Table 7.8, for different engine sizes and technologies. Specific NOx emissions are higher for diesel cars compared to petrol cars, and decline with the improvement of technologies. Table 7.9 shows the relative emission of diesel cars, compared to petrol cars of the same technology standard and engine size. For cars with Euro 3/4/5 NOx specific emissions are about 8 to 9 times higher for diesel cars, compared to petrol cars. For Euro 6 standard, the specific emissions of diesel cars are still a factor of 3 to 4 higher.

7.4.3 NOx emissions for each scenario

Activity data (car stock, mileage by technology and engine size) presented in section 7.3.1 is fed into the COPERT model to calculate NOx emissions for the three

Table 7.8: Specific emissions in g NOx/km

Vehicle class	Conventional	Euro 1	Euro 2	Euro 3	Euro 4	Euro 5	Euro 6
PC petrol < 1.4 l	1.83	0.41	0.23	0.10	0.06	0.05	0.05
PC petrol 1.4 - 2.0 l	2.17	0.40	0.23	0.10	0.06	0.05	0.05
PC petrol > 2.0 l	2.52	0.38	0.21	0.09	0.06	0.05	0.05
PC diesel < 2.0 l	0.54	0.66	0.69	0.76	0.55	0.40	0.18
PC diesel > 2.0 l	0.87	0.66	0.69	0.76	0.55	0.40	0.18

Table 7.9: Relative specific emissions Diesel vs Petrol car of same engine size

Diesel vs petrol	Conventional	Euro 1	Euro 2	Euro 3	Euro 4	Euro 5	Euro 6
PC < 2.0 l	0.2	1.6	3.0	7.4	8.6	7.4	3.3
PC > 2.0 l	0.3	1.7	3.3	8.1	9.5	8.3	3.7

scenarios. Results are shown in Table 7.10, Table 7.11 and Figure 7.9.

The PRE scenario shows a decrease in total NOx emissions of 50% between 2008 and 2020. The decrease in NOx emissions from petrol cars is 65% and from diesel cars 39%. This decrease is due to the replacement of older cars with ones applying better emission standards.

The POST and REB scenarios also show a decrease in 2020, compared to 2008. However, relative to the baseline, they show an increase in NOx emissions. This increase over baseline amounts to 24% in the POST scenario, and to 28% in the REB scenario in 2020. Both post-tax scenarios show a decrease in NOx emissions from petrol cars that is more than offset by an increase in emissions from diesel cars.

Table 7.10: NOx emissions for scenarios PRE, POST, REB for 2008 and 2020

Tonnes of NOx	2008	2020			2020 vs 2008		
		PRE	POST	REB	PRE	POST	REB
Petrol	4,250	1,475	1,184	1,214	-65%	-72%	-71%
Diesel	6,100	3,729	5,251	5,448	-39%	-14%	-11%
Total	10,350	5,204	6,435	6,662	-50%	-38%	-36%

Table 7.11: Relative NOx emissions (tonnes) in 2020, for scenarios POST and REB compared to PRE

	POST vs PRE		REB vs PRE	
Petrol	-291	(-20%)	-262	(-18%)
Diesel	+1,522	(+41%)	+1,720	(+46%)
Total	+1,231	(+24%)	+1,458	(+28%)

7.5 Conclusions

This paper examines the potential unintended impact of a specific CO_2 mitigation measure on NOx emissions in Ireland over the period 2008-2020. This measure was introduced in 2008 and linked vehicle registration and motor taxes to CO_2 emissions. While the policy has led to a significant decline in new-car specific emissions, it

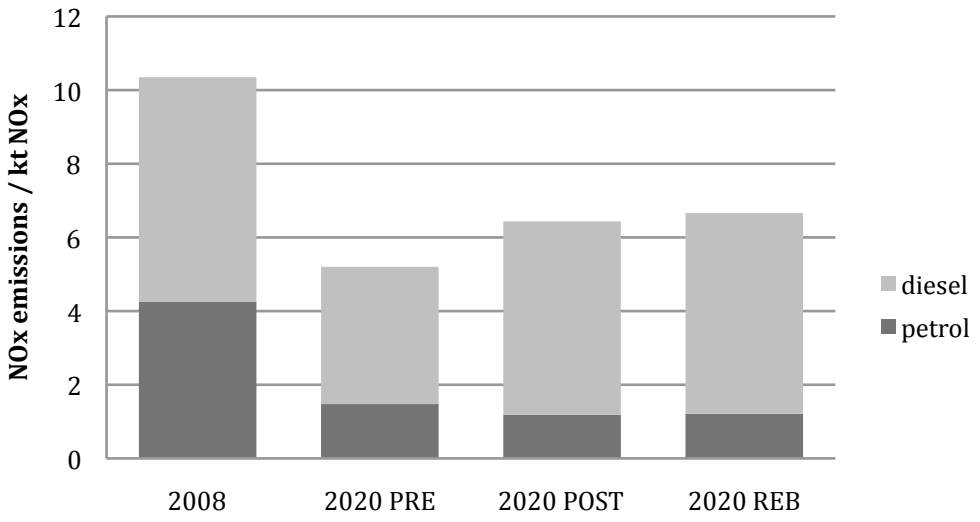


Figure 7.9: NOX emissions for 2008; and for 2020 PRE, POST, REB scenarios

would appear that this is due to a switch in purchasing behaviour to diesel vehicles rather than a move to smaller and less powerful vehicles. Diesel cars represented 73% of new car purchases in 2011, compared with 28% in 2007. Daly & Ó Gallachóir (2011*a*) simulated this taxation measure and project a CO_2 saving of 7% in 2020. Using the same methodology and approach, this paper simulates the impact of the change in taxation policy on NOx emissions over the period 2008-2020. The results indicate a 28% increase in private car-related NOx emissions in 2020 compared with a baseline pre-tax scenario.

While there is a reduction in absolute NOx emissions in the post-tax scenario (36% reduction on 2008 emissions in 2020), this compares with a 50% reduction for the pre-tax scenario. This improvement in simulated emissions is due to the turnover of the car stock and improved Euro standards for air pollutants. The current NEC ceiling, 65 ktonnes for NOx for Ireland, was exceeded by 10.7 ktonnes in 2010 and continues to apply for future years. This will increase the effort required to meet the NOx emission targets.

This paper has shown that climate mitigation policies, which are generally associated with the co-benefit of reduced air pollution, can have negative impacts on air pollution, particularly when CO_2 savings come from fuel switching. This switch towards diesel use will likely have a similar effect on other pollutants such as particulate matter (PM).

This paper points to important interdependencies in emissions targets: While a reduction in air pollution is often a consequence of energy efficiency and climate mitigation policies, fuel switching can lead to negative effects. While the current focus on policy action is on climate change, rather than air pollution, it is important

for policy-makers to be cognisant of possible negative side effects of climate change policies on air pollutants.

