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Enhanced Modelling of Transport Decarbonisation and Policy Pathways for Ireland

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ii. Declaration

This is to certify that the work I am submitting is my own and has not been submitted for another degree, either at University College Cork or elsewhere. All external references and sources are acknowledged and identified within the contents. I have read and understood the regulations of University College Cork concerning plagiarism and intellectual property.

Vera O'Riordan

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iv. Executive Summary

The release of increasing human-induced greenhouse gas emissions and the corresponding global temperature rise has prompted a growing political consensus on a decarbonised future to prevent any sustained economic or environmental harm. Many countries are using energy system modelling tools to develop strategies and policy measures to deliver timely and effective reductions of harmful greenhouse gas emissions across all energy-related sectors. Ireland, with ambitious legally binding carbon budgets, and decarbonisation targets for transport, is a country in the process of assessing and addressing key transport decarbonisation challenges faced by high-emitting countries. This thesis - with its scientific contributions on transport emissions, methodological advancements for transport and multi-sector energy systems simulation modelling, and policy recommendations on how effective measures have been in the past or could be in the future - serves as a small, but novel, piece of this process.

The thesis updates the Irish Car Stock Model to investigate the importance of taxation policy using a novel bottom-up stock simulation approach. The simulation model evaluates the 2008 car tax policy in Ireland and finds that while the policy was effective at reducing CO_2 emissions, it had a high cost of carbon abatement, between €1,500 – 2,200 per tCO_2.

The thesis develops the Irish Passenger Transport Emissions and Mobility (IPTEM) model, which for the first time, calculates the overall passenger transport demand in Ireland by trip purpose, trip distance, and mode type. The methodological advancement is in the combination of passenger transport demand from all modes of transport and information from the National Travel Survey, national transport providers, and the Irish Car Stock Model. The study finds that 82% of passenger transport demand is met by cars in Ireland, and the main reason for travel is for work (30%), shopping (19%), and companion journeys (16%). The study also finds that 40% of emissions come from journeys less than 8 kilometres.

In Chapter 4, this thesis develops a new model, the LEAP Ireland ASI (Avoid-Shift-Improve) model which projects emissions and demand for passenger and freight transport up to 2030. It is novel in its application of the Avoid-Shift-Improve framework for scenarios focused on reducing the need to travel in the first instance (“Avoid”), then on modal shifting towards increased public transport use and active travel (“Shift”), and then on scenarios focused on improving the fuels used to ones with a lower carbon intensity (“Improve). These scenarios are modelling in combination with one another and the interaction between the policies is also determined.

In Chapter 5, the thesis develops a new methodology for simulation modelling to project carbon dioxide emissions, how different scenarios could reduce carbon dioxide emissions, and how these fit in with sectoral emissions ceilings within carbon budgets. The thesis tracks past sectoral emissions and simulates the mitigation potential of a suite of scenarios for transport, residential, electricity, services, and industry sectors. The LEAP Ireland model developed in Chapter 5 can simulate the impact of additional policies, track policy performance, and simulate mitigation potential. The data sources, methodology, and carbon budget analysis are outlined in this novel simulation modelling framework designed to support countries with their carbon budgeting commitments. This thesis also examines the interaction effect between these policy scenarios and discusses their combinations' synergistic and antagonistic effects.

The contribution of this thesis is the improvements made to the modelling methods and more robust evidence base for developing sound decarbonisation transport policy measures by shifting the focus beyond car efficiency and electrification.

v. Abbreviations

AMT – Annual Motor Tax

ASI – Avoid-Shift-Improve

CAP – Climate Action Plan

CB1 – Carbon Budget 1 (2021 – 2025)

CB2 – Carbon Budget 2 (2026 – 2030)

CC – Cubic Capacity (of engine)

CDM – Clean Development Mechanism

CMATS – Cork Metropolitan Area Transport Strategy

CSO – Central Statistics Office

DART – Dublin Area Rapid Transit

DIB – Data in Brief

DOT – Department of Transport

EU – European Union

EPA – Environmental Protection Agency

ESR – Effort Sharing Regulation

ETS - Emissions Trading Scheme

EV – Electric Vehicle

GDATS – Greater Dublin Area Transport Strategy

GMATS – Galway Metropolitan Area Transport Strategy

GHG – Greenhouse Gas

HDV/HGV – Heavy Duty Vehicle / Heavy Goods Vehicle

IAM – Integrated Assessment Model

IEA – International Energy Agency

IPCC – Intergovernmental Panel on Climate Change

IPTEM – Irish Passenger Transport Emissions and Mobility Model

LDV/LGV – Light Duty Vehicle / Light Goods Vehicle

LEAP – Low Emissions Analysis Platform

LMATS – Limerick Metropolitan Area Transport Strategy

LTN – Low Traffic Neighbourhood

LULUCF – Land use, Land use change, and Forestry

MoMo – International Energy Agency's Transport "Mo"bility "Mo"del

NDCs – Nationally Determined Contributions

NCT – National Car Test

NEDC – New European Driving Cycle

NETs – Negative Emissions Technologies

NST – Standard freight goods classification for transport statistics

NTA – National Transport Authority

NTS – National Travel Survey

OECD – Organisation for Economic Co-operation and Development

OSF – Open Science Framework

SEAI – Sustainable Energy Authority of Ireland

SC – Sectoral Ceiling

TII – Transport Infrastructure Ireland

UCC – University College Cork

UKTCM – United Kingdom Transport Carbon Model

UNFCCC – United Nations Framework Convention on Climate Change

WLTP – World Harmonized Light-Duty Vehicle Testing Procedure

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Chapter 1. Introduction

1.1. Background

Atmospheric concentrations of anthropogenic greenhouse gases (GHG) have reached levels unseen for at least the previous 800,000 years. This rise in GHG emissions has been the dominant cause of the observed warming since the middle of the twentieth century, and action needs to be committed *now* to secure a sustainable future (IPCC (Intergovernmental Panel on Climate Change), 2023). In response to this, the United Nations Framework Convention on Climate Change (UNFCCC), whose aim is to tackle the dangerous human interference with the climate system, brings together member states from around the world to reach consensus on how best to address the rise in GHG emissions. In 2015, at a Conference of Parties hosted by the UNFCCC, global leaders signed up to the Paris Climate Agreement to limit global average temperature rises to below 2°C, while pursing efforts to limit the increase even further to 1.5°C. The Paris Agreement united 193 countries in agreeing that global warming needed to be limited to 1.5°C, as scientific evidence showed that increases above 1.5°C significantly increased the risk of extreme climate change. This extreme climate change increases the risk of more frequent and severe heat waves, heavier rain, intense flooding, and sea-level rises. Globally, cumulative GHG emissions, stand at 1,800 $GtCO_2eq$. in 2022. There is a remaining global GHG budget of less than 380 $GtCO_2eq$. to stay within this 1.5°C average global temperature rise limit (Friedlingstein et al., 2022).

Global warming is primarily caused by emissions of carbon dioxide (CO_2) and methane (CH_4). Emissions of CO_2 come from the combustion of fossil fuels, which arise from electricity generation, steel production and other industrial processes, heating and cooling buildings for services, and the modes of transport that people and goods require to get from A to B. Due to the past 150 years of growing GHG emissions because of anthropogenic industry and agriculture, the need to transform systems humans use to service their demands systems has emerged. The transition will involve a suite of measures and systematic transformation in our technology and culture, affecting how we heat our homes, where we get our goods and services from, how these goods and services are delivered, how we produce electricity, what we eat, how we farm, and – central to this thesis – how people and goods travel. Understanding how to decarbonise the energy system is a wicked problem, alongside the many other sustainability issues we face, and continual, flexible, and transparent research focusing on addressing this problem is required to support decision-making for climate action in society. The decarbonisation of transport is the primary focus of this thesis (Chapter 2 – 4), multi-sectoral analysis, and modelling of GHG emissions from the commercial, services, industry, and residential sectors and analyses of policies for their reduction is also addressed in this thesis (Chapter 5).

1.2. Transport CO_2 Emissions – A Problem that has Grown

Globally, since 1990, road transport emissions (which include passenger and freight transport) have continued to grow. For example in Ireland, transport emissions grew at an annual average rate of 1.7% from 1990 to 2021, faster than any other end-use sector (Environmental Protection Agency, 2022). A comparison of transport emissions growth in Ireland and worldwide from 1990 to 2021 is shown in Figure 1. Annual GHG emissions have grown globally except in 2021 due to the travel restrictions arising from the COVID-19 pandemic. Transport is a key sector to be addressed in energy systems modelling and decarbonisation planning as ambitious targets for net zero emissions are set globally for 2050.

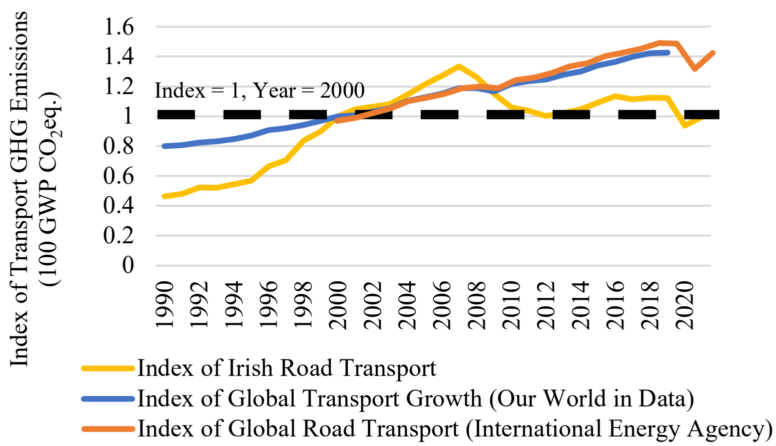

Figure 1: Index of Transport GHG Emissions (1990 - 2021) Source: EPA (Ireland), Our World in Data (Global: 1990 - 2019), International Energy Agency (Global: 2000 - 2021)

Overall the transport sector is responsible for 24% of GHG emissions globally (International Energy Agency (IEA), 2023a), and the transport sector needs to be decarbonised alongside all other emitting sectors to keep in line with Paris Climate Agreement goals. Therefore, the need to understand the transport sector has emerged. Energy and Transport systems models are tools used by scientists and policy makers to provide an evidence base for action on how to decarbonise the transport sector. What these models are, and what techniques, frameworks, conventions, and gaps are currently in the energy and transport systems modelling eco-system is discussed in the next section.

1.3. Energy and Transport System Modelling

Energy system models are used to analyse different aspects of the energy system – this involves the supply of energy by the fuel types, how these energy sources are processed, any losses associated with them along the way, and the link to their end use – whether it be for transport, residential heating, electricity production, industrial manufacturing or providing services. The models' emphasis can focus on the supply side, where the energy comes from, or the end-use demands, which look at some of the reasons and drivers behind our energy use and energy needs. Some techniques and considerations when designing transport multi-sector energy system models are outlined in the next section.

1.4. Modelling Techniques, Frameworks and Considerations

In modelling design techniques, this thesis identifies four critical framings for energy system modelling development and focus – 1) Modelling techniques, 2) Bottom-up versus top-down modelling, 3) Temporal arrangement, and 4) Geography. This list is not exhaustive but was the most relevant to this thesis.

1.4.1. Modelling Techniques – Simulation, Optimisation, Agent-Based, Discrete Choice Modelling

Energy systems models are broadly defined as a) simulation or b) optimisation models (Herbst et al., 2012).

Simulation models develop scenarios based on adjustments to a reference "business as usual" projection into the future, spanning between 10 – 80 years into the future. Simulation model inputs can be tweaked and handle variability in a way that optimisation models may not. While this technique may give a more realistic representation of the system being modelled, it does not give an optimal solution to a specific measure. It can leave a conversation open for the exploration of policy measures.

When simulation modelling, the modeller specifies the uptake, retirement, and usage of technologies and can input "one-off" or adjustment parameters. Parameters can be more flexible to adjustments than optimisation modelling tools . For example, in Anable et al. (2012), the potential impact of lifestyle changes on emissions reductions within the passenger transport sector is explored using simulation modelling techniques. Various methods can be used to set the rules by which simulation models are developed – it can range from regression analysis looking at past developments, econometric projections into the future or more computationally advanced methods such as agent-based models or discrete choice models.

Agent-based models (ABMs) are simulation models that analyse interactions between individuals, objects, places, and time. ABMs can capture transportation systems' complexity and dynamic nature by modelling the agents' behaviour and interactions. ABMs facilitate learning, converging, and networking amongst actors in a sustainability transformation and can capture a "contagion" of sustainable transport technologies, fad behaviour and trendiness in a way that simulation models may not envisage (Lopolito et al., 2013).

Discrete Choice Models (DCMs) are also applied to individual actors define consumer choices based on safety perceptions, prices, grants, and availability. DCMs use empirical data from consumers' historical or hypothetical technology choices to determine the relative importance of technology attributes to adopting that technology. It is popular in assessing the uptake of singular home-based or transport technologies and in determining, on a micro-scale, what the market shares of new fuel types and technologies – including transport technologies - would be in the household or general market context (Haghani et al., 2021; Jridi et al., 2015; Ma et al., 2018; Motz, 2021).

Energy System Optimisation Models (ESOMs) determine the least-cost or second-best least-cost (Price & Keppo, 2017) design for an energy system. Optimisation models provide sharper decision support by providing a single or a handful of "best" fuel mixes and choices. Optimisation models may generate least-cost pathways given a specific constraint on the system under analysis, e.g., identifying the least-cost method of limiting CO_2 emissions to comply with a GHG constraint based on limiting the temperature rise to 1.5°C.