Chapter 8

Modelling HGV freight transport energy demand in Ireland and the impacts of the construction bubble

Abstract

Freight transport is both significant and fast growing in terms of energy use but there are few papers that focus on modelling future freight transport energy use. This paper addresses this knowledge gap, focussing on Ireland, which is an interesting case study because it has witnessed a significant increase in energy use for freight from 1990 – 2007 followed by a dramatic drop in the following two years due to the property construction bubble bursting and economic recession. The paper focuses on HGV freight only due to gaps in LGV data and the focus on construction activity. We disaggregate freight activity (tkm) in terms of three commodity groupings (reflecting sectoral activity) and weight class, and estimate historical HGV energy demand by commodity group using specific energy consumption (MJ/tkm) by weight class. We then determine the most significant economic driver behind the activity trends for each commodity grouping and the associated elasticity of demand. Finally we use these elasticities along with national economic forecasts to project future HGV activity and energy for each commodity grouping. Comparing the approach presented with an aggregated GDP-tkm-MJ approach, it is clear from the results that the disaggregated approach captures better the trend in the period 2008 – 2010.[1]

Keywords: Freight transport, energy modelling, HGV

[1]Chapter submitted for publication as: Whyte et al. (2012), 'Modelling HGV freight transport energy demand in Ireland and the impacts of the property construction bubble', *Energy*, in review. Submitted on June 6th 2012.

8.1 Introduction

Energy use in transport accounts for 27% of total final energy demand globally, with the figure increasing to 32% for OECD countries (IEA 2010*b*). The IEA estimate that the transport sector is responsible for 23% of energy-related carbon dioxide (CO_2) emissions (IEA 2009). In addition to concerns this raises regarding climate change, transport is 94% oil based, which leads to concerns about energy security issues.

While nearly half (47%) of transport energy use is in light duty vehicles (mostly cars), truck and rail transport (mostly road freight) accounts for a significant proportion (27%). Within the European Union (EU-27), freight transport represented 29% of transport energy demand in 2005 while private car transport accounted for 50%. Freight transport energy grew however by 40% (2.3% per annum) between 1990 and 2005, compared with 22% private car transport growth over the same period (1.4% per annum). In Ireland, the case study for this research, freight transport energy grew by 8.2% per annum over the period 1990 – 2007, compared with a 5.2% annual average growth in private car energy demand over the same period (Howley, Dennehy & Ó Gallachóir 2009). Freight transport is thus both significant and fast growing in terms of energy use.

Despite this, the focus of energy modelling research and of energy policy has been more centred on private car energy use (Acutt 1996, Hennessy & Tol 2010, Han & Hayashi 2008). A number of papers have attempted to quantify the effects of freight activity on energy demand and to understand what is driving freight activity. There are only a small number of papers that focus on modelling future freight transport energy use and this paper addresses this knowledge gap.

Schipper et al. (1997) carries out a Laspeyres decomposition analysis on freight energy usage in ten industrialised countries over the period 1973 – 1992, which points to increased freight volumes and energy from freight transport growing faster than from passenger transport. Kamakate & Schipper (2009) extended this Laspeyres decomposition analysis for five of these countries up to 2005. This cross-country comparison highlights in part the influence of geography, transportation infrastructure, and truck utilisation patterns on energy and carbon intensity from this sector. It points to the possibilities of reducing trucking energy use and emissions from better logistics and driving, higher load factors, and better matching of truck capacity to load. Sorrell, Lehtonen, Stapleton, Pujol & Champion (2009) carries out a decomposition analysis on freight transport energy in the UK, although in this case using a log mean Divisia index (LMDI) rather than the Laspeyres method. The results demonstrate that the main factor contributing to the decoupling of UK road freight energy consumption from GDP was the decline in the value of domestically manufactured goods relative to GDP. McKinnon & Piecyk (2009) uses UK data to

examine a number of methods to quantify road freight transport CO_2 emissions and compares the results both for a single year (2006) and over a time period. It highlights a series of statistical anomalies and approximations and tries to explain discrepancies that have arisen in the UK data sets. Eom et al. (2012) uses a cross-country comparison of freight energy in 11 IEA countries over the period 2007-2010 to examine the coupling between GDP and freight activity: No evidence of a decrease in coupling is found.

Other papers focus specifically on energy efficiency in the fright transport. For example, Vanek & Morlok (2000) proposes a commodity based approach as an alternative to mode-based approaches, i.e. freight energy use is disaggregated by contribution of major commodity groups, in order to support efficiency improvement at the commodity level. The rationale for this was that despite substantial improvement in the technological efficiency of freight modes and robust growth in the use of intermodal rail since 1980, total freight energy use across all modes in the US has grown by approximately 33%. Ruzzenenti & Basosi (2009) evaluates energy efficiency in the European freight transport sector over three decades. Two different indicators (energy intensity and fuel economy) are initially taken into account to select the most suitable for evaluating vehicles' efficiency. Top-down and bottom-up methods are used to measure fuel economy, which are then adjusted to account for maximum power available. Leonardi & Baumgartner (2004) analyses road freight energy efficiency in Germany in the year 2003. The results show potential for improvements given a low level of vehicle usage and load factor levels, scarce use of lightweight vehicle design, poorly selected vehicles and a high proportion of empty runs.

The focus of these papers has largely been on understanding the trends in freight energy use, the underlying factors and on quantifying energy efficiency. Most of the available literature deals with historical rather than future trends. In the case of future trends, Piecyk & McKinnon (2010) constructs a BAU forecast of road freight activity and associated CO_2 emissions in Great Britain to the year 2020 based on expert opinion using focus group discussions and Delphi questionnaire surveys. Two further scenarios were developed by changing the assumptions regarding modal share, vehicle utilisation and fuel efficiency.

This paper builds on the limited literature available on modelling future freight transport energy demand. The paper focuses on Ireland as a case study but can readily be applied to other countries where similar data is available. Ireland is chosen because it has witnessed a significant increase in energy use for freight in the period 1990 – 2007 (Howley, Ó Gallachóir & Dennehy 2009) from 334 ktoe to 1,296 ktoe (8.1% per annum on average) followed by a dramatic drop in the following two years to 810 ktoe (21% per annum on average). The increase and drop are assumed to be a

direct response to the property construction bubble bursting and economic recession and this paper also investigates the extent to which this assumption is valid.

The transport freight vehicle stock, activity and energy demand can be disaggregated according to heavy goods vehicles (HGV) and light goods vehicles (LGV). For the latter, the key activity driver of energy use is the distance (vehicle kilometres, vkm) the goods are transported, whereas for HGV the weight of goods transported is also a key factor, hence the amount of tonne kilometres (tkm) is the key activity driver. Due to LGV data limitations and to the focus on construction freight, this paper focuses on modelling HGV freight transport energy only.

The methodology comprises two key elements, drawing respectively on top down macro-economic modelling and bottom-up techno-economic modelling techniques. The bottom-up modelling in Section 8.2 disaggregates freight activity in terms of commodity groupings and weight class as far as available data allows, and calculates historical energy demand using specific energy consumption (MJ/tkm) by weight class. Using this disaggregated energy series, the relative contributions of different commodity groups to the rise and fall of freight energy demand is analysed up to 2010, particularly in relation to building activity. Section 8.3 then uses a top-down modelling methodology to determine the most significant economic driver behind the activity trends of each commodity grouping and the associated elasticity of demand. Section 8.4 uses these elasticities along with national economic forecasts to project activity and energy for each commodity grouping. Section 8.4 also compares aggregate sectoral freight transport energy demand with a disaggregated approach to illustrate the benefits of the latter. Section 8.5 draws some initial conclusions and discusses possible improvements and next steps.