Hybrid models combine two or more different modelling techniques or methods to create a new model that incorporates the strengths of each technique. The idea behind hybrid models is to take advantage of the complementary nature of different modelling approaches so that the resulting model can provide more accurate predictions or insights than any single approach could achieve (Pfenninger et al., 2014). Hybrid modelling has also been applied with discrete choice models (DCMs). DCMs can be used to inform the behavioural parameters of a hybrid model to produce an integrated model that is behaviourally realistic and technologically explicit (Rivers et al., 2003).

One advantage of hybrid models is their flexibility, as they can be tailored to specific problems or data sets. They also have the potential to provide more accurate predictions or insights than single-method models, as they can capture a broader range of phenomena and relationships.

Models can also be linked in a "soft link" or coupled simultaneously in a "hard link". For example, Mulholland et al. (2017a) soft-linked a past version of the TIMES Ireland model, an optimisation model of the Irish energy system, was with the LEAP (Low Emissions Analysis Platform) Ireland simulation model and used in an iterative way to validate and troubleshoot some of the results produced by each model.
Sector-specific models, such as the PLEXOS Ireland model, developed time-sliced and merit-based generation data for the electricity sector in Ireland, which in turn serves as a soft-linked input for the Irish simulation (LEAP Ireland) and optimisation (TIMES Ireland) models (Deane et al., 2012).

1.4.2. Bottom-up (Techno-economic) and Top-down (Macro-economic) Modelling

Top-down macroeconomic methods are appropriate for modelling global and multi-sector systems over extended periods. Top-down, macro-economic modelling enables a 'birds' eye' view of modelling for higher-level insights without time-consuming data collection. It requires broader assumptions and applying macroeconomic relationships to energy systems, and it facilitates concentrating on key drivers of energy demand and emissions reductions in energy systems. Bottom-up, techno-economic models provide a detailed representation of energy systems by simulating the behaviour of individual components such as buildings, appliances, and vehicles. They allow for granular analysis and can capture unique sector-specific features. They can provide a more realistic view of energy systems than top-down (macroeconomic) models, making them valuable for designing effective policy interventions. However, they must be equipped to capture the macroeconomic relationships highlighted by top-down models.

As mentioned in hybrid modelling earlier - top-down modelling can be combined, discussed alongside, and blended with bottom-up (techno-economic) policy modelling to enhance the robustness of the model (Böhringer & Rutherford, 2008).

1.4.3. Temporal Arrangement : Ex-post and Ex-ante Analyses

Ex-post (past) and ex-ante (future) models refer to the time horizon studied with the energy model. Ex-post analyses look at historical data, international comparisons, and past policies and observe the change over the past and tease out macro or micro relationships of the policy intervention, the technology uptake, the financial changes, or the behavioural changes. Ex-ante models project information into the future, and the methodologies are then applied to highlight the future possibilities based on a set of parameters and model developments into the future. Ex-ante models' time horizon lengths significantly impact the granularity and uncertainty. Longer time horizons open models to more uncertainty as assumptions on future developments are baked into the modelling methodology (Fodstad et al., 2022). Greater exploration of the need for ex-post modelling to facilitate policy learning is covered in greater detail in Section 1.5: Gaps in Modelling Knowledge.

1.4.4. Geography - Regional and Spatial Modelling

Energy systems models can be developed and applied at a town, country, regional or global bases. The geographic scope can enable or limit which type of policies can be modelled – global policies or regional economic policies and the interplay between them can be assessed with global and multi-regional models and interventions that have global and far-reaching consequences – such as modifications to international trade, aviation and maritime transport rules and routes which operate on a global market. Regional models can facilitate proactive participatory methods and local empowerment of concrete emission reduction measures (McGookin et al., 2022) and highlight regional differences in cost-effective energy solutions (Aryanpur et al., 2022).

In summary, the modelling technique best fitted to the research question, the data availability, the temporal arrangement of the modelling research question (whether the modeller is looking at the impact of past policies or inferring what could happen in the future), and the size of the region being studied are key parameters to be considered when designing models. This thesis will now address the gaps in modelling knowledge noted in the energy systems modelling research space and how the novel tools and methods outlined in this thesis contribute towards addressing these knowledge gaps.

1.5. Gaps in Modelling Knowledge

This thesis identifies six critical gaps from the literature in modelling knowledge and these gaps are directly addressed in this thesis: 1) linking ex-post and ex-ante modelling to facilitate policy learning, 2) the variance of geographical scope and detail, 3) reproducibility of model inputs and outputs, 4) a greater understanding of multi-modal passenger transport, 5) ensuring energy systems modelling reflects, keeps up with, and engages with, the rapidly changing climate policy landscape, and 6) for Ireland specifically, modelling the deep decarbonisation of the Irish energy system in light of ambitious carbon budget targets. These gaps in modelling knowledge are explored in more detail below.

1.5.1. Linking ex-post and ex-ante modelling to facilitate policy learning

Ex-post policy evaluation can provide different insights to ex-ante policy evaluation, as scientific modelling knowledge has limitations, and social learning is an essential factor in climate policy design. In this way, working on models with an ex-ante focus is vital to reflect on "lessons learned" that can be applied to future policy ideation and implementation. Ex-post evaluations can be instructive in the short term to evaluate the robustness of projections for years that have since happened (Wilson et al., 2021). Previous ex-post policy evaluations have proven to be essential learning exercises for the energy system (Dennehy & Ó Gallachóir, 2018; Liu et al., 2019; Trotta, 2020; Valentová et al., 2019), and ex-post policy analysis provides a valuable opportunity to evaluate the success of past policies so that future policy making can be improved (Herrick & Sarewitz, 2000; Hertin et al., 2009).

Strachan recommends that energy models use a more dynamic approach considering the changing policy landscape and the potential for policy interactions. Strachan emphasises the importance of energy models in informing policy decisions and the need for continued development and improvement of these models (Strachan, 2011). As part of this movement favouring dynamic energy systems modelling to support policy, additional ex-post studies are required to provide up-to-date information on low-carbon policies and their performance as they are implemented.

Increased engagement with policymakers can be achieved via ex-post policy modelling as it provides helpful insights into the effectiveness of their policies and recommendations for future policy, thus providing a helpful means of research-informed peer-reviewed and objective feedback based on the modelling tools and assumptions openly explained and made. Co-production is considered a best practice to ensure that the questions posed by policymakers are addressed, while also preserving the impartiality of research institutes that operate independently from the realm of policy decision-making (Collins et al., 2019). Policy learnings are sensitive to regional cases, and, for verification so that the research used to inform decision-making is robust, these findings must be reproducible and openly reported. Reproducibility is a key issue discussed next.

1.5.2. Variance in geographical scope and detail

Ellenbeck & Lilliestam (2019) notes that assumptions for parameters in complex models are numerous, and not all assumptions can be interrogated. Simplifying modelling tools can prevent incorrect discourses on economics and society from being perpetuated based on a modeller's biases. More straightforward modelling techniques enable results that can be interpreted more clearly and assumptions that can be interrogated more openly and be applied across larger regions – which can be helpful to build a knowledge base where modelling capacity is limited. Pfenninger et al. (2014) noted a trade-off between breadth and depth in the complexity of energy systems models. Accessible modelling methodologies, downloadable spreadsheets and explicit visual representations can help to quickly transfer information about modelling insights (Pacala & Socolow, 2018).

Fitting models for specific purposes and based on regional studies can help us understand key transport demand requirements in the future and the types of transport we also use, which is another key modelling gap addressed next in this thesis. Different regions can cast light on new insights, for example, in Aryanpur et al. (2022) reshaping regions for light duty cost analysis found that a multi-regional model determined the co-benefits were greater on an NO_X emissions-based policy on light duty vehicles than when the benefits were calculated for a single region of Ireland. This logic also applies to disaggregating Global or European-wide models to a national level in the case of Ireland. Additional modelling detail can identify regional nuances and provide a more accurate view on the local costs, emissions, or demands – depending on the modelling questions being asked.

1.5.3. Reproducibility of Model Inputs and Outputs and Open Sharing of Model Assumptions

Given the great uncertainty observed in base year data across models and the biases that can emerge in assumption-making, there is a great need to increase data collection, particularly in developing countries where systematic efforts in collecting transportation-relevant data at the national level still need to be improved. Cuenot remarks on the need for more regionalised modelling to capture discrepancies (Cuenot et al., 2012). For transport decarbonisation solutions – Creutzig advocates for regional modelling and data collection to better represent the local realities of decarbonisation, behaviour, and landscape unique to those areas (Creutzig, 2016).

It is critical that models are reproducible by other researchers and that the input and output data can be easily accessible by stakeholders (J. F. DeCarolis et al., 2012). Model data that is open, tractable, and possible to re-generate is essential for advancing, appraising, and improving research quality in energy systems modelling. Reviews in best practice for energy systems modelling recommend that modellers show their workings, and that the methodology must be understandable and repeatable by other modellers (J. DeCarolis et al., 2017; Pfenninger, 2017). The reproducibility and accessibility of modelling tools can facilitate future model comparison work, and external experts see great value in conducting ongoing, coordinated efforts to align input assumptions and historical data (Yeh et al., 2017). Central to creating energy systems models and analysis tools that can be reproduced is the ability to design and share energy system models whose data and methodologies are easily followed and retrieved by other energy system modellers.

Lopion et al. (2018) noted that there is a specific need for fitted and specific models for custom cases and that both perfect-foresight optimisation style models can provide a longer-range view of the most cost-effective options in the here and now, while short-term myopic style models offer a closer model of what real-life outcomes are likely to be in the following number of years and immediate problems that are likely to arise.

1.5.4. Detailed Understanding of Passenger Transport Demand and Multi-modal Passenger Transport Behaviour

Bottom-up technology stock modelling techniques for car passenger transport are evident in literature (Daly & Ó Gallachóir, 2011; de Jong et al., 2004; Fridstrøm et al., 2016; Gnann et al., 2015; Huo & Wang, 2012; International Energy Agency (IEA), 2020; Mulholland et al., 2016). In the Irish context, information on public transport and active travel was disparate and separate from knowledge on the private car stock, despite both contributing to the overall passenger transport demand (O'Riordan, Rogan, Ó Gallachóir, Mac Uidhir, et al., 2022b). Internationally, information on passenger transport is inconsistent across countries. Information on 24 countries' net passenger kilometre energy intensity – which accounts for public transport and active travel use, is available from the IEA (International Energy Agency (IEA), 2019). Car stocktakes and usage rates are recorded in some cases, but not all. Therefore, the methods used with the Irish Car Stock Model (updated as part of this thesis) and the Irish Passenger Transport Emissions and Mobility (IPTEM) model (developed as part of this thesis) are useful to countries seeking to analyse their own regions' passenger transport data.

Creutzig (2016) concludes that the mitigation potential of behavioural and infrastructural mitigation options is higher than what is assumed in many modelling studies. The domination of electrification and efficiency in passenger transport decarbonisation literature overlooks the role of alternative means of passenger transport decarbonisation, such as large-scale modal shifts, active travel uptake, or public transportation infrastructure projects. The maximum mitigation potential of the transport sector can only be realised if modellers expand the parameters and input assumptions available for use and include modelling parameters for modal shift, active travel, and public transport uptake, not just car efficiency and electrification (Gota et al., 2019). In the case of regional studies and the differences between developed and developing countries, more work is needed to reflect on the possibilities and the probable solution space and emissions reduction ranges that can be met.

Since models can incorporate individual decision-making as well as social processes, such models can be helpful in the design and evaluation process of policies and could be used to model the trend effect and the exposure effect of consumer choices for recent technology uptakes among communities and micro-economic decisions (Gilbert et al., 2018; Klein et al., 2019).
Other countries can adopt lessons from transport behaviour and multi-mode transport in Ireland's transport, and this brings about the next key modelling gap

addressed in this thesis, the need for modelling to inform policy and reflect the evolving transport policy landscape.

1.5.5. Modelling for an Evolving Transport and Climate Policy Landscape

The origins of modelling climate change mitigation in transport were reviewed by Schwanen et al. (Schwanen et al., 2011), which pointed to the work of Rouse as how transport models developed with a techno-economic mindset and argued that the enduring way of popular methods and the "winner takes all" effect in popular scientific development could mean that alternative means of evaluating transport in society could be underexplored. Rouse elaborated on this by noting that normal science is not so much a study of an object as it is a particular way of manipulating and dealing with the world (Rouse, 1981). By going through the modelling process, both modellers and policymakers are given space and time to reflect on policy options and choices. Strachan emphasises the importance of energy models in informing policy decisions and the need for continued development and improvement of these models (Strachan, 2011).

The solution space associated with models must reflect the evolving policy options and societal desires. For transport specifically, in recent years, the focus has shifted from improving and electrifying cars to the decarbonisation of passenger transport to a broader range of measures to reduce emissions from passenger transport, including reducing the need for travel in the first place and encouraging a shift to walking, cycling or modes of mass/public transportation (Creutzig et al., 2018; Gerboni et al., 2017; Grubler et al., 2018; Pye & Daly, 2015; Salvucci et al., 2018a).

In response to the need for sustainability in transport, the Avoid-Shift-Improve framework was developed by the German Parliament's Enquète Commission in 1994 (Deutsche Gesellschaft fur Internationale Zusammenarbeit (GIZ) GmbH, 2019). The approach was first used to structure policies for reducing the environmental impact of transport in cities – and it was not limited to GHG emissions. It has been widely adopted in the international energy modelling and analysis community as the key framing for passenger transport decarbonisation planning (International Energy Agency (IEA), 2022). Transportation policies may be categorised similarly, and modelling tools should reflect the latest advances in policy thinking to provide timely analytical insights to support or test qualitative analysis on transport policy best practice.