The motivation for this paper is to address some of the limitations inherent in the projections for freight transport energy demand in current national energy forecasts in Ireland, which are published each year by Sustainable Energy Authority of Ireland (Clancy et al. 2010). The modelling underpinning these forecasts is carried out by the Economic and Social Research Institute using the macro-economic model HERMES with energy as a derived demand (Di Cosmo & Hyland 2011), modelling freight transport energy demand for the economy at an aggregate level rather than the disaggregate approach proposed here, which differentiates freight energy as a result of building and construction. The model developed here also incorporates specific unit consumption, which enables consideration of technical developments within the fleet stock, building on previous work by the authors on modelling private car energy demand (Daly & Ó Gallachóir 2011*a*,*b*).

8.2 Historical trends

8.2.1 Fleet and activity disaggregation

An ideal bottom-up energy demand model would consider all factors contributing to energy demand, which breaks down as follows in the case of HGV transport: the composition of the vehicle fleet disaggregated by the unladen weight of vehicles, where larger vehicles transport a greater number of goods; the age profile, which effects vehicle efficiency and activity; activity demand disaggregated by the commodity group of goods; and the efficiency profile of activity in MJ/tkm, including the percentage fill of vehicles, which is related to logistics, the weight profile of goods delivered, the individual engine efficiency of vehicles and the on-road efficiency, which is effected by driving styles and road type. As bottom-up modelling is data based, it is inevitable that data limitations only allow a subset of these factors to be modelled in detail.

For Ireland, the annual *Road Freight Survey*, undertaken and published by the Central Statistics Office (Central Statistics Office 2009), is used here to characterise the HGV fleet between 1995 to 2009 disaggregated by unladen weight class (2 tonnes – 5 tonnes unladen weight, 5 tonnes – 7.5 tonnes unladen weight etc.) and the commodity group of goods carried (crude and manufactured minerals, chemicals etc.), and the activity associated with these vehicles in terms of distance travelled (vehicle-kilometres, vkm) and tonne-kilometres (tkm).

This fleet and activity data is used to create a profile of fleet activity in terms of tkm travelled by fleet size (weight) class (Figure 8.1) and commodity group (Figure 8.2). The most significant commodity groups in terms of their contribution to HGV activity in 2008 are *Crude and Manufactured Minerals* (24.4%), *Foodstuffs* (22.6%), *Machinery*, *Transport Equipment* (15%), *Mixed Loads* (14%) and *Agricultural* (10%). These five sectors represent 82% of fleet activity. The trend of activity in the *Crude and Manufactured Minerals* class, in the context the property construction bubble in Ireland is examined in Section 8.2.2.

The overall profile of tkm by unladen vehicle weight class is significant for energy demand. The two heaviest weight classes account for 86% of activity, with the greater than 12.5 tonnes class representing 48% and the 10 – 12.5 tonnes class representing 38% of activity.

We aggregate activity data into commodity groups that act as a proxy for three sectoral groupings, namely agriculture, construction and other. Specifically, *Agricultural* and *Foodstuffs & Fodder* are combined to form to *Agricultural & Foodstuffs*, *Crude* and *Manufactured Minerals and Machinery*, *Transport Equipment* are aggregated to *Crude & Machinery* and all other commodity groupings are aggregated to *Other*.

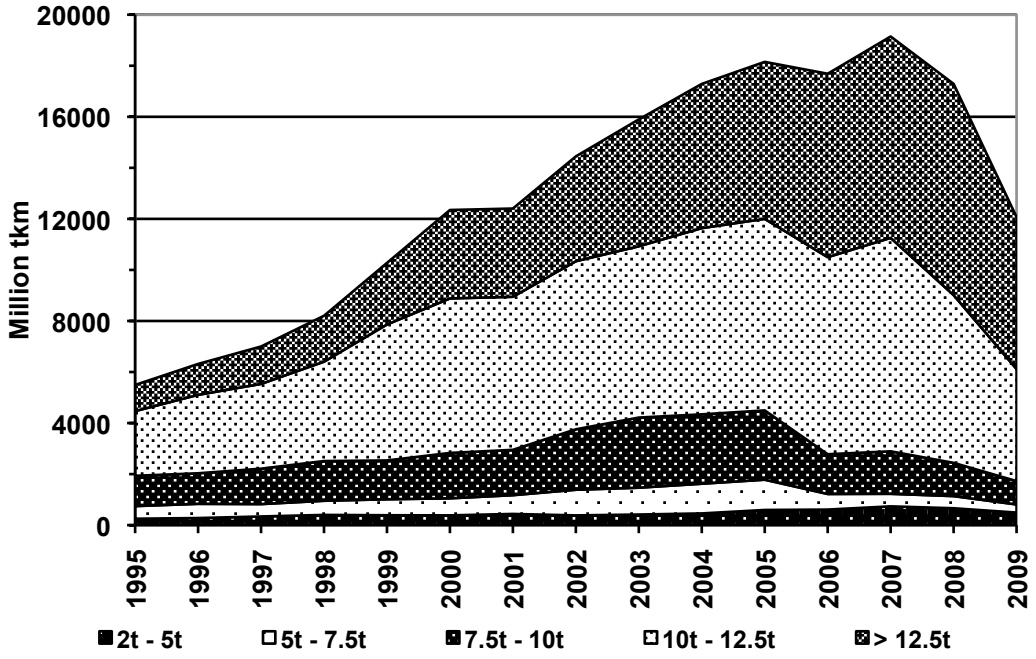


Figure 8.1: Historical HGV activity trends in tonne-kms by weight class, Ireland 1995 – 2009

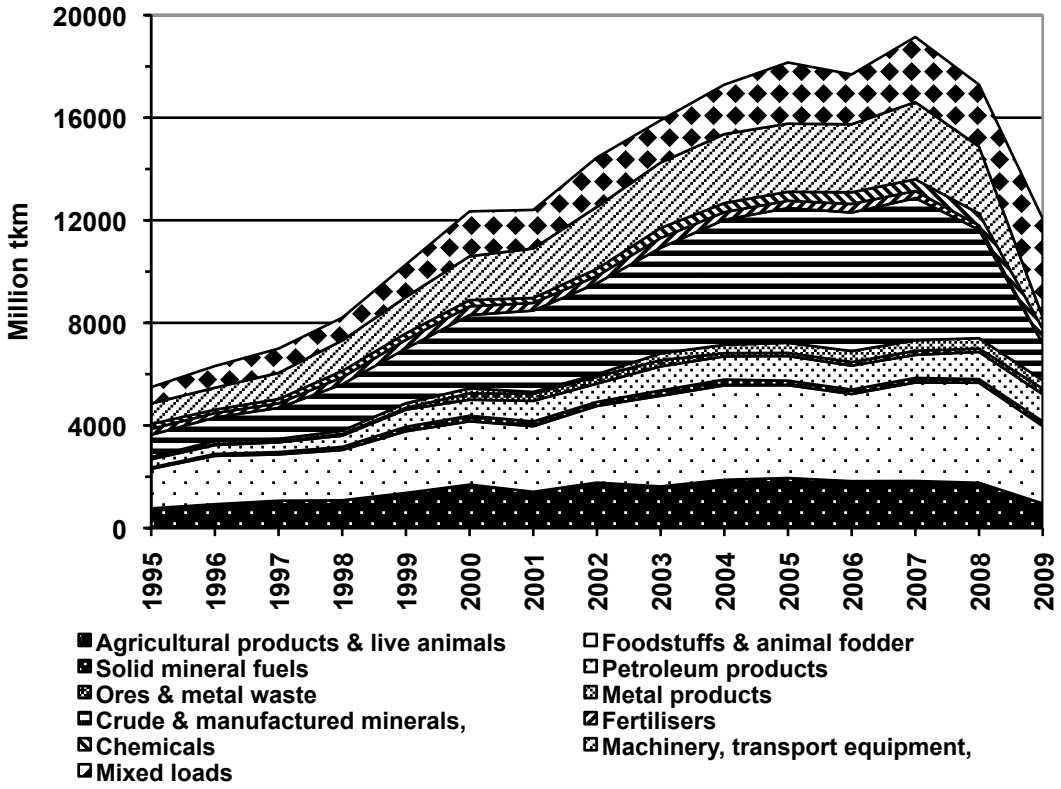


Figure 8.2: Historical HGV activity trends in tonne-kms by commodity, Ireland 1995 – 2009

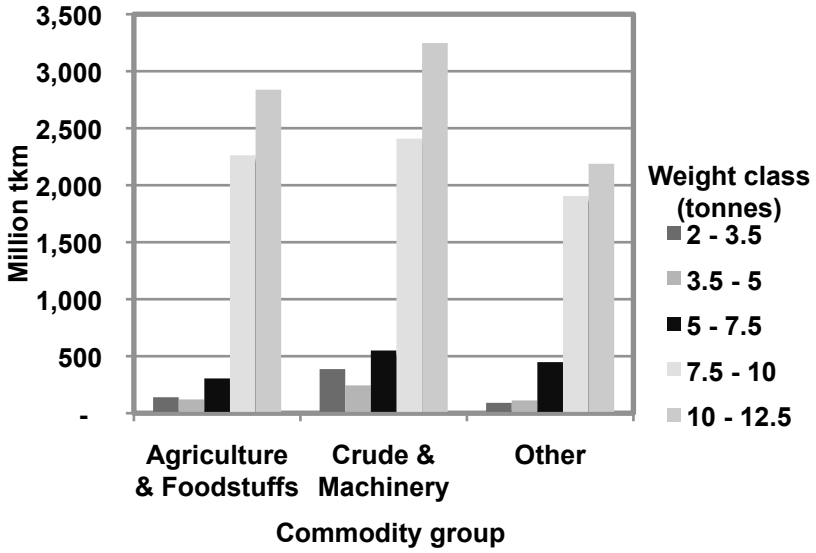


Figure 8.3: Activity profile in 2008 by unladen weight class and commodity group

Using the 2008 Freight Survey, activity in each of these commodity groups is characterised by unladen weight class for 2008, shown in Figure 8.3.

8.2.2 Energy demand

The profile of activity in each commodity grouping according to vehicle weight class, shown in Figure 8.3, is used in combination with specific energy consumption (SEC in MJ/tkm) figures by weight class to estimate historical energy demand in each of the three commodity groupings.

In the absence of Ireland specific data on SEC for freight vehicles, this paper uses values from the Road Transport Department of Finland, who carry out dedicated studies into both emissions and fuel use of freight vehicles in Finland under the LIPASTO, "Unit Emissions of Vehicles in Finland" programme (Makela & Auvinen 2007). Fuel consumption figures are derived from manufacturers' stated efficiency and testing by the Technical Research Centre of Finland (VTT), and are dependent on vehicle weight class, vehicle fill proportion and route type (urban/highway driving, etc.). Vehicle weight class is characterised in this model from the 2008 Freight Survey (Section 8.2.1), while the values for vehicle fill and route type are derived from a 2009 UK benchmarking survey on freight behaviour (UK DfT 2010). While these data are not Ireland-specific, this methodology is an improvement on the current Irish freight energy calculation, where an aggregate specific energy demand figure for freight as a whole (HGV and LGV) across Europe is used (Howley, Dennehy & Ó Gallachóir 2009). Table 8.1 shows the specific energy consumption figures for each weight class derived and used to calculate energy demand.

Table 8.1: Specific energy consumption figures for each weight class used to calculate energy demand.

	Specific Energy Consumption (SEC)	
Unladen weight (tonnes)	g diesel / tkm	MJ/tkm
2 - 3.5	72.64	3.6
3.5 - 5	37.85	1.63
5 - 7.5	29.8	1.28
7.5 - 10	32.91	1.42
10 - 12.5	32.91	1.42
> 12.5	24.34	1.13

The resulting historical HGV energy demand trend by commodity group for the period 1996 – 2010 is presented (along with HGV activity) in Table 8.2. According to these results, HGV energy demand in the period 1996 – 2007 grew more than threefold, and subsequently dropped by 44% between 2007 and 2010. The significant commodity groups showed quite different trends. HGV energy demand associated with *Agricultural and Foodstuffs*, for example, fell by 6.4% between 2007 and 2010. In stark contrast, and consistent with a property construction bubble bursting, HGV energy associated with the construction industry *Crude & Machinery* fell most significantly, by 81.4% over the same period after a growth of 383% in the period 1996 – 2007. The growth in HGV energy demand due to construction over 11 years of growth was negated in three years of recession.

Table 8.2: HGV freight activity and energy demand by commodity group, 1996 – 2010

	Activity (Million tkm)				Energy demand (ktoe)			
	Agriculture & foodstuffs	Crude & machinery	Other	Total	Agriculture & foodstuffs	Crude & machinery	Other	Total
1996	2,815	1,770	1,731	6,316	89.13	59.21	54.77	203.11
1997	2,872	2,231	1,895	6,998	90.93	74.64	59.96	225.53
1998	3,044	3,000	2,159	8,203	96.38	100.36	68.31	265.05
1999	3,774	3,547	2,954	10,275	119.49	118.66	93.47	331.62
2000	4,163	4,565	3,620	12,348	131.81	152.72	114.54	399.06
2001	3,972	5,103	3,330	12,405	125.76	170.71	105.36	401.84
2002	4,761	5,969	3,719	14,449	150.74	199.69	117.67	468.1
2003	5,158	6,667	4,072	15,897	163.31	223.04	128.84	515.19
2004	5,563	7,564	4,161	17,288	176.13	253.04	131.66	560.84
2005	5,571	7,912	4,670	18,153	176.39	264.69	147.76	588.84
2006	5,227	8,054	4,406	17,687	165.49	269.44	139.41	574.34
2007	5,677	8,554	4,916	19,147	179.74	286.16	155.55	621.45
2008	5,666	6,835	4,787	17,288	179.39	228.66	151.47	559.52
2009	5,416	2,176	4,476	12,068	171.48	72.8	141.63	385.9
2010	5,314	1,587	4,023	10,924	168.25	53.09	127.29	348.63

Figure 8.4 shows the trends in HGV energy demand by commodity group in the period 1996 – 2010 and how they compare with the trend in overall economic growth (GDP) (Bergin et al. 2010). While HGV energy associated with agriculture and foodstuffs grows in line with GDP, HGV energy demand due to construction activity grew faster and also contracted faster than GDP during the different stages of the property construction bubble.