The evolving need to update deep decarbonisation scenarios not only applies in transport but across the entire energy system. For example, Hallegatte and Mach (2016) commented on the need for IPCC climate assessments to be more relevant and place policy at the centre of its approach. This same ideology can and should be applied to all energy and emissions modelling forms – putting actionable and imaginable policy at the centre of the explored scenarios. For example, Schweizer (2018) noted that assumptions in the scenarios underpinning the Shared-Socioeconomic Pathways (SSPs) were too limiting and that the future of the field lies in searchable databases. In that way, researchers and policymakers can define the pathways, build upon multiple narratives, develop multiple scenarios, and explore uncertainties in our collective future. There is a specific need for low-energy demand scenario development to explore deep decarbonisation options (Gaur et al., 2022) and additional ambition and vision to be explored to provide ambitious and multiple options for the deep decarbonisation journey that must be undertaken.

The continued importance of modelling stems from providing a crucial quantitative underpinning to scenarios and, more importantly, structured stories about the future based on an organised exploration of data and assumptions. The ongoing challenge for modellers is to ensure that energy systems modelling can continue to deliver this critical insight. Models can be used at various stages of the policy and decision-making processes. Therefore, providing relevant models to illuminate decision-makers understanding of the key climate and energy issues and solution possibilities is critical. An overview of how modelling can inform and support the policymaking process is shown in Figure 2.

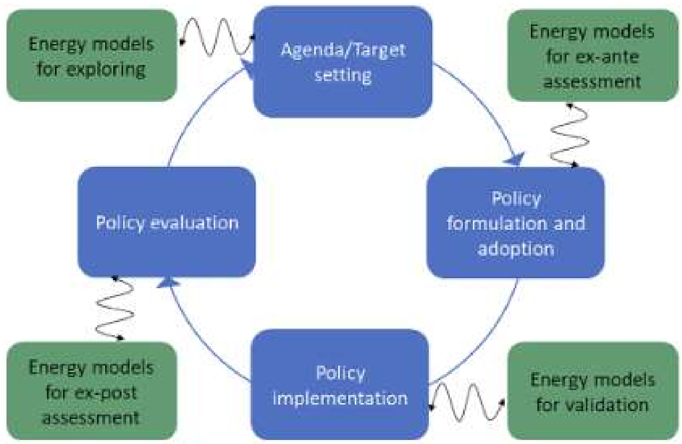

Figure 2: The policy cycle and potential use of models in the distinct stages Source (Süsser et al., 2021)

1.5.6. Modelling of Irish Deep Decarbonisation Policy

Ireland has among the highest per-capita GHG emissions in Europe and has been described as a climate laggard. The Climate Change Performance Index (CCPI) has noted in particular that "government implementation remains weak with necessary actions and measures delayed or ignored in many areas" (Climate Change Performance Index, 2023). This has led to political commitments to undergo deep decarbonisation of all GHG emitting sectors (Government of Ireland, 2020, 2021b, 2022a). Ireland has now set among the most ambitious deep decarbonisation targets in the European Union, and imaginative solutions and modelling techniques are required to explore the possibilities to achieve, and the kinds of behavioural changes and technologies required to meet these targets (Ó Gallachóir, 2021).

To tackle the problem of GHG Emissions nationally in Ireland, the Government passed the Climate Action Bill, which provided for legally binding sectoral emissions ceilings and carbon budgets for the transport, residential, agricultural, electricity, services, and industry sectors. The Irish Government agreed on Carbon Budgets over the period to 2030, setting limits for cumulative GHG ($MtCO_2eq.$)[1] emissions over the Carbon Budget 1 (CB1) period of 2021 – 2025 and Carbon Budget 2 (CB2) period of 2026 – 2030 (inclusive) (Government of Ireland, 2022a). These budgets reinforced the urgent need to track and develop capacity for monitoring current emissions and modelling future emissions under various policy interventions.

Modelling carbon budgets is a key issue in Irish policy. The carbon budget mechanism was only formally adopted by four countries in 2023 - the United Kingdom, Denmark, New Zealand, and Ireland. The mechanism is notable for its legal heft (in Ireland, these carbon budgets are legally binding under the Climate Action Bill) and their novelty. Other countries could adopt this mechanism widely (A. Z. Smith, 2021).

The level of annual emissions cuts required to meet reduction commitments for Carbon Budget 1 (2021 – 2025), Carbon Budget 2 (2026 – 2030), and Carbon Budget 3 (2031 – 2035) are unprecedented. Additional modelling of technology,

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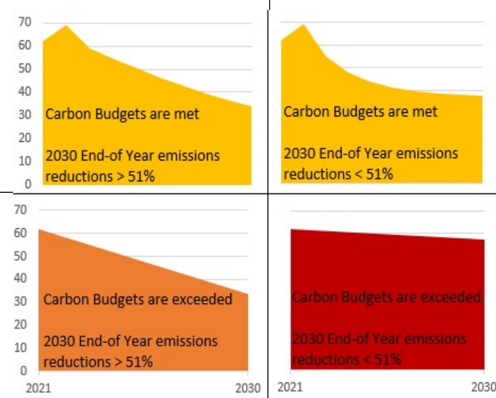
[1] MtCO2eq. This is the abbreviation of Million Tonnes of carbon dioxide equivalent. 1 tonne is equal to 1,000 kilograms. This unit allows a comparison with the potential warming impact of an emission of: one greenhouse gas (like nitrous oxide) to an emission of the same amount of carbon dioxide.

behaviours, and policies is required to explore ways to meet these carbon budgets.

Analytical tools developed and used in the thesis contribute to enhanced evidence for better policy decision-making for transport and the energy system in Ireland.
What is interesting about the carbon budgets is their relationship with other European-wide policies of sectoral emission ceiling targets. It is possible to meet end-of-year emissions targets and miss the overall continual carbon budget (which runs over the years rather than focus on an end-of-year emissions goal at the end of a specified period). It is also possible to miss the end-of-year emissions target and achieve the overall carbon budget, particularly in the case of early and sustained moderate emissions reduction and the case of an ambitious end-of-year target that is hard to achieve. An overview of the possibilities with carbon budgets and end-of-year targets is outlined in Table 1.

Table 1: Carbon Budgets versus End-Of-Year Sectoral Ceilings performance matrix

		Meeting the End of Year Sectoral Ceilings	
		✓	×
Meeting the cumulative Carbon Budgets over the specified time	✓	*Early and sustained action*	*Early action, insufficient continual cumulative reductions*
	×	*Delayed action, end-of year 2030 target met but interim emissions too high to meet cumulative target*	*Business as usual Insufficient action*



Further detail on why Ireland is interesting as a case for other regions to study on transport decarbonisation is discussed in the next section.

1.6. Ireland – A Case Study in Transport Decarbonisation

As mentioned previously, the transport sector specifically, the key focus of this thesis, is responsible for 24% of GHG emissions globally (International Energy Agency (IEA), 2023a). Transport emissions are also a problem in Ireland, transport emissions are responsible for 16% of GHG emissions, excluding Ireland's share of international aviation and maritime transport emissions (Figure 3).

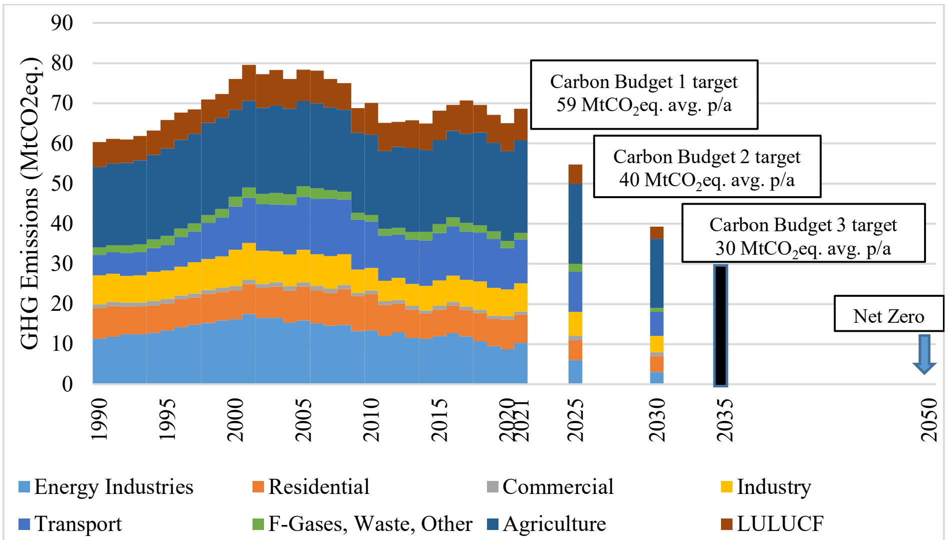


Figure 3: GHG Emissions by sector, past calculated emissions (1990 - 2021, source: Environmental Protection Agency, 2022a) legal commitments (2025 - 2050, source: Government of Ireland, 2022b)

In Ireland, transport emissions had significant (+125%) growth in during the 1990s and these emissions have been in fluctuation since 2000, overall are levelling off to 2000-era levels by 2022 (Environmental Protection Agency, 2022). Transport accounted for 13 MtCO$_2$eq. of GHG emissions (excluding aviation and shipping) in 2022. The transport sector has among the more ambitious carbon budgets, with limitations of 54 MtCO$_2$eq. for CB1 (2021 – 2025) and 37 MtCO$_2$eq. for CB2 (2026 – 2030). Over 60 specified measures devoted to the transport sector were set out in Ireland's Climate Action Plan 2023 to meet the carbon budgets.

Ireland is one of four countries (UK, New Zealand, Denmark, Ireland) that has adopted the carbon budgeting method, and understanding how to simulate and plan out carbon budgets for the transport sector (Chapter 4) and all GHG emitting sectors (Chapter 5) are key modelling questions addressed in this thesis. As cumulative emissions are the chief cause of global warming, carbon budgets align with best practice in climate science and the need to effectively communicate the importance of limiting cumulative GHG emissions rather than single-year GHG emissions (Glynn, 2021). Carbon budget governance is emerging as a method to align national climate policy with global climate action targets. The modelling methods developed for the case of Ireland to plan for carbon budgets for the transport sector (Chapter 4) and for all sectors (Chapter 5) are instructive to other countries who will choose the adapt carbon budgets in the future.

1.7. Overview of this Thesis

Aims of this thesis

The aims of this thesis are as follows:

- Apply techno-economic modelling approaches to identify the cost per tonne of CO_2 emissions abated for Irish car tax policies (Chapter 2)
- Develop models to determine passenger transport demand in Ireland, and better understand the emissions from passenger transport and where they come from (Chapter 3)

- Integrate current developments in transport policy frameworks into energy system simulation models (Chapter 4)
- Develop multi-sector energy simulation modelling tools to model emissions by end use and fuel type on recent policy (Chapter 5)
- Link energy systems models to carbon budgets to determine the cumulative emissions for policy-based target setting (Chapter 5)

Techno-economic modelling was applied in the case study on the impact of the 2008 Irish Car Tax (Chapter 2). The bottom-up car stock model was beneficial to isolate the impacts of the switch over to an engine cc based on an emission-based change in taxation. The changes in taxation, the influence of the on-road factors and the subsequent divergence in industry specified "on-road" factors as defined by the older New European Driving Cycle (NEDC) test and how that impacted government taxation revenue was accessed. This techno-economic bottom-up approach was constructive as the individual characteristics of the new car sales and the overall car fleet estimated the tax revenue. The carbon abatement cost could then be quantified in euros per $MtCO_2$ avoided. This metric is beneficial to compare costs with other decarbonisation policy options available to governments.

Combining the previously developed Irish Car Stock Model, data from the Irish National Travel Survey, and information from public transport annual reports, the bottom-up spreadsheet modelling format was particularly useful in combining the energy consumption values of different mode types in the Irish passenger transport system. These bottom-up demand and technology energy and CO_2 emissions models inform the current state of the Irish transport system and model the performance of carbon intensity, the passenger kilometre demand by trip purpose, trip mode and trip distance with a high degree of disaggregation. The modelling efforts resulted in the Irish Passenger Transport Emissions and Mobility (IPTEM) model (O'Riordan, Rogan, Ó Gallachóir, Mac Uidhir, et al., 2022b) that develops a picture of passenger transport emissions and demand by trip purpose, mode type and trip distance (Chapter 3).

Passenger transport information such as this helps inform demand reduction and modal shift scenarios in both the simulation and optimisation models developed within the Energy Policy and Modelling Group (Balyk et al., 2021; Mac Uidhir et al., 2020c). The thesis also updates the Irish Car Stock Model, and private vehicle stock, emissions, and activity information are now openly available (O'Riordan, Mulholland, et al., 2021).

Considering the 2023 Climate Action Plan, deep decarbonisation for passenger transport was explored using the "Avoid-Shift-Improve" Framework (Chapter 4).

The passenger transport sector was modelled alongside Ireland's residential, services, industry, commercial, and freight transport sectors in the multi-sector energy system model for Ireland, the LEAP Ireland model (Chapter 5). This provided carbon budget insights for the entire energy system in Ireland and how to cumulatively model future carbon budgets using scenario analysis with the Excel-VBA-based simulation modelling tool, the LEAP Ireland model.

Thus far, with the CAPACITY project, the work outlined in this thesis provides information to policymakers on walking and cycling targets, electric vehicles, working from home and transport in general (MaREI (Marine and Renewable Energy Institute) SFI Centre for Energy Climate and Marine, 2023).
By engaging with and referring to policy documents, policymakers and academic literature throughout the energy systems modelling development process, we can and have produced instructive low-carbon pathways and projections for how we could achieve our ambitious emissions reduction targets.

The aim of this research is, therefore, threefold. Firstly, to use and build upon current methodologies to assess the impact of past car-centric emissions-based policy interventions. Secondly, to develop a clear picture of overall passenger transport demand, emissions intensities by mode type, and the impacts of pandemic-related travel restrictions on these demands and mode shares. Thirdly, it is to develop robust evidence-based policies capable of informing policymakers on policy measures to reduce GHG emissions from the passenger transport sector and inform policymakers of decarbonisation pathways across the entire multi-sectoral energy system.

Research Questions addressed in this thesis

Following these key aims, this thesis sets out to answer the following research questions (RQs):

RQ 1. What was the impact of a past emission-based car tax transport policy at reducing GHG emissions?

RQ 2. What are the range of transport modes, purposes, and distances travelled for passenger transport demand in Ireland? What are the emissions arising from this?

RQ 3. How can modal shift and demand reduction interventions contribute to transport climate mitigation targets?

RQ 4. How can simulation models help us plan for cross-sectoral carbon budgeting?

An overview of the research questions and how they relate to each of the thesis chapters is shown in Figure 4.

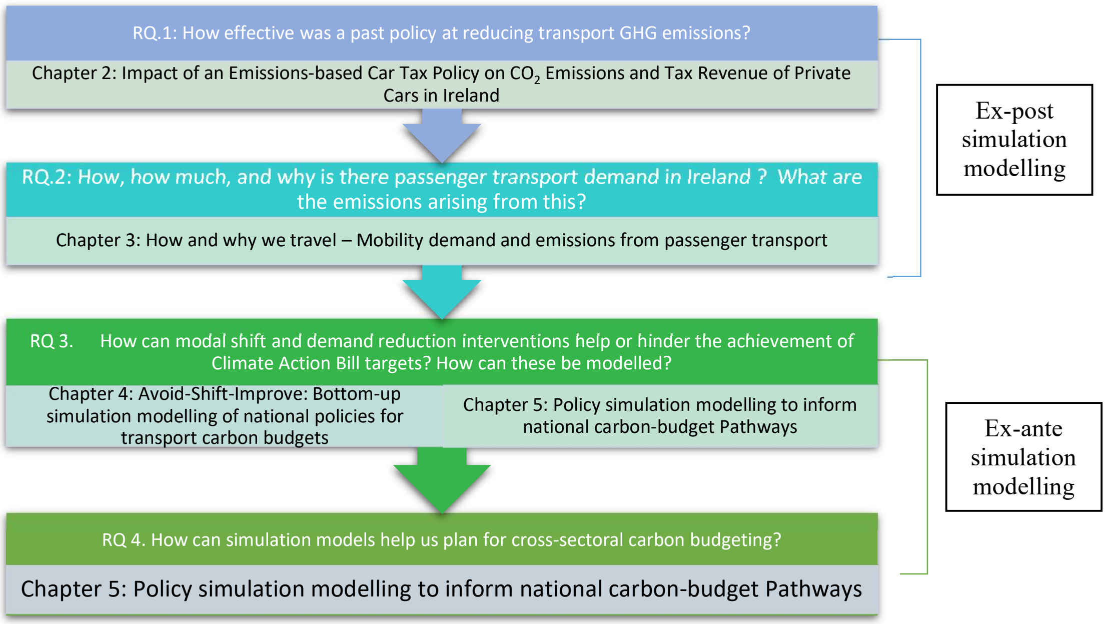


Figure 4: Overview of thesis research questions and chapter layout

The thesis chapters are outlined as follows:

- **Introduction**
- **Part I – Ex-Post Passenger Transport Modelling**
  - **Chapter 2:** Impact of an Emissions-based Car Tax Policy on CO_2 Emissions and Tax Revenue of Private Cars in Ireland, based on journal publication: **O'Riordan, V.,** Rogan, F., Gallachóir, B.Ó., Daly, H., 2022. "Impact of an emissions-based car tax policy on CO_2 emissions and tax revenue of private cars in Ireland", International. Journal of Sustainable Transportation https://doi.org/10.1080/15568318.2022.2132562
  - **Chapter 3:** How and why we travel – Mobility Demand and Emissions from passenger transport based on journal publication: **O'Riordan, V.,** Rogan, F., Ó Gallachóir, B., Mac Uidhir, T., Daly, H., 2022a. "How and why we travel – Mobility demand and emissions from passenger transport", Transport Research Part D. Transport and Environment 104. https://doi.org/10.1016/j.trd.2022.103195
- **Part II – Ex-Ante Simulation Modelling for Transport Decarbonisation Policy**

- **Chapter 4:** Avoid-Shift-Improve: Bottom-up simulation modelling of national policies for transport carbon budgets based on journal publication in submission **O'Riordan, V.,** Mac Uidhir, T., Daly, H., Rogan, F., "Avoid-Shift-Improve: Bottom-up simulation modelling of national policies for transport carbon budgets" (In preparation
- **Chapter 5:** Policy simulation modelling to inform national carbon-budget Pathways based on journal publication: O'Riordan, V., Mac Uidhir, T. and Rogan, F. (2023) 'Policy simulation modelling to inform National Carbon Budget Pathways', Energy Strategy Reviews, 50, p. 101237. doi:10.1016/j.esr.2023.101237.

- **Conclusions**

The research detailed in this thesis contributed to a wide range of academic, advisory, and educational outputs. An overview of some of the outputs arising from the research in this thesis is listed below.

1.7.1. Journal Papers and Working Papers

O'Riordan, V., Rogan, F., Gallachóir, B.Ó., Daly, H., 2022. "Impact of an emissions-based car tax policy on CO_2 emissions and tax revenue of private cars in Ireland", International. Journal of Sustainable Transportation https://doi.org/10.1080/15568318.2022.2132562

Contributions - **Vera O'Riordan:** Conceptualization, Methodology, Software, Data curation, Writing- Original draft preparation; Visualisation; **Fionn Rogan:** Conceptualization, Supervision, Methodology, Funding Acquisition, Writing – Reviewing and Editing**; Brian Ó Gallachóir:** Conceptualization , Supervision, Methodology, Funding Acquisition, Writing –

Reviewing and Editing; **Hannah Daly:** Conceptualization , Supervision, Methodology, Funding Acquisition, Writing – Reviewing and Editing

O'Riordan, V., Rogan, F., Ó Gallachóir, B., Mac Uidhir, T., Daly, H., 2022a. "How and why we travel – Mobility demand and emissions from passenger transport", Transport Research Part D. Transport and Environment 104. https://doi.org/10.1016/j.trd.2022.103195

Contributions - **Vera O'Riordan:** Conceptualization, Methodology, Software, Data curation, Writing- Original draft preparation; Visualisation; **Fionn Rogan:** Supervision, Funding Acquisition, Writing – Reviewing and Editing; **Brian Ó Gallachóir:** Supervision, Funding Acquisition; **Tomás MacUidhir:** Writing – Reviewing and Editing, Software; **Hannah Daly:** Conceptualization , Supervision, Methodology, Funding Acquisition, Writing – Reviewing and Editing

O'Riordan, V., Rogan, F., Uidhir, T. Mac, Ó Gallachóir, B., Daly, H., 2022b. "Passenger transport demand, fuel consumption, and emissions data for the Irish Passenger Transport Emissions and Mobility (IPTEM) model", Data in Brief 42, 108154. https://doi.org/10.1016/j.dib.2022.108154

Contributions - **Vera O'Riordan:** Conceptualization, Methodology, Software, Data curation, Writing- Original draft preparation; Visualisation; **Fionn Rogan:** Supervision, Methodology, Funding Acquisition, Writing – Reviewing and Editing; **Brian Ó Gallachóir:** Supervision, Funding Acquisition; **Tomás MacUidhir:** Writing – Reviewing and Editing, Software; **Hannah Daly:** Conceptualization , Supervision, Methodology, Funding Acquisition, Writing – Reviewing and Editing

O'Riordan, V., Mac Uidhir, T. and Rogan, F. (2023) 'Policy simulation modelling to inform National Carbon Budget Pathways', *Energy Strategy Reviews*, 50, p. 101237. doi:10.1016/j.esr.2023.101237.

Contributions - **Vera O'Riordan:** Conceptualization, Methodology, Software, Data curation, Writing- Original draft preparation; Visualisation, Writing – Reviewing and Editing; **Tomás MacUidhir:** Conceptualization, Methodology, Software, Data curation, Writing- Original draft preparation, Writing – Reviewing and Editing, Software; **Fionn Rogan:** Conceptualization, Supervision, Methodology, Funding Acquisition, Writing- Original draft preparation; Writing – Reviewing and Editing, Software

O'Riordan, V., Mac Uidhir, T., Daly, H., Rogan, F., "Avoid-Shift-Improve: Bottom-up simulation modelling of national policies for transport carbon budgets" (In preparation)

Contributions - **Vera O'Riordan:** Conceptualization, Methodology, Software, Data curation, Writing- Original draft preparation; Visualisation; **Fionn Rogan:** Supervision, Methodology, Funding Acquisition, Writing – Reviewing and Editing; **Tomás MacUidhir:** Writing – Reviewing and Editing, Software; **Hannah Daly:** Conceptualization , Supervision, Methodology, Funding Acquisition, Writing – Reviewing and Editing

1.7.2. Conference Proceedings

O'Riordan, V., Mac Uidhir, T., Rogan, F., "Policy Simulation Modelling to Inform National Carbon Budget Pathways," International Energy Workshop, Colorado School of Mines, June 2023

O'Riordan, V., "Ex-post and Simulation Modelling to Inform Low Carbon Transport Policy in Ireland," ENVIRON, Atlantic Technological University, Letterkenny, Donegal, April 2023

Urquhart, D., Deakin, D., **O'Riordan, V**., "The shared road to improving policy-based, research-informed road transport emissions models – a case study of collaboration between academia, government and industry from Ireland" European Transport Conference 2022, Milan, Italy

O'Riordan, V., H. Daly, T. Mac Uidhir, B. Ó Gallachóir, F. Rogan, "Beyond car efficiency and electrification: Examining the role of demand reduction, public transit, and active travel measures to reduce GHG emissions in transport" 24th Annual Transport and Air Pollution Conference, Graz, Austria 2021 (Online)

O'Riordan, V., "Going Beyond Cars" Behaviour, Energy and Climate Change (BECC) Conference, 2021

O'Riordan, V., Daly, H., Mac Uidhir, T., Ó Gallachóir, B., Rogan, F., "What impact could work from home have on Irish passenger transport CO_2 emissions", Irish Transportation Research Network, Online Conference, University of Limerick, August 2021

O' Riordan. V., Rogan, F., Ó Gallachóir, B.P., Daly, H.E. "How did the 2008 car tax change impact vehicle emissions and revenue?" ENVIRON Virtual Conference, September 2020

1.7.3. Invited Talks and Presentations

O'Riordan, V., Mac Uidhir, T., Rogan, F., "Policy Simulation Modelling to Inform National Carbon Budget Pathways", ESRI (Economic and Social Research Institute) and MaREI Symposium, Dublin, May 2023

O'Riordan, V., "What is the potential for active modes to reduce Ireland's transport emissions?" ESRI & MaREI Virtual Symposium, May 2022

O'Riordan, V., "N9 Galway Road Panel Debate", NUIG Energy Society's Energy Week, November 2021

O'Riordan, V. "COVID-19 and the Irish Energy System" CIGRE Workshop, 9th December 2020

O' Riordan V., Rogan F., Ó Gallachóir, B.P., Daly, H.E., "Modelling with the Irish Car Stock Model", Department of Transport- UCC (University College Cork) Virtual Workshop, 14th July 2020

O'Riordan, V., Rogan, F., Ó Gallachóir, B.P., "An ex-post analysis of transport policy in Ireland", Scientific Advisory Council, Beaufort Building, Ringaskiddy, Cork, 13th December 2019

O'Riordan, V., Rogan, F., Ó Gallachóir, B.P., "Private Vehicle transport trends 2008 - 2018", MaREI Symposium, UL, 14th November 2019

1.7.4. Available Models and Spreadsheet Data

O'Riordan, V., Mulholland, E., Rogan, F., Gallachóir, B. O., & Daly, H. E. (2021). *Irish Car Stock Model V 2.4* (2.4). https://doi.org/10.5281/zenodo.4651477

O'Riordan, V., Rogan, F., Gallachóir, B. O., & Daly, H. E. (2021b). *Irish Passenger Transport Emissions and Mobility (IPTEM) V2.9* (2.9) https://doi.org/10.5281/zenodo.6359991

1.7.5. Reports and Policy Briefs

O'Riordan, V., Rogan, F., Daly, H., 2021, "Cycling, Walking and Public Transport in the Climate Action Plan" Policy Brief submitted to the Department of Environment, Climate and Communications

Rogan, F., Mac Uidhir, T., **O'Riordan, V.**, Deane, P., Ó Gallachóir, 2021, "How to achieve the 7% p/a. emissions reduction ambition?" Policy Brief submitted to the Department of Environment, Climate and Communications

Carpenter, G., & Antich, A., 2022, "The good tax guide: A comparison of car taxation in Europe." (Contributing Researcher for Ireland – **O'Riordan, V**.,)

Gallachóir, B. Ó., Deane, P., Mac Uidhir, T., **O'Riordan, V**., McDonagh, S., Aryanpur, V., & Rogan, F. ,2021. "Emissions Reduction in Transport: Submission to Oireachtas Committee on Climate Action"

1.7.6. Media Articles and Podcasts

O'Riordan, V., Hollands, A., 2023, RTÉ.ie "Why the Government needs to go beyond cars to cut transport emissions."