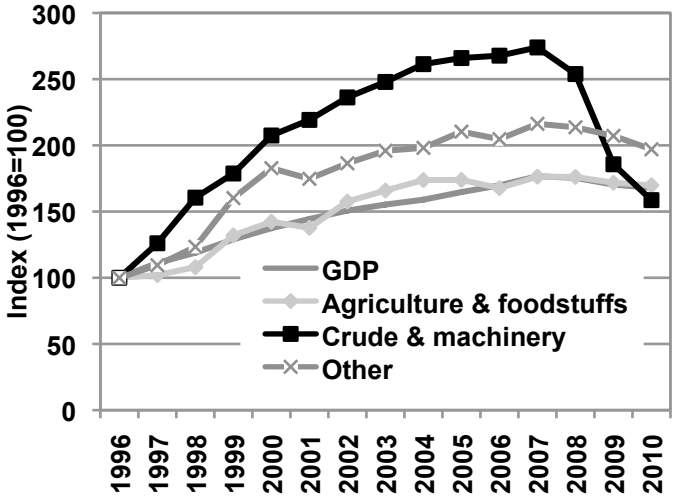


Figure 8.4: Index of GNP and HGV energy demand, 1997 – 2010

8.3 Linking economic activity and freight transport activity

In order to model future HGV freight transport activity for each of the three commodity groups, we investigate the relationship between economic activity in different sectors and freight transport activity. To build a simple relationship, a number of economic activity indicators are tested, namely, Gross Domestic Product (GDP) and Gross Value Added (GVA) in the Transport, Building, Industry, Market Services and Distribution sectors, for correlation with HGV freight transport activity in each of the commodity groups (Bergin et al. 2010). Equation 8.1 was used to determine the driving economic equator and the corresponding elasticity:

$$Tkm_c^T = Tkm_c^{T-1} \times (1 + G_I^T \times \epsilon_{c,I}) \tag{8.1}$$

where Tkm_C^T is the activity in commodity group c in year T, G_I^T is the annual growth of economic indicator I, and $\epsilon_{c,I}$ is the elasticity of activity in commodity group c with regard to indicator I. The appropriate driving economic indicator for a commodity group is chosen as that with the least R^2 value when generating elasticities. Elasticities are a measure of the degree of sensitivity of the annual growth of activity to an economic indicator or driver. They are calculated as the best-fit using linear regression of observed activity between 1995 and 2010 and generated activity, using Equation 8.1.

Table 8.3 contains the driving economic indicator, the elasticity and the R^2 error for each freight commodity sector. The building sector has the strongest link to the movement of *Crude & Machinery* goods, with a very high elasticity, at 2.07: For every 10% increase in Building economic activity, there was a 20.7% increase in *Crude &*

Machinery freight activity. The growth and burst of the property bubble had a strong bearing, consequently, over freight energy demand in the period, and in the next section, this relationship is used to model the future of freight energy.

Table 8.3: For each freight commodity group, the driving economic indicator, elasticity and error

Freight sector	Driving economic indicator	Elasticity	R^2
Agriculture & Foodstuffs	GDP	1.10	0.93
Crude & Machinery	Building (GVA)	2.07	0.96
Other	Industry (GVA)	1.31	0.97

8.4 Modelling future freight transport activity and energy demand

Projections of GDP and the GVA of the Building and Industry sectors are used as drivers to model future freight activity of *Agriculture & Foodstuffs*, *Crude & Machinery* and *Other*, respectively. Projections of the economic drivers are taken from economic forecasts generated by the Economic and Social Research Institute (ESRI) using HERMES, a macro-economic model for activity in different sectors of the economy (Bergin et al. 2010). Forecasts with a 2010 base year are used to model future freight activity projections, but Section 8.4.1 compares these with results from freight activity projections carried out using 2008 economic forecasts to illustrate the improvement in modelling due to differentiating between three commodity groupings.

Figure 8.5 shows the three economic indicators used as drivers for the three freight commodity groups generated by the ESRI HERMES model with a 2010 base year. It can be seen that the economy as a whole is anticipated to return to growth and recover to 2007 levels by 2013, and the industrial sector is expected to recover quickly. It is also anticipated that building activity never fully recovers over this time horizon from the deep decline of the housing bubble. This has significance particularly for the projection of *Crude & Machinery* freight activity.

Equation 8.1 is used to forecast HGV activity demand by commodity group to 2020, using 2010 as the base year and elasticities from Table 8.3. Figure 8.7 shows projected activity for each freight sector. The drop in *Crude & Machinery* activity (driven by the Buildings sector) is stark, both in absolute and relative terms: In 2006, at the height of the building boom, this sector represented 46% of freight activity. In the projections, this reaches a low of 5% in 2011 and reaches 13% by 2020.

When using this to forecast energy demand, we assume that both the profile of activity by weight class and the specific energy consumption factors shown in Table 8.1, remains constant throughout the modelling horizon.

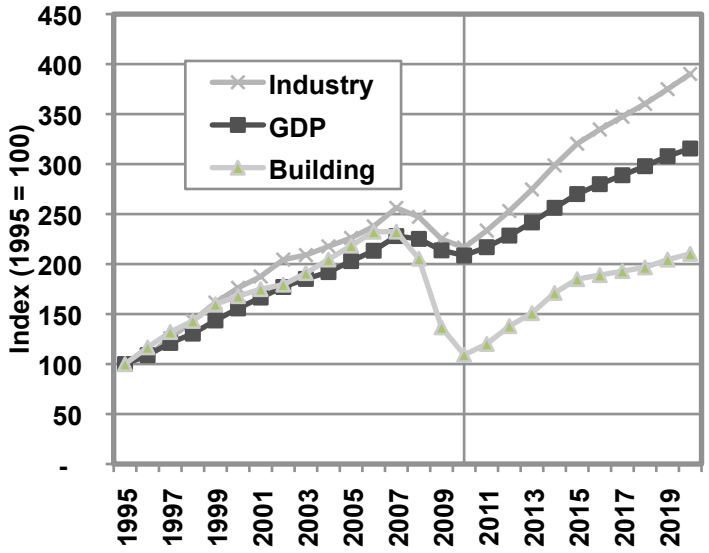


Figure 8.5: Historic and projected economic indicators used.