O'Riordan, V., Daly, H., 2020, COVID-19 and Irish Transport Emissions: RTÉ.ie Analysis: The massive reduction in traffic and emissions will not necessarily help Ireland meet its climate change targets, RTÉ Brainstorm

O'Riordan, V., Rogan, F., Ó Gallachóir, B. and Fitton, J., 2020, RTÉ.ie., Here's How More Walking and Cycling Will Reduce Carbon Emissions. [online] RTE.ie.

Chapter 2. Impact of an Emissions-based Car Tax Policy on CO_2 Emissions and Tax Revenue of Private Cars in Ireland[2]

2.1. Abstract

This chapter assesses private car CO_2 emissions and car tax revenue in Ireland over the 10-year period following the introduction of an emissions-based car taxation policy in 2008. A model of the new Irish car stock is built, which has new car sales, car fleet mileage, and CO_2 emissions intensity data to develop a bottom-up picture of historic CO_2 emissions from the car fleet. In this chapter, a counterfactual scenario following car purchasing trends in EU countries that did not introduce an emissions-based purchase and annual car taxes over the same period is developed. Relative to this counterfactual scenario, the CO_2 emissions intensity of the new car sales would have been 9% higher in 2018. This results in an estimated cumulative saving of 1.2 Mt CO_2 from 2008 to 2018 brought about by the tax change. Total annual emissions from private cars were 4.4% higher in the counterfactual scenario. The tax change also led to a fall in annual motor tax revenues. Recorded receipts from annual motor tax were €0.77 billion in 2018. Our study shows that this would have been €1.1 billion in 2018 under the pre-2008 tax regime. The estimated cost of abatement in

[2] Based on the publication: "O'Riordan, V., Rogan, F., Gallachóir, B.Ó., Daly, H., 2022. "Impact of an emissions-based car tax policy on CO_2 emissions and tax revenue of private cars in Ireland", International. Journal of Sustainable Transportation https://doi.org/10.1080/15568318.2022.2132562

this case ranges from €$_{2018}$1,500–€2,220 per tonne of CO_2 avoided over the period 2009 — 2018. The study uses the novel technique of applying a technology stock model to better understand the longer-term consequences of a government policy.

2.2. Introduction

2.2.1. Policy Context

In the European Union (EU), cars are responsible for around 12% of total CO_2eq. emissions (European Commission, 2020); for Ireland it is 15% (Environmental Protection Agency, 2019). In the EU, transport emissions targets are set under the EU Effort Sharing Regulation (ESR) 2018/842 covering non-emissions-traded sectors (non-ETS) (European Parliament, 2018a). In Ireland, despite a commitment to a 20% reduction in non-ETS emissions by 2020 relative to 2005 levels, a reduction of 8% has been achieved (Environmental Protection Agency, 2021b) . According to 2019 EPA projections, without the impact of COVID-19, transport emissions would have been only 2.7% lower (Environmental Protection Agency, 2020). This makes meeting Ireland's 2030 target of a 30% reduction in non-ETS emissions even more challenging. Therefore, policymakers are now focusing on other policy measures to decarbonise private car transport. To that end, the Irish government issued a Climate Action Plan in 2019 which outlines ambitious future policy measures and instruments to reduce CO_2 emissions from the transport sector, focused on car electrification, rail electrification, and bus system updates (Department of Communications Climate Action and Environment, 2019). Considering this, it is necessary to ask: to what extent can future policy reduce emissions? Some insight to this question can be achieved by looking at the impact of previous policy. Transport emissions are lower due to the recession, but also due to government policy, which is something this study seeks to quantify. This will be true not just in Ireland, but in every country that is seeking to reduce emissions particularly in the transport sector, by common consensus one of the most difficult sectors to decarbonise.

One policy instrument to reduce CO_2 emissions from private cars, which is at the heart of this study, is changing the car taxation regime to favour low-emitting cars. Such a measure was previously introduced in Ireland in 2008 so that the motor tax rates reflected the carbon intensity (carbon dioxide [CO_2] emissions per kilometre driven) rather than engine size (*Financial Statement of the Minister for Finance*, 2019). Vehicle Registration Tax (VRT) was changed from a tax based on the car sales price to one based on the emissions class of the car. Annual Motor Tax (AMT) was changed from a rating based on engine size to one based on CO_2 emissions intensity (Department of Finance, 2019). While the VRT also had an impact on the vehicles chosen, the revenues lost from the AMT is considered only in the cost of this analysis, as through its annual payment, it accumulates to be 80 - 90% of the total tax base from motor taxes (Department of Finance, 2019).

Ex post policy analysis is challenging, especially because of the interaction of multiple factors impacting car purchase and usage decisions. However, without an understanding of the impact of past policy interventions, future policy planning and implementation may be designed suboptimally. The key innovations in this chapter include developing a car stock scenario by simulating counterfactual Irish new car sales that follow purchasing trends in countries (Estonia and Lithuania) that did not introduce purchase or annual taxes based on the CO_2 emissions intensity of the new cars over the period of 2009 2018. An OECD performance review on environmental policies for both Estonia and Lithuania found that other policies introduced in the passenger trans- port sector were marginal over the period of 2009 - 2017 (OECD, 2017, 2021). This counterfactual scenario is com- pared with real-life sales of new cars in Ireland over the same period, which is the reference for the ex-post scenario simulation. By using a counterfactual based on trends in CO_2 emissions intensity of new cars from European countries that did not introduce emissions-based purchase and annual taxes, capturing European-wide improvements in manufacturer specifications in car engine efficiencies that occurred due to the transition from Euro V to Euro VI vehicles standards in 2013 (European Commission, 2022) while isolating the effect of the emissions-based annual and purchase taxes for new cars. A tool is also developed to calculate the revenue from annual motor taxes based on new car sales and the overall car stock.

2.2.2. Past Policy Analysis

An ex-ante 2008 study of projected impacts of a carbon-emission differentiated car tax system on CO_2 emissions intensity from new car purchases in Ireland showed that the car tax change would result in a reduction of 3.6 – 3.8% in CO_2 emissions intensity and a reduction of annual tax revenue of €191 million (Giblin & McNabola, 2009). The study specified a potential for future work in the revisiting of the modelling exercise following several years of the operation of the July 2008 tax system to assess the accuracy of model predictions, this study aims to address this recommendation. Other ex-ante studies of the car tax change included a total life-cycle cost model, which is used to estimate the mileage break-even point at which the purchaser will opt for the more efficient car and choose a diesel (Hennessy & Tol, 2011). This ex-ante model assumes rational behaviour in purchase choice and aggregates an average annual distance travelled across all car types. The ex-ante analysis anticipated that the cost of carbon dioxide emissions abatement per tonne under the new taxation regime would be "high, if not very high".

Regarding ex post analysis, a study on the impact of the 2008 car tax changes include a one-year analysis of the 2008 change in Irish car tax, which found that in the first year of the policy, average specific emissions intensity of new cars fell by 13% to 145 gCO_2/km (Rogan et al., 2011). This study used a disaggregated stock profile and monitored trends in emission bands, engine sizes and fuel types in the year following the introduction of the taxation change to quantify the weighted CO_2 emissions of new cars and expected car tax payments. Dennehy et al. adopted the car stock-model simulation approach for an ex-post decomposition analysis over the period of 2005 – 2015, examining the impact of seven underlying factors in driving energy demand. This analysis saw the increasing new diesel car purchases and overall diesel share in the Irish car fleet. It also highlighted the historical difference between average laboratory test values and on-road performance for the Irish car stock (Dennehy & Ó Gallachóir, 2018).

Looking further afield for ex-post studies on the impact of emissions-based car tax systems, a six-year ex-post analysis of the Dutch car taxation change found that the tax incentives were remarkably effective in encouraging changes towards lower-emitting cars. This contributed to a 6% reduction in private car emissions. The study noted the growing gap between rated performance and on-road performance, and how the scheme was not revenue neutral (Kok, 2015).

Across the EU, Dineen et. al., studied the implications of the CO_2 emissions taxation across all member states (Dineen et al., 2018). The qualitative study analysed factors, in particular national car taxes. The study noted the influence of confounding factors such as economic instability in the EU. By observing the trends in new passenger car carbon intensity, the analysis found that the majority of member states that shifted to CO_2-based car taxes were found to have improved their new passenger car emissions intensity more than other EU member states that did not change to CO_2 based car taxes (Dineen et al., 2018).

Ex-post policy analysis is particularly challenging, especially because of the interaction of multiple factors impacting car purchase and usage decisions; however, without an understanding of the impact of past policy interventions, future policy planning and implementation is more at risk of an unsuccessful fate. For example, this can happen when an unintended consequence of a policy is falsely asserted as being part of the original policy goals, the net effect of which can undermine future policy planning capability. The key innovations in this study include developing a car stock counterfactual scenario based on historical Irish new car sales concerning EU-wide new car sales, the development of a tool to calculate the revenue for different car taxation regimes based on the car stock model.

2.2.3. Outline

The chapter is structured as follows: in Section 2.3, this chapter describes the methods used for this analysis, the Irish car stock model, the factual and counterfactual scenarios for exploring the impacts of the car tax change and the method. In Section 2.4, the results section, the study highlights: i) the emissions trends over the period of 2008 – 2018 for the factual and counterfactual cases, ii) the stock carbon intensity impacts, iii) the revenue impacts of the taxation change. Section 2.5, the discussion section, covers areas of uncertainty in the analysis and draws comparisons with other ex-ante and ex-post studies on the car tax change. The conclusion, Section 2.6, discusses these results and draws insights for policy makers.

2.3. Methods

2.3.1. Irish Car Stock Model

The model used in this chapter is a technology stock simulation model, which relies on revealed preferences of car choice. This was selected over a cost optimisation model to estimate car choice, due to the unavailability and uncertainty associated with cost data on private cars across various dealerships that is needed for a techno-economic optimisation model. This chapter builds from a technological stock model of the Irish private car fleet, which was first developed in Daly & Ó Gallachóir, (H. Daly & Ó Gallachóir, 2011). The car stock and activity profile are disaggregated by car technology, engine class, fuel type and age (or car vintage) to produce a detailed look at private car activity and energy consumption over the period 2000 to 2008. An overview of the private car transport model is provided in Figure 5, which includes the relationship between the inputs (left), the calculation programs (centre) and the output calculations (right). The model combines distance travelled, information on the fuel consumption performance with cars with the number of vehicle sales and survival rates of older cars in the Irish car stock. The code base and data input files for the model are available on Zenodo (O'Riordan et al., 2021).

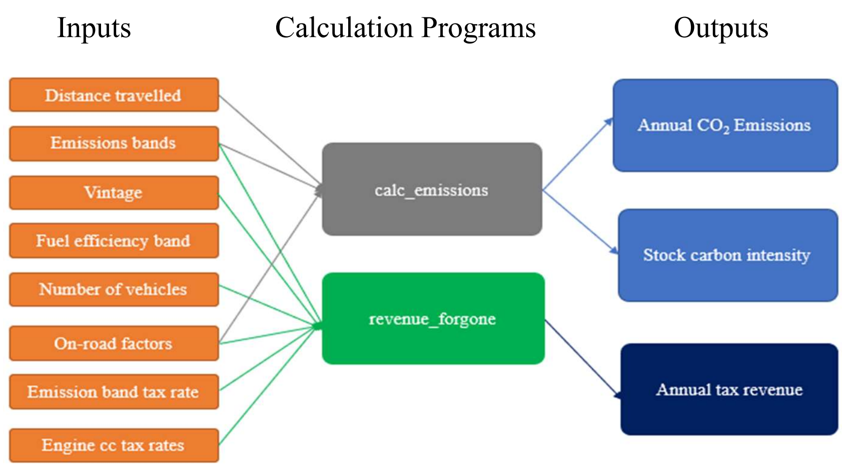


Figure 5. Overview of private car stock model

2.3.1. Total car fleet CO_2 emissions, 2001 – 2018

CO2 emissions are calculated as described in Equation [1]

$$Private\ Car\ Emissions = \sum_{f,a,c} S_{f,a,e} \times D_{f,a,e} \times CI_f \times ORF_{f,y} \quad [1]$$

Where;

- S - car stock (number of cars)
- D – distance travelled (km/year)
- CI – CO_2 emissions intensity (GCO_2/km)
- ORF – the on-road factor which outlines the difference between the test values (or rated values) and actual, or on-road fuel consumption based on the fuel type f and year y
- a – age of the car, which in turn defines the measured mileage and emissions intensity for cars of a given age and emissions band OR engine cc (engine

cubic capacity, also known as the volumetric size of the engine) for pre-2008 purchased cars.

- f – fuel type of the car, which in turn defines the measured mileage and emissions intensity for a car of a given age and emissions band OR engine cc for pre-2008 purchased cars
- e – emissions band OR engine cc of the car for pre-2008 purchased cars, which calculated the measured mileage and emissions intensity value for a car of a given age and fuel type.

Data is sourced from a range of publicly available sources (see Appendix A).
The activity -weighted CO_2 emissions intensity takes the distance travelled by each car type into account. It is import- ant to weigh by activity because this is the most representative of actual fleet emissions, representing the fact that different car types have different annual mileages. Based on information from the National Car Test centre on annual distance travelled, new cars travel further than cars of older vintages and cars of a larger engine capacity also travel further.

The on-road factor (ORF) is derived from a study on the on-road performance of passenger cars. Earlier literature (Daly & Ó Gallachóir, 2011a; Dennehy & Ó Gallachóir 2018) estimated the on-road factor by comparing manufacturer specified specific fuel consumption with household consumption of petrol and diesel from the Household Budget Survey conducted by the Central Statistics Office. The on-road factors derived from the Household Budget Survey highlighted their increasing trend as also noted in a study on passenger cars conducted in Germany for diesel cars (Tietge et al., 2017). The German study was corroborated with a method for calculating the car stock on-road factor by using a top-down estimate from Irish household budget spends on fuel, as described in Hennessy and Tol (2011) and Kok (2015). The study calculated an increasing on road factor from a mean divergence of 13% in 2008 to 33% in 2014 for gasoline cars, 16% in 2008 to 39% in 2014 for diesel cars (Tietge et al., 2017), and the Household Budget Survey determined an increase in on-road factor from 14% in 2008to 30% in 2015 for gasoline cars, and 22% in 2008 to 43% in 2015 for diesel cars (Dennehy & O Gallachóir, 2018). As the laboratory study recorded the on-road factor for a car of a given build year, the on-road factors from the German passenger car study were applied to the Irish Car Stock model.

2.3.2. Counterfactual scenario: average CO_2 emissions intensity of new cars, 2008 -2018

Counterfactual scenarios for *ex post* analysis can be basedon cost-price models. Previous *ex post* transport infrastructure studies used cost-benefit models coupled with qualitative methods to assess the success of the projects (De Jong et al., 2019; Welde, 2018). Cost-benefit models can also be used to compare future choices in new cars based on updated taxes, which could be adjusted to consider how purchases have occurred over the period of 2008 - 2018 (De Jong et al., 2019). Decomposition analysis can also be usedto assess the separate elements involved in policy-based interventions. *Ex post* analyses of transport infrastructure projects use a mix of cost-benefit analysis and qualitative analysis reflecting on other projects. Multisector log-meandivisia index (LMDI) decomposition analyses have also been used to evaluate the effectiveness of past energy efficiency policies and transport policies over extended periods (Dennehy & O'Gallachóir, 2018; Trotta, 2020), and single years (Rogan et al., 2011). As there was an availability of information on the CO_2 emissions intensity of new car sales across all the EU countries over the period of 2000 - 2018, and new sales and stock data available from Irish cars over the period of 2008 - 2018, a counterfactual based on alternative car sales following trends in CO_2 emissions intensity reductions of countries that did not introduce emissions-based car taxes was used.

The counterfactual reflects a modelled scenario of post-2008 average CO_2 emissions intensity of new cars in the absence of an emissions-based taxation change for Ireland. To do this, it is assumed that the trend in the emissions intensity of new car sales would have followed that of the two EU countries that did not introduce such tax changes. Based on a study conducted by the European Environmental Agency (European Environment Centre, 2016), Estonia and Lithuania did not introduce CO_2 and proxy-based incentives at the point of sale for new cars over the period of 2008-2018. Every other country in the EU did. The relative annual reductions in the CO_2 emissions intensity of new cars from an aggregate of Estonia and Lithuania form the basis of the counterfactual scenario for the Irish car stock. Net reductions in car carbon intensity are easier to achieve if starting from a higher emissions intensity, and thus calculating the relative reduction in emissions intensity in percent terms to 2007 values counterbalances this. The CO_2 emissions intensities of new cars purchased over the period of 2000-2019 are included in Appendix A, and the reduction in carbon intensities of new cars purchased by country over the period of 2008- 2018 indexed to the 2007 average emissions intensity of new cars sold in that year are highlighted in the results section in Figure 3. The average reduction in CO_2 emissions intensity of new cars for each year over 2008-2018 amongst the two countries (Estonia and Lithuania) was applied to the Irish car stock, using Irish car sale numbers for each year.

The stock-based approach involves bottom-up calculations of the counterfactual CO_2 emissions from private transport, based on car sales following a counterfactual average CO_2 emissions intensity and being added to the stock each passing year. Total private car emissions from the Irish car stock for each year was calculated as shown previously in Equation [1].

2.3.3. Annual motor tax revenue

Revenue from annual motor tax is recorded by the Government Climate Action and Tax Strategy Group (Department of Finance, 2019). These values are compared with the revenue calculated from the Irish Car Stock Model. The stock model calculates the revenue as follows: Tax revenue from cars registered before 2008 (Equation [2]):

$$Revenue = \sum_{engine\ cc,\ \ year} Taxation\ rate_{engine\ cc,year} \times Number\ of\ vehicles_{engine\ cc,year} \quad [2]$$

where engine cc refers to the volumetric size of the engine, also known as the cubic capacity. For cars registered after 2008, the revenue generated from annual motor tax is calculated as a function of the manufacturer specified emissions band as follows (Equation [3]):

$$Revenue = \sum_{emission\ band,year} Taxation\ rate_{emissions\ band,year} \times Number\ of\ vehicles_{emissions\ band,year} \quad [3]$$

The revenue from Annual Motor Tax for the following scenarios were recorded:

1. Recorded Receipts: the documented revenues from the Parliamentary Budget Office (House of the Oireachtas, 2019).

2. Modelled Revenue: the expected revenue over the period of 2001–2018, which applied the tax bands and the stock of cars as recorded in the Irish Car Stock Model. The calculations factor in the change in taxation for cars registered after 2008.

3. Counterfactual revenue: the revenue calculated based on the counterfactual car stock scenario as described in the methods section (Subsection 2.3). All cars in the stock have a motor tax based on the pre-2008 engine cc-based rates as documented in Appendix A.

Table 2: CO_2 emissions intensity of new cars in the Irish car fleet for the actual and counterfactual scenario

Average CO_2 emissions intensity of new cars sold by year (gCO_2/km)												
Year	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Actual (reference scenario)	185	184	171	160	159	158	159	159	157	155	155	158
Counterfactual scenario	185	184	178	171	169	168	170	171	167	164	165	176
Difference	0	0	7	11	11	11	12	11	10	9	10	18

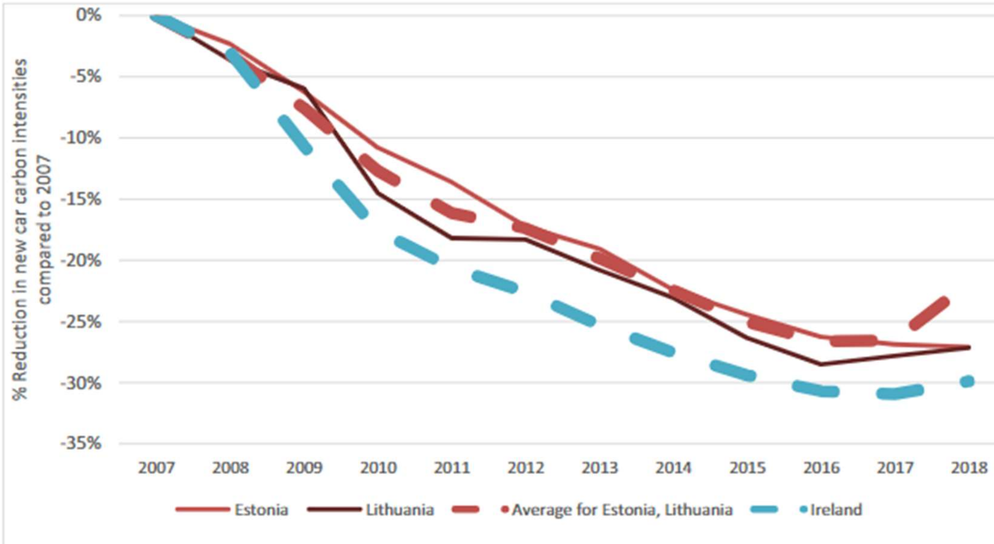


Figure 6: Percentage reduction in CO_2 emissions intensity of new cars by country from 2008 to 2018 compared to their respective 2007 values

2.4. Results

2.4.1. Average CO_2 emissions intensity of new cars

Average CO_2 emissions intensity of new cars in Ireland over the period of 2009 2018 form the basis of the reference scenario which the "counterfactual scenario" is compared against. The counterfactual scenario assumes that the average CO_2 emissions intensity of new cars follows the same trends as countries that did not introduce an emission-based purchase and annual car tax. Values for CO_2 emissions intensity of new cars in the Irish car fleet for the actual (Eurostat, 2022), and the counterfactual scenario are listed in Table 2.

For 2018, the average CO_2 emissions intensity of a new car was 158 g of CO_2 emissions per kilometre (gCO_2/km) compared to counterfactual scenario, calculated to be 175 gCO_2/km. A comparison of CO_2 emissions intensity of new Irish cars versus the countries did not introduce emissions-based car taxes is shown in Figure 2.

2.4.2. Overall car fleet emissions

Compared to actual emissions in 2018, the emissions in the counterfactual scenario for 2018 are 2.8% higher than thereference. This results in a net annual saving of 0.25 $MtCO_2$ in 2018 compared to the counterfactual, and a cumulativesaving of 1.2 $MtCO_2$ over the 2008 2018 period. The results for overall car fleet emissions from the counterfactual scenario compared with the actual private car CO_2 emissions are shown in Table 3.

Table 3: Summary of emissions model results

Year	Actual emissions	Counterfactual emissions
2007	6.2	6.2
2008	5.7	5.7
2010	6.1	6.1
2011	5.6	5.6
2012	5.5	5.5
2013	5.1	5.1
2014	5.4	5.5
2015	5.5	5.6
2016	5.8	5.9
2017	6.0	6.2
2018	6.1	6.3
2019	5.8	6.1

2.4.3. Tax revenue from the annual motor tax

Tax revenue collected from annual motor taxes was calculated for both the reference and counterfactual scenarios to evaluate the cost implications of the policy on the exchequer. To validate the bottom-up stock method used to determine modelled revenue in-take from the counterfactual, revenue for the modelled reference scenario was compared with recorded receipts from the Department of Transport from annual motor tax. For 2018, the modelled actual revenue is 9% lower than the recorded revenue from the Department of Transport. The modelled actual revenue modelled counterfactual revenue and recorded receipts are shown in Figure 3 (below)

Differences between the recorded receipts could be determined by overdue payments of the fee which would not have yet been recorded for the latter years, i.e., 2017, 2018, and from modelling discrepancies asthe emission band is approximated across the car fleet from aggregated efficiency band calculations. By 2018, reference tax revenue was calculated as €0.7 billion, revenue which is €0.4 billion lower than the counter-factual scenario, which had a revenue intake of €1.1 billion. Progression of the revenue generated from the Annual Motor Tax based is illustrated in Figure 7 (below).

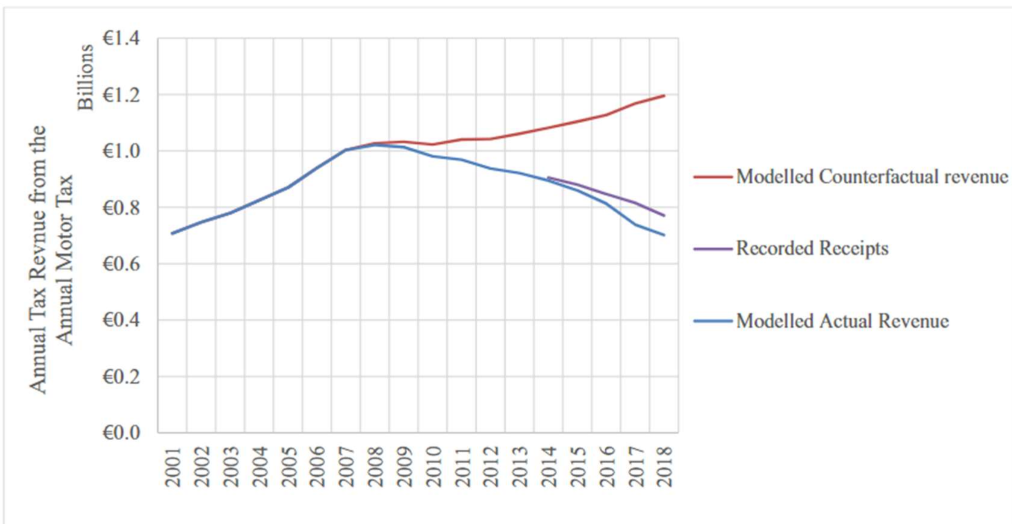


Figure 7: Annual tax revenue from the Annual Motor Tax

2.5. Discussion

2.5.1. Discussion and policy implications

Following a comparison of the reference scenario with the counterfactual scenario, actual private car CO_2 emissions calculated in this study were 2.8% lower than that wouldhave been relative to the counterfactual scenario in 2018. This suggests that the change in taxation had a marginal impact on overall private car CO_2 emissions by 2018. Whatis also interesting to note is that the difference in new car carbon intensity between actual and counterfactual developsin the first few years, and then stabilizes at a level of about10 gCO_2/km, with a slight decrease in the last year.

However, despite this, as indicated in Table 3 absolute car fleet emissions grew by 1.7% over the period 2008 -2018, because of robust growth in activity which offset gains from efficiency. In the counterfactual scenarios, private car emissions for 2018 would be 3.9% higher thanfor 2008. This analysis indicates that the change in annual motor tax reduced the rise in CO_2 emissions from privatecars to an extent, but the effect was not strong enough to reduce overall private car CO_2 emissions.

Regarding the overall CO_2 emissions intensity of the private car fleet, Rogan et al. also concluded that the average specific emissions of new cars fell by 13% in 2009 becauseof the policy change, resulting in a 5.9 kt reduction in CO_2 emissions that year (Rogan et al., 2011).