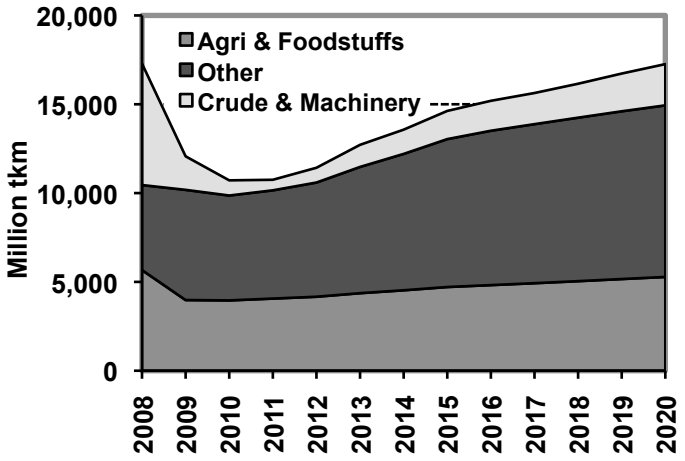


Figure 8.6: Projected HGV activity demand by commodity group

Table 8.4 shows the key results of the paper, the projected overall HGV freight energy demand and annual growth and results for the three commodity groups. *Crude & Machinery* shows the most significant changes, as the economic driver, Building, falls the most in economic forecasts, and the elasticity is very high at 2.07. Projections indicate energy demand will reach 516.1 ktoe in 2020, effectively returning to 2008 levels of 509.3 ktoe. Total HGV freight energy demand reaches a periodical low of 313.1 ktoe in 2011, some 38.5% below 2008 levels. Again, the *Crude & Machinery* commodity grouping shows the most extreme drop, falling from 204.21 ktoe in 2008, to 18.02 ktoe in 2011, a 91.2% decrease. Contrastingly, the *Other* commodity grouping shows little evidence of recession, observing just a 4.8% decrease in 2010 before immediately returning to growth, because its corresponding economic driver returns to growth. Subsequently, its significance as a commodity grouping continues to grow

markedly from 27.3% of all HGV energy demand in 2008 to 55.7% of all energy demand in 2020. Much of this HGV fleet energy demand composition change must be attributed to the *Crude & Machinery* commodity grouping collapse. The commodity grouping represented 40.1% of all HGV energy demand in 2008 but fell to just 5.7% of all HGV energy demand in 2011 before re-establishing a 14% share by 2020.

Table 8.4: HGV freight activity and energy demand by commodity group, 1996 – 2010

	Energy demand (ktoe)				Energy demand (% growth)			
	Agriculture & foodstuffs	Crude & machinery	Other	Total	Agriculture & foodstuffs	Crude & machinery	Other	Total
2008	164.2	204.2	140.9	509.33	-	-	-	
2009	115.3	57.2	180.6	251.33	-29.8	-72	28.2	-50.7
2010	114.7	25.9	171.9	257.2	-0.5	-54.7	-4.8	2.3
2011	117.7	18	177.4	285.26	2.6	-30.4	3.2	10.9
2012	120.7	25.2	187.1	375.65	2.5	40	5.5	31.7
2013	126.5	37.8	206.9	425.55	4.8	49.6	10.5	13.3
2014	131.2	41.4	223.5	409.6	3.7	9.7	8	-3.7
2015	136.5	48.1	242.4	447.23	4.1	16.1	8.5	9.2
2016	139.7	51.1	252.9	452.27	2.3	6.3	4.3	1.1
2017	142.8	53.2	260.6	462.75	2.2	4	3	2.3
2018	146.1	58	267.9	483.3	2.3	9	2.8	4.4
2019	149.5	64.4	274.9	502.46	2.4	11.2	2.6	4
2020	152.9	70.4	281.2	516.14	2.3	9.3	2.3	2.7

8.4.1 Comparing disaggregated and aggregated projections

In this paper we select three commodity groups to reflect the different trends within specific sectors and in particular to capture the particular trend in construction. It is useful to compare this disaggregated approach with an aggregated approach that captures all HGV freight trends as a single commodity group. The same regression analysis as described above is performed on aggregated historic HGV activity using different economic driving variables, and the relationship with GDP is strongest (lowest R^2 value). We generate HGV energy demand forecasts using these two approaches, disaggregated and aggregated.

We also generate the aggregate and disaggregate sets of forecasts using 2008 rather than 2010 as a base year for projecting forward (Bergin et al. 2009). This allows us to compare forecasts using both approaches to observed data within the period 2008 – 2010.

The Irish economy changed dramatically and unexpectedly in the period between 2008 and 2010 due to the global financial crisis: Economic forecasts using 2008 as a base year anticipated a short recession and a relatively quick return to growth, capturing the construction bubble impacts but not the added impact of the global financial crisis. Table 8.5 shows two sets of projections for the period 2010 – 2020 for GDP, industrial GVA and buildings that were generated in 2010 and 2009

respectively. Baseline economic forecasts changed rapidly in the period, notably the 2010 ESRI "revised recovery scenario" forecasts a slower recovery than the 2008 "recovery scenarios" forecasts scenario and different sectors of the economy responded differently to the recession.

Table 8.5: Annual average growth rates of the three driving economic indicators between 2008 and 2010, as observed, and as forecast for 2010-2020 from ESRI's 2010 forecast and 2008 forecast.

	2008-2010 annual growth	2010-2020 annual growth	
	Observed	2010 forecast	2008 forecast
GDP	- 4%	2.6%	4.2%
Industry (GVA)	- 6%	4.9%	6.1%
Building (GVA)	- 27%	6.3%	6.9%

Figure 8.7 compares the future HGV freight energy demand results using the two baseline years and the disaggregated and aggregated approaches. It is clear from the results that the disaggregated approach captures better the trend in the period 2008 – 2010. The disaggregate approach projects energy demand to fall to 341.67 ktoe in 2009, or a corresponding activity level of 11,673.7 million tkm. This compares more favourably to the actual recorded activity level in 2009 of 12,069 tkm, a 3.3% agreement. The aggregate 2008 projection does not show the same level of agreement with recorded activity, with a 24.4% difference in 2009. Therefore the aggregate approach over-projected activity in 2009 by 31.45%, failing to fully capture the effects of economic recession on the activity of HGV fleet activity.

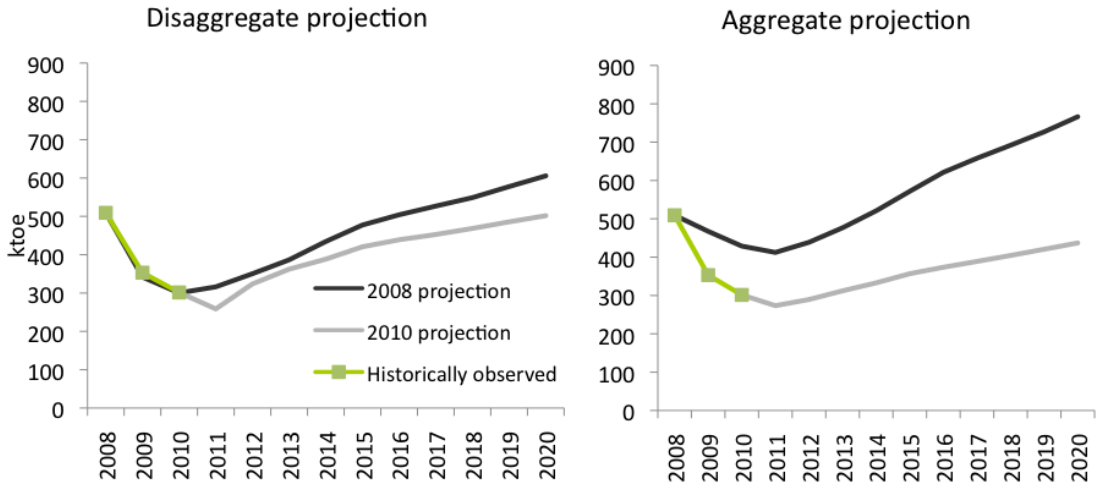


Figure 8.7: Comparison of HGV freight energy projections based on 2008 and 2010 economic forecasts using the disaggregated and aggregated modelling approaches

The greater accuracy in the disaggregate methodology is partially attributed to the separation of activity due to buildings, which due to the bursting of the property bubble, declined at a much greater pace than other sectors of the economy, effecting freight activity in the *Crude & Machinery* sector similarly, which fell from 6,835 tkm in

2008 to 1,887 tkm in 2009. The difference in projections is less pronounced in the disaggregate projection, because the effect of building trends is confined to activity in *Crude & Manufacturing* commodities only. Greater accuracy in the disaggregate approach is also due to the separate derivation of commodity groupings' elasticities with regard to different economic drivers: This method captures the different behaviour of *Crude & Machinery* from other sectors, with a high elasticity of 2.07.