The tax change had the effect of incentivizing the purchase of diesel cars that had lower CO_2 emissions and lower taxes under the new taxation scheme. However, because the tax change had been designed in part to counteract a trend

toward larger cars, there had been an expectation that its successful implementation would lead to the purchase of smaller cars. Analysis done during the first year of the tax change noted a shift toward diesel cars but was not pre- pared to predict if this shift would become a trend (Ó Gallachóir, 2009). As it happened diesel cars were particularly susceptible to excessive NOx and SOx emissions under the New European Driving Cycle (Rogan et al., 2011). The ensuing "Diesel-gate" scandal highlighted the extremely high NOx emissions from new diesel cars that the CO_2- emissions based tax change had incentivized (Leinert et al., 2013). The switch to diesel also led to interaction with the Biofuel Obligation

Scheme (National Oil Reserves Agency, 2020; Ryan et al., 2018). The switch to diesel enabled Ireland to achieve a higher share of renewable energy in transport (due to double accounting for the increased bio- diesel mixing rates in diesel cars compared to bioethanol mixing rates for petrol cars), than would have been the case without such a switch (Mulholland et al., 2014).

The 2008 car tax change culminated as a tax cut in disguise for car owners and resulted in the high cost of carbon abatement of $€_{2018}$1,500- 2,220 per tonne of CO_2 (in 2018 real value terms). This loss of revenue was anticipated in the *ex-ante* car choice model study from 2009 by Giblin and McNabola (2009). The study found that the introduction of new CO_2-based taxes in Ireland would result in a reduction of 3.6%-3.8% in CO_2 emissions intensity and an annual revenue loss of e191 million. The one-year ex post analysis of the 2008 car tax also noted that the scheme, which was intended to be revenue neutral, was not (Rogan et al., 2011). Hennesey and Tol's (Hennessy & Tol, 2011) ex ante cost-based car-choice model for the car tax regime showed that the cost of CO_2 emissions abatement would be "high, if not very high". Our results indicate a reduction of 4.4% by 2018, with the net reductions accumulating with each year as the emissions reductions permeate throughout the car stock.

Since 2021, the Irish government has introduced an update to the annual motor tax (Department of Transport, 2020). The new taxation scheme includes a greater number of subcategories for emissions classes, with additional subdivisions for the emission band category, which allows for a greater specification of super low emission cars (those with a less than 50 gCO_2/km emissions intensity). However, the emission band taxation rates for the higher emissions categories have remained unchanged. In addition, the new taxation rates will only apply to cars registered in Ireland after 2021.

This study highlights the importance of monitoring ongoing developments in revenue following car taxation changes, as the policy resulted in a reduction of car tax revenue when compared to the pre-2008 rates based on engine displacement. Ongoing adjustment of the policy design is necessary to maintain revenue neutrality.

The study also highlights the importance of ongoing analysis of the effectiveness of policy design for CO_2 emissions reductions. Overall, emissions from private cars were higher in 2018 than in 2008, which suggests that improvements in car efficiency resulting from the taxation policy were not sufficient to offset the increase in emissions from private car because of growing activity. As noted in Dennehy & Ó Gallachóir increased energy consumption and emissions from growing demand for private car transport outweighed any energy and emissions reductions from efficiency improvements in private cars (Dennehy & Ó Gallachóir, 2018). The finding illustrates the importance of car transport demand management in parallel with financial incentives to encourage a switch to low emission and high efficiency cars. The issue of managing car activity increases also emerges in the guideline for making transport-based emissions reduction policy from the Department of Transport, Environmental Protection Agency, and the IPCC (Intergovernmental Panel on Climate Change) (Department of Transport, 2019b; Environmental Protection Agency, 2020; IPCC, 2014). They recommend following the Avoid- Shift-Improve framework, which focuses initially on avoiding transport demand with demand management strategies, then pursuing a course to encourage modal shift to public transport or active modes of travel and as a last resort, improving the fuel efficiency or fuel type of the car through technology adoption and financial incentives. The car tax strategy focuses on the "Improve" aspect of the framework, and regarding the new car tax as a financial mechanism to reduce CO_2 emissions, our study found that the cost of the policy per tonne of CO_2 abated was very high relative to other emissions abatement measures, and that while finance measures can be helpful, they are not sufficient to address the structural factors of passenger transport emissions in Ireland, such as transport demand, car lock-in and mode choice.

The tax policy also highlights the pitfalls of setting an environmental policy based on laboratory-based manufacturer specified measurements that cannot be continually monitored on the road. The manufacturer specified emissions used to set the Irish car tax rate were subject to "gaming" in what is now known as the "Diesel-gate" scan- dal. While emissions of nitrous dioxides (NO_x) and sulfur dioxides (SO_x), rather than CO_2, were in the spotlight throughout the scandal, the growth of the CO_2 on-road factor in Ireland over the period of 2008 — 2018 as highlighted in Appendix A.B contributed to CO_2 emissions being higher than they otherwise would have been. This also impacted the tax revenue collected by the Irish government as cars were increasingly in lower taxation classes than they would be if they were rated according to real-world driving. As internal combustion engines are emitting more than the tax policy specifies, the relative tax benefit of switching to a no-emission car, such as an electric car, is subsequently reduced. Increasing the relative difference between the emissions bands, combined with the new World Harmonized Light Vehicle Test Procedure (WLTP), would result in a stronger price signal for switching to super low emission cars such as EVs (Electric Vehicles) could be helpful toward Ireland's 2030 EV uptake and sustainable transport targets. Retrospectively updating taxation rates on higher emission cars are also an option to be considered, as current updates to the taxation policy only focus on cars registered after the date of implementation. An iterative approach to taxation policy allows for continual monitoring of tax revenue fromthe new taxation schemes and prevents the revenue losses suffered because of the 2008 car tax rate changes.

2.5.2. Uncertainty

Several sources of uncertainty arise in calculating the emissions impact of a change in car taxation. These sources of uncertainty can be categorized as first, uncertainty in the calculation of emissions although technical and behavioural characteristics of fuel consumption, and second, uncertainty in distinguishing the impact of the policy change on car sales from other trends impacting car sales. First, there is a significant source of uncertainty in deter- mining the real-world driving emissions relative to those calculated in standardized tests, referred to as the on-road factor. In Rogan et al. (2011) the on-road factor was high- lighted as a potential source for uncertainty. It is well established that the carbon intensity of cars in real-world driving conditions is higher than measured in test conditions, due to factors such as driving technique, road surfaces and engine conditions. For this study, the on-road factor is derived from comparing data from the Irish household budget survey with modelled fuel consumption according to test values and corroborated with a study of on-road factors of new German passenger cars (Tietge et al., 2017). This data is available up to 2015 is available, however data from 2016 to 2018 is not readily available and 2015 rates are applied in this study up to 2018.

A second source of uncertainty arises from the specification of counterfactual scenario, in distinguishing the impact of the car tax change relative to other background changes.The counterfactual scenario is based on assuming that new car

CO_2 emissions intensity of new cars purchased in Ireland would follow the same average reduction as European countries that did not introduce such emissions-based car purchasing incentives over the period of 2008 2018. Not included in the counterfactual are the effects of the taxation change on the adoption of electric cars. In 2018, electric cars accounted for 1% of sales, with 99% of sales applying to petrol/diesel and hybrid varieties (Central Statistics Office, 2020). Overall carbon intensity of new car sales in Ireland and across the EU from Eurostatinclude hybrid and electric car varieties.

Another unanticipated occurrence when the car tax scheme was introduced was the increase in second-hand car imports over the period of 2009 2018. In 2019, these now account for nearly 50% of new car registrations (CSO, 2020a). While accounted for in the car stock model through calculating the average car age of the car stock, the impactof second-hand imports is a research question worthy of deeper analysis. Furthermore, car scrappage schemes were introduced in Ireland during 2001-2002 and 2007-2008, the latter which may have impacted sales from 2009 coinciding with the car tax, however, this was not within the scopeof this study. van wee et al found that private car emissions reductions were modest and short-term, with the cost-effectiveness of these schemes being quite poor. The cost effectiveness of scrappage schemes is often quite poor (van Weeet al., 2011). Similarly, Kagawa et al.'s study on the Japanese scrappage scheme showed that CO_2 emissions would onlydecrease if users of the scheme retained their new gasoline passenger cars for at least 4.7 years. It also found that the scheme was costly considering the emissions reductionachieved from the intervention (Kagawa et al., 2013).

Another source of uncertainty arises from the knock-oneffects of the increased tax payments in the counterfactual “no-tax change” scenario. For example, as annual motor tax revenue was reduced, this meant that car owners who purchased their car after 2008 were spending less on car taxeach year than would have been the case under the pre-2008 engine-size based taxation regime. This would reduce the cost of car ownership compared to a higher-tax counterfactual and in turn, would incentivize car ownership by making it lower in cost. It is common knowledge in the field of consumer behaviour that upfront costs are more important than an assessment of the cost of car ownership and operating costs during the car’s lifespan, and hence, the taxes being added for car registration has an added significance.

The uncertainty issue is one aspect of the discussion on whether energy systems models are fit for purpose (CSO,2020b). Gilboae et al. (Department of Transport, 2019a) argue that economic models are most usefully seen as describing specific, theoretical systems rather than general rules, and as such, are simply one source of knowledge alongside other data such as experimental or empirical results. A simulation technology stock-based model shouldbe viewed as a source of possible storylines rather than of fundamental truth. The situations modelled by *ex post* ana- lysis cannot be fully observed and measured, and do not exhibit a reliability of structure in time and across variationsin conditions not specified in the model: therefore, they can- not be properly validated (European Environment Centre, 2016). However, by comparing the results with car choice models such as Hennessy and Tol (2011), Giblin andMcNabola (2009), and Rogan et al. (2011), we can gather valuable insights.

In addition, the model does not consider the rebound effect of such reductions in CO_2 emissions intensity, whereby perceived improvements in technology, efficiency, and emissions are coupled with an increase in kilometres travelled. This may act to negate the positive effects of this tax policy change and further measures should be put in place to protect the predicted CO_2 savings. Dynamic effects of the tax change, which lead to reduced tax revenue for the government and lower taxes for the consumer and how that could have impacted consumer behaviour was not investigated. Car manufacturers also optimize cars for the driving tests that are connected to the Euro Standards, this is different from optimizing the cars for real world driving performance, and results in cars being rated with lower emissions of NOx, SOx, and CO_2 emissions than what would be the case in day-to-day use. These intentional and misleading design decisions encompassed is now known as the "Diesel-gate" scandal. In the Irish Car Stock Model, an on-road factor is applied to fuel consumption figures to adjust for the discrepancy between on-road and manufacturer specified fuel consumption values, these figures are listed in Appendix A.B.

As mentioned in Section 3, Results, I compared the modelled tax revenue from the Irish car stock model with the recorded receipts from the motor taxes (House of the Oireachtas, 2019). The recorded receipts from the motor taxes were up to 9.5% higher. This discrepancy can be explained by factors such as delayed payment of taxes from previous years and discrepancies between the actual on-road car fleet and the car stock model. A table of the percentage difference between recorded receipts and the calculated revenue from the Irish Car Stock Model is shown below (Table 5).

Table 4: Difference in recorded and modelled tax revenue from motor tax

Year	%
2014	1.1
2015	2.2
2016	3.9
2017	9.5
2018	9.0

2.6. Conclusions and policy implications

2.6.1. Conclusions of the ex-post study

Several important findings arise from this study.

The 2008 car tax change influenced purchasing patterns. This change in purchasing patterns caused a slight shift in new car purchasing trends toward more efficient cars. In 2018, actual private car CO_2 emissions were 2.7% lower than as calculated in the counterfactual "no-tax change" scenario. Cumulative CO_2 savings over the 10-year period following the introduction of the tax change amounted to 1.2 $MtCO_2$, when compared to the counterfactual.

However, despite the increase in new-car efficiency arising from this policy, this did not cause a net annual decrease in private car transport emissions over the 10-year period itself. There was a strong fall in emissions after 2008, but this was caused by a reduction in car activity following the economic crash of 2008 and private car emissions rebounded alongside the economy (Sustainable Energy Authority of Ireland, 2018). Net CO_2 emissions from private cars in 2018 were 4.4% higher than in 2008. This suggests that technical and policy efforts to improve internal combustion engine efficiency improvements do not sufficiently reduce emissions and will need to be complemented by changes to mobility and fuel type. The relatively small reduction in carbon dioxide emissions could also be due to the policy being too soft and small in scope, and that the relative differences in taxes between cars that have emissions and those that are zero-emission is not enough. Irish policy is reflecting this: a ban on new fossil fuel cars by 2030 is currently under discussion (Department of Communications Climate Action and Environment, 2019) and the new policy focuses on car electrification and mode shifting to public transport, walking, and cycling rather than efficiency improvements (Government of Ireland, 2021).

As for whether the policy was revenue neutral, it is estimated that annual motor tax receipts would have been €207 million higher in 2018 without the policy. This happened because the design of the taxation bands did not anticipate consumer purchasing trends toward cars in lower emissions classes. It also resulted in a tax-cut in disguise, as tax rates based on emissions bands were lower overall than those previously based on engine displacement. Lastly, the car tax change resulted in the high cost of carbon abatement of $€_{2018}$1,500 — 2,220 per tonne of CO_2.

Chapter 3. How and Why We Travel – Mobility Demand and Emissions from Passenger Transport[3]

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3.1. Abstract

Due to the need for faster reductions in transport greenhouse-gas emissions, policy makers are increasingly paying attention to the role of reducing mobility demand and shifting towards low carbon transport modes. This chapter develops the novel open-source Irish Passenger Transport Emissions and Mobility (IPTEM) Model and uses it to calculate passenger transport demand by trip mode, purpose, and distance over the period of 2009 – 2019. The chapter quantifies carbon dioxide emissions intensities by mode type, and for the first time for Ireland, passenger transport occupancy rates. Light rail has the lowest CO_2 emissions per passenger kilometres among motorized modes. In 2019, travel for work purposes contributes the greatest to overall passenger transport demand (30% of all passenger kilometres) followed by shopping

[3] Based on the publication: O'Riordan, V., Rogan, F., Ó Gallachóir, B., Mac Uidhir, T., Daly, H., 2022a. "How and why we travel – Mobility demand and emissions from passenger transport", Transport Research Part D. Transport and Environment 104. https://doi.org/10.1016/j.trd.2022.103195

(19%) and companion journeys (16%). Journeys under 8 kilometres were responsible for 37% of passenger transport emissions.

3.2. Highlights

- Method of calculating passenger transport demand and CO_2 emissions by mode type, trip purpose and trip distance is developed
- Calculations of occupancy, fuel consumption and carbon intensity by mode type are included
- Data provides insights of the end use purpose of travel and basis for modelling policy interventions based on trip type i.e., remote working
- The Irish Passenger Transport Emissions and Mobility model is openly available on Zenodo (O'Riordan, et al., 2021)

3.3. Introduction

3.3.1. Global Context

Globally, the transport sector is responsible for 23% of total energy-related CO_2 emissions (International Energy Agency, 2021). Growth in greenhouse gas (GHG) emissions has continued due to growing demand despite the trends towards more efficient vehicles and adoption of climate mitigation policies. Due to the need for faster reductions in transport emissions, and the failure of efficiency and fuel-switching policies to deliver the required reductions, policymakers are increasingly paying attention to the role of mobility demand and modal choice in reducing transport GHG emissions. In this chapter, a spreadsheet model is developed to link passenger kilometre demand by mode type, trip purpose and trip distance with CO_2 emissions. This allows readers to draw greater insights of the contributions of transport mode type, trip purpose and occupancy has on passenger transport CO_2 emissions.

The Intergovernmental Panel on Climate Change (IPCC) has advised on a comprehensive sustainability approach to transport through the Avoid-Shift-Improve (ASI) framework (IPCC, 2014). This approach involves reducing passenger transport emissions through a hierarchy of actions: first, avoid – avoiding journeys where possible, through innovative spatial planning, and demand management; then, shift – shifting to the more sustainable modes of travel such as walking, cycling and public transport; and lastly, improve – improving the energy and carbon efficiency of the chosen transport mode. This framework goes beyond the current dominant policy emphasis of improving private car efficiency through design improvements, increasing biofuels, and switching to electric powered cars. The Avoid-Shift-Improve framework for transport encompasses the broader recognition that meeting long-term climate goals will require a focus on demand as well as technologies and fuels. The framework recognizes that car use has many other negative externalities other than carbon dioxide emissions – including and not limited to, road safety concerns, negative health effects due to commuter physical inactivity, traffic issues, and land use costs. The Avoid-Shift-Improve approach has been adopted in a multi-sector energy system optimisation study which discusses demand reduction scenarios and a study from the International Energy Agency which includes net zero scenarios that include demand reduction and modal shift (Grubler et al., 2018).

3.3.2. Model Representation of Demand Reduction, Modal Shift, and Active Modes

The Avoid–Shift–Improve approach originated in the early 1990s in Germany to structure policy measures that reduce the environmental impact of transport (Creutzig et al., 2018) . The "Avoid" aspect of energy policy involves investigating what the passenger transport demand is used for and determining methods that would reduce those needs (Kutani, 2012). According to this approach, policies to limit GHG emissions in the transport sector need to consist of measures aimed at avoiding the need to travel, for example by improved urban planning, or teleworking; and only then shifting travel to the lowest-carbon mode, such as cycling; followed by improving the chosen mode type to be more energy-efficient and fuels to be less carbon-intensive.

The "Shift" dimension of the "Avoid-Shift-Improve" (ASI) framework is also underexplored, despite being endorsed by the Intergovernmental Panel for Climate Change (IPCC, 2014). Following from this, in Ireland, the Environmental Protection Agency and the Department of Transport have also concluded that the Avoid-Shift-Improve approach is best practice for sustainable transport planning in Ireland, provided the emissions intensity per passenger kilometre of public transport remains lower than private cars (Environmental Protection Agency, 2020), (Department of Transport, 2019c). This "Shift" approach refers to using alternative modes of transport, and not choosing private passenger cars, as the carbon dioxide emissions intensities per passenger kilometre of modes alternative to the passenger car such as cycling, walking or public transport, are generally lower than that of passenger cars.

Up until now, most passenger transport studies on carbon dioxide mitigation focussed on the "Improve" dimension of the "Avoid-Shift-Improve" (ASI) framework. “Improve” refers to achieving carbon dioxide emissions reductions through upgrading the overall efficiency of the car, or by improving or switching the fuel type used by the car. I will now discuss studies that investigated transport emissions using either a combination or an element of the Avoid-Shift-Improve approach.

On a global scale, future projections on the emissions impact of widespread low carbon modal shifts were investigated in Cuenot et al. (Cuenot et al., 2012). Here, the International Energy Agency developed an estimation of passenger travel by mode for major countries around the world. The International Energy Agency’s Mobility Model (MoMo) is a spreadsheet model that projects road transportation demand by mode, energy use, and CO_2 emissions for 22 world regions/countries together forming the world (Lew Fulton et al., 2009). The study specified that a more detailed, policy-oriented analysis at a national level is needed to better understand the full potential and relationship to specific policy packages.

However, many transport energy models typically cannot quantify potential emissions savings from demand reduction or mode choice measures. (Creutzig et al., 2015) also emphasized that global integrated assessment models lack necessary spatial or jurisdictional resolution to represent local or regional possibilities for a low carbon transport transition. The study noted that while integrated assessment models (IAMs) are important for the big-picture global scale goals, transport-specific models and technological data can complement IAMs and show mitigation possibilities that are unique to specific regions, including behavioural interventions such as modal shift to improved public transport, remote working policies, or urban restrictions on car use.

For example, Pietzcker et al. developed a global integrated assessment model which looked at linking both energy and economic models. The results indicated a huge reliance on liquid fuels up to 2050 (Pietzcker et al., 2014). This chapter looked at final energy and CO_2 projections until 2011 from 5 energy economy models. The study found that total demand for mobility can be reduced through increased travel costs, improved (urban) infrastructure, and changes in consumer preferences or socio-cultural norms. It also found that modal shift from travel modes with high carbon intensity, such as aviation or private vehicles, to ones with lower carbon intensity, such as buses, trains, or ships, will reduce GHG emissions. The study went on to emphasize the importance of incorporating all decarbonization options along the chain of causality, e.g., price-responsive mobility demand, a better representation of modal shift, finer granularity of investments into vehicle efficiency, as well as more complete representation of the technological options to use advanced fuels (including hydrogen) in both passenger and freight sectors. The study noted that detailed comparisons with bottom-up scenarios are needed to validate the chosen parameterization, and this is currently lacking. This gap in comprehensive bottom-up passenger transport data was also noted in Pye et al., which concluded that the transport sector was particularly sensitive to uncertainty of demand response to price elasticity in energy systems models (Pye et al., 2014).

In addition, a study on vehicle purchase decisions found that transport mode type decisions are often non-rational and therefore, cost-price interventions have limited scope in addressing passenger transport transitions (McCollum et al., 2017). Therefore, the passenger transport sector should be the focus of demand reduction interventions. The data-rich provisions of the Irish Passenger Transport Emissions and Mobility model aims to address some of the issues regarding parameterization of modal shift and the possibilities in the uptake of public transport and active modes in Ireland.

An integrated assessment modelling framework showed how changes in the quantity and type of energy services drive structural change in intermediate and upstream supply sectors such as energy and land use (Grubler et al., 2018). Down-sizing the global energy system dramatically improves the feasibility of a low-carbon supply-side transformation.

The scenario in this study meets the 1.5 °C climate target as well as many sustainable development goals, without relying on negative emission technologies (NETs). Over-reliance on NETs for carbon dioxide abatement in IAMs has been discussed in Pye et al., which noted that demand-side measures, such as those focusing on avoiding the need for travel and modal shift, were often overlooked, and that there was a prevailing overreliance on carbon dioxide removal technologies (Pye et al., 2021). According to the study, there is significant scope for improvements and models should incorporate techniques that improve the robustness of new strategies (i.e., increasing uptake of public transport and active modes, or remote working) that would align well with policy goals stated by policymakers. That said, a comparative study on Integrated Assessment Models noted that modal shift and demand reduction scenarios alone will only have limited emissions reductions, and the inclusion of such interventions would be with a view to complement improvements in technologies (Edelenbosch et al., 2017).

Another study, which used time travel budgets in Ireland and California to model modal shift scenarios within TIMES, an energy systems optimisation model, noted that developers of these models often impose constraints assuming this is manifested in exogenous projections of passenger kilometre demand for each mode individually. These methods overlook that energy demand in passenger transport is a derived demand for mobility, and not private car travel itself. It does not factor in the role of *why* we may or may not travel, or the role of *how* we travel, in simulating passenger transport futures (Daly et al., 2014).

Urban transport modal shift from a systems-wide perspective is also explored in a UK model for urban areas (Pye & Daly, 2015). It focused on mitigation options that go beyond the promotion of low emission technologies, focusing on time travel budgets as a method of calculating modal shift in the UK. This model expands the modes covered in the modelling sphere to include active modes, such as walking and cycling, so that increased rates of uptake can be projected in energy system models. Another UK study highlighted the importance of pursuing both demand and supply side solutions in the pursuit of emissions reduction and energy security (Anable et al., 2012). By expanding the modelling framework to include trip-purpose, occupancy rates, and multiple modes, the IPTEM model can provide a basis for emissions reduction calculations.

Shifting the focus away from IAMs and towards empirical case studies on modal shift and transport related CO_2 emissions, a previous study from 7 European cities highlighted the carbon-reducing impacts of city-based lifestyle changes (Brand, et al., 2021). It reveals that increases in active mobility significantly lower carbon footprints.

The above studies highlight the importance of the demand side reductions and modal shift in addressing our climate targets, and how it can support a low-carbon technology transition.

3.3.3. Irish Context

The growing share of transport emissions within Ireland's greenhouse gas emissions profile is a cause for concern.

Just as global transport policy planning has focused on car-centric solutions, Irish passenger transport research up until now has focused on technology switching in private vehicle transport, whether it is through switching to more efficient cars, alternative fuelled vehicles, or electric cars. An ex-ante study of the impact of a car tax introduced in 2008 showed that the car tax change would result in a reduction of 3.6 – 3.8% in CO_2 emissions intensity and a reduction in annual tax revenue of €191 million (Giblin & McNabola, 2009). Other ex-ante studies of the car tax change included a total life-cycle cost model (Hennessy & Tol, 2011). This ex-ante analysis anticipated that the cost of carbon dioxide emissions abatement per tonne would be "high, if not very high," and the ten-year ex-post analysis of the 2008 car tax outlined in Chapter 2 reported that the average cost of abatement over the period of 2008 to 2018 was between $€_{2018}$1,500 – 2,200 per tonne of CO_2. Another ex-post analysis of this same car tax, a one-year analysis of the 2008 car tax change, found that the average specific emissions intensity of new cars fell by 13% to 145 gCO_2/km in the first year of the policy (Rogan et al., 2011).

As well as the above-mentioned car tax studies, there are several Irish studies drawing on car stock modelling. For example, Daly et al. estimated future private car transport emissions from 2011 up to 2025. The study investigated the role of improved efficiency and biofuels in car energy consumption and carbon dioxide emissions. The bottom-up stock simulation asserted that private car emissions overall would increase due to increases in activity related energy demand (Daly and Ó Gallachóir, 2012a). The role of EVs in the low carbon passenger transport transition (Mulholland et al., 2016), and factors influencing EV uptake (Mukherjee & Ryan, 2020) have been examined. The role of energy efficiency, biofuel blending, and electric vehicle uptake rates were discussed in a report commissioned by the Environmental Protection Agency (Mulholland et al., 2014) . However, the report notes that the role of modal shift “has not been explored.” Further issues with a car-centric approach to sustainable transport solutions were identified in Dennehy et al. (Dennehy & Ó Gallachóir, 2018). The ex-post analysis highlighted the increasing new diesel car purchases and highlighted that activity is the biggest driver of transport energy consumption and emissions.

3.3.4. Irish Passenger Transport Emissions and Mobility Model

The above global and regional studies build an argument for an “Avoid-Shift-Improve” approach for emissions reduction strategies, as demand reduction management is key to countering increases in emissions due to increases in activity. The chapter is structured as follows; Section 3.4 covers the methods and data sources used to develop the IPTEM model, Section 3.5 covered the results, Section 3.6 covers the uncertainties, implications and use cases for the results, and Section 3.7 covers concluding remarks on the relevance and novelty of the IPTEM model.

3.4. Methods and Data

In response to the growing need for a comprehensive look at how and why we travel, this chapter develops the Irish Passenger Transport Emissions and Mobility (IPTEM) model.

The IPTEM model broadens the opportunity for passenger transport policy analysis. It provides a basis for looking at passenger transport demand and associated emissions from a trip purpose-based point of view and looking at why we travel.

The IPTEM model builds on and combines previous knowledge from the technology-rich Irish Car Stock Model (Daly and Ó Gallachóir, 2012a, O'Riordan, Mulholland, et al., 2021) and the National Travel Survey (Central Statistics Office, 2020). It is a model of mobility and modal choices in Ireland that provides an estimate of passenger transport demand, energy use and associated emissions. The analysis in this chapter provides a basis for trip purpose, demand reduction, and modal shift focused policy design and implementation. Reported fuel consumption and passenger data on bus, train, and cars provide the basis for the technical information used in the IPTEM model. This study aims to push beyond fuel switching and private vehicle transport improvements to investigate the role of modal shift