8.5 Discussion

This paper presents a straightforward and reproducible approach for modelling the energy demand of heavy goods vehicles. The model builds on a commodity-based methodology proposed by Vanek & Morlok (2000) by projecting freight activity by commodity on the basis of economic projections. The disaggregate methodology looks at the profile of HGV activity by both commodity transported, allowing relationships between commodity movement and different economic sectors to be established, and by vehicle weight class, giving a better picture of energy demand. This represents an improvement on the current Irish modelling methodology for freight, and attempts to address a gap in the literature, where most transport energy modelling is focussed on private cars.

The disaggregated historical analysis of HGV fleet activity established relationships between freight activity levels in different commodity groups and economic activity in different sectors. Three major commodity groupings that experienced similar behaviour patterns were identified and used as the basis for historic and future energy demand modelling. The econometric analysis on the three commodity groupings identified the relevant macroeconomic indicators that drive changes in activity within the groupings and calculated elasticities of demand associated with the drivers. Most significantly, freight activity in the *Crude & Machinery* (largely representing construction activity) was linked with economic activity in the building sector, and a high elasticity was calculated. Separating construction activity allowed the analysis of the impact of the property bubble on the growth and decline of historic freight energy, and gave a more nuanced model of future energy. When a previous set of economic forecasts (base year 2008) was used for the future modelling, results for 2009 – 2011 fit very well with observed data, compared with a more aggregate modelling approach. This was due to the dramatic fall in construction activity and its slow forecasted recovery.

Decarbonising freight transport presents a significant challenge to Ireland, yet there has been no action to date in Ireland to bring about a reduction in emissions from goods vehicles. Currently tax bands, for example, are based on unladen weights, with the cost of motor tax increasing with the unladen weight of the vehicle. Given

that emissions in gCO_2/tkm decrease with increased weight class, this tax regime acts as a disincentive to efficiency. No database of HGV efficiency exists for Ireland, which has limited the scope for analysis in this paper, and which also limits the degree of insight available for informing policymakers.

This paper modelled the rise in energy demand using an approach focussed on commodities and vehicle weight classes. The commodity-based approach provides interesting insights into the economic drivers of demand growth, particularly into the effect of a building bubble, but the limited availability of efficiency data for the Irish fleet prevented a full analysis of the effects of the vehicle stock on energy demand. The lack of data for light goods vehicles (LGV) limited this study to HGVs, but work is ongoing to make activity and SEC data available for LGV.

A number of caveats are associated with this work: The limits of data restricted time-series analysis in Section 8.3 to a 15 year period, relatively short for calculating accurate elasticities. Moreover, the economy over this period underwent dramatic growth and recession, which could distort elasticity calculations. Finally, fuel price was not taken into account in the modelling of demand.

Though more data-intensive, the results compiled using the bottom-up and top-down hybrid, techno-economic model used in the paper returned more informative short-term projections, which fit very well with observed data. The approach facilitates the capture of the disaggregated effects of technical and economic shifts within energy-consuming sectors. The composition and structure of the model allows more a detailed, and subsequently responsive, representation of the actual HGV fleet and its associated energy demand.

Chapter 9

Conclusion

The growth of passenger mobility has brought many benefits but also poses significant challenges to countries, who will have to take action to mitigate harmful effects over the coming decades. Policymakers and energy analysts are confronting questions of how to best reduce the impacts of transport on the climate and how to ensure energy security, and how to build tools in order to address these issues. This chapter concludes the thesis with an analysis of the insights gained, firstly in terms of Irish energy and transport policy, and secondly of the contribution towards improving the modelling tools which can help inform policymaking in the future.

9.1 Policy

A central focus of this thesis has been to understand the role that car transport has played in contributing to Ireland's exceptional increase in energy demand and related GHG and transboundary emissions over the past two decades, how these trends are likely to play out in the future, and what the likely effects of different policy measures will have on future demands.

Chapter 1 examines efficiency and activity trends in Irish private car energy demand between 2000 and 2008. It shows that there while there was an improvement in the efficiency individual car types over the period, there was no overall improvement in the efficiency of the car fleet. Factors including the ageing of the fleet and a move towards greater activity in more fuel intensive vehicles contributed, but the main reason behind this was a structural change in purchasing to heavier and more powerful cars. Increasing wealth and concern for safety standards were likely to have contributed, but there was a clear lack of incentive in the tax regime to buy more fuel efficient cars until 2008. There was, during the period, strong political will at national and EU level to reduce air pollutants from cars, and Chapter 7 analyses trends in a

vehicle pollutant, NOx. EU regulation applied gradually stricter Euro standards, and effectively reduced NOx emissions and other air pollutants in the 1990s and 2000s, showing that political will can lead to improvements. This will was lacking for CO_2 emissions: there was an attempt to address this at EU through agreements with car manufacturers for average new-car emissions by 2012, but these voluntary and non-mandatory targets have not been met. Consequently, there were negligible improvements in energy efficiency over the period.

This lack of political will to address energy demand and CO_2 emissions from transport is further demonstrated by the way in which a 4% annual rise in private car activity was enabled up to 2008. Transport 21 was a capital investment framework under the National Development Plan, through which Ireland's transport network was to be developed from 2005 to 2015. Funding was allocated to a number of major infrastructural improvements – roadworks, including several new motorways and major bypasses, and public transport investment, particularly light rail developments in Dublin (Smyth et al. 2010). While the majority of roadworks were completed by 2011, most public transport projects were not started by the time the programme was suspended in 2012 because of the financial crisis and budget cuts . This improvement in the road network facilitated the huge increase in private transport and shift away from public transport. Furthermore, planning policies over the period enabled dispersed settlement patterns, which has increased car dependence in Ireland: Census data shows that the proportion of children driven to school has more than doubled between 1986 and 2006, while the proportion of children walking and cycling to school has halved (Daly et al. 2012). While this is likely in part influenced by the increasing number of women in the workplace, the lack of political will to promote and incentivise sustainable transport behaviour accelerated trends in unsustainable travel behaviour.

Looking at recent policy developments and their likely future impact, Chapter 2 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 in 2008 is also included: In some senses, this is a good news story for car energy demand in Ireland and a positive review of recent policy movements. What had grown at a fast rate of 4.5% between 2000 and 2008, energy demand 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 patterns between 2008 and 2010 is also a significant factor. This, while taking place in a recession, is largely attributable to a change in taxation incentivising lower emitting cars.

The 2008 car tax change is examined in Chapter 7 in terms of the unintended consequences for the emissions of an air pollutant, NOx. With the recent focus of policy action on climate change, it is important to investigate the possible negative side effects of energy policies on air pollutants. The tax change successfully caused a step change in purchasing patterns towards more fuel efficient cars, but our model suggests that the resulting dieselisation of the car fleet will lead to NOx emissions from passenger cars being 28% higher in 2020 when compared with a pre-tax scenario. While there is still projected to be a net decrease in NOx emission up to 2020 as a result of Euro standards and a turnover of the car fleet, Ireland is obliged to meet air pollutant emissions ceilings. This chapter points to important interdependencies in emissions targets: While a reduction in air pollution is often a consequence of energy efficiency and climate mitigation policies, fuel switching can lead to negative effects. This could be mitigated by pricing diesel fuel tax and car taxes at a higher rate than petrol equivalents, to internalise the negative effect of pollution.

Looking ahead, a strict EU target on non-ETS emissions for Ireland will have to guide how private car energy plays out in the future. In the 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. Chapter 3 simulates the potential impact of several such policies on CO_2 emissions, car fleet efficiency and renewable energy demand. In terms of efficiency measures, meeting the EU target obliging car manufacturers not to exceed the average new-car emissions of 95 gCO_2/km by 2020 in Ireland can contribute significant emissions savings. This target is currently assumed to be met in the baseline national energy and emissions forecasts, but the target is an obligation on manufacturers' averages across the EU, and as such will not be met in Ireland without legislation. Furthermore, while efficiency improvements have been made in new-car purchasing between 2008 and 2012, this effect is unlikely to continue, as new car purchases are almost entirely in the the two lowest emitting CO_2 bands and there is no further incentive to improve fuel efficiency. Further and ongoing refinements to the car taxation bands will be required to meet this emission target. by 2020.

Chapter 3 also analyses the potential impact of alternative technologies and fuels on meeting 2020 targets. There is an ambitious target for fleet electrification for 2020, which can achieve significant GHG savings by shifting emissions to the emissions trading scheme. The analysis also finds that the impact of the target varies significantly depending on the electricity generation portfolio, the car types displaced by EVs and the timeline of achieving the targets: Emissions savings in a coal portfolio scenario are nil, and a scenario where EVs displace petrol cars gives almost half the savings of EVs displacing diesel cars. Caution should be exercised in making technology goals considering that any such target would require large capital

investment to break out of the technology lock-in the car stock is subject to with petrol and diesel ICE vehicles, and that there is as yet no harmonised EU approach to alternative vehicle infrastructure. We also examine the impact of the diffusion of compressed natural gas vehicles into the fleet. There are efficiency and pollution benefits from CNG, but it would be important to combine combine any measure to encourage CNGVs with a plan for injecting biomethane to the natural gas grid in order to achieve the full emissions reductions as indicated.

While the focus of the car stock model is technology, we also look at the role of activity and behaviour in future scenarios. The effect of activity growth between 2000 and 2008 contributed more CO_2 than all efficiency measures modelled above offset. Emissions only stabilise in future scenarios with demand management – and with more activity there are diminishing returns from efficiency policies. However, the patterns of dispersed housing development and road building during prosperous years have created a lock-in to private car demand, and it will take significant political will and long term vision to change this trajectory. Insights from the modal shift modelling in Chapter 6 show that projects which aim to relieve congestion can induce greater travel demand and increasing congestion in other parts of the road network.

Chapter 8 goes beyond passenger transport and analyses the past and future simulated energy trends of HGV freight transport. Decarbonising freight transport presents a significant challenge to Ireland, yet there has been no action to date in Ireland to bring about a reduction in emissions from goods vehicles. Currently tax bands, for example, are based on unladen weights, with the cost of motor tax increasing with the unladen weight of the vehicle. Given that emissions in gCO_2/tkm decrease with increased weight class, this tax regime acts as a disincentive to efficiency. No database of HGV efficiency exists for Ireland, which has limited the scope for analysis, and which also limits the degree of insight available for informing policymakers.

The limitation of statistics in Ireland also extends to passenger transport: Chapter 6 uses the first pilot National Travel Survey to calculate travel parameters, such as modal share, load factors and travel speeds which were previously unknown in Ireland. The UK has 40 years of travel surveys to gain insights on travel behaviour, which would be invaluable to transport research in Ireland. This research was also limited by the poor dissemination of public transport statistics by publicly owned companies.

9.2 Modelling

A key aim of this research was to develop the capacity for modelling and quantitative policymaking for transport energy in Ireland. Against a backdrop of technological changes and measures, including the fleet electrification and renewable energy targets, a model with a high level of technical detail and desegregation was developed. The contributions of the factors influencing transport energy demand need to be understood before any level of fuel reduction can be achieved, and efficiency and structural changes are key drivers. We have found that the disaggregation of activity by technology type and age gives a more nuanced and accurate analysis of historical energy demand, and that weighting fleet efficiency by activity gives a higher value for energy intensity then averaging efficiency across the feet.

While it is useful to improve the accuracy of historical energy demand in order to detect and analyse patterns, the main purpose of simulated scenarios is not to develop more accurate energy "forecasts". Instead, the focus of Chapters 2 and 3 is to gain insight into possible alternative futures based on policy directions, and scenario analysis using a stock model was used as a tool for this. The insights gained in the previous section would not be apparent without the bottom-up approach used.

In order to further improve the modelling capacity in Ireland, there was a strong focus on integrating the private car model developed with other energy demand models for Ireland, so that assumptions are standardised and results can be compared. Chapter 4 describes how the car stock model was assimilated into LEAP, an energy demand and supply model for Ireland, and how this enabled results from scenarios across the sectors to be compiled into policy packages. Chapter 5 compares the car stock model and private car energy modelling withinTIMES, an energy system optimisation model, and describes how they can be complementary. As well as contributing outputs to the LEAP, TIMES and COPERT models, this research has used outputs from other Irish models developed, the PLEXOS electricity dispatch model and the HERMES macroeconomic model. Furthermore, the car stock modelling methodology was adapted to analyse HGV freight demand in a similar way. This demonstrates how the model developed here is well embedded in the Irish energy modelling landscape and has been used outside of this research project alone.

A final significant modelling contribution from this research is described in Chapter 6, which makes a first step towards incorporating competition between modes in a linear optimisation energy model. The poor representation of behaviour in techno-economic models has frequently and correctly been identified as a flaw: there is generally a tradeoff in energy models between technology detail and behaviour or economic representation, and this new method addresses this gap. In a novel way, it

uses a methodology based on the empirically observed, stable and global daily travel time budget to realistically represent the mode choice behaviour, allowing the cost to decision-makers of inducing a shift towards more sustainable modes to be represented alongside technological options.

As discussed in the thesis Introduction, projections for the future are inherently uncertain. There are a number of caveats associated with techno-economic modelling, which we have highlighted in every chapter. This research relies largely on data from national statistics and economic projections. We also depend on the accuracy of surveys, data and reporting of other institutions for parameters and data. Not producing our own data means that no measurement accuracy or confidence intervals can be produced, which adds to the uncertainty of projections for use as forecasts of the future. There are no sound "expected values" of many future parameters and these are sometimes based instead on hypothesis or published values. We have sought to make the source of each parameter transparent and to use sensitivity analysis to examine the dependence of model outputs on different parameters.

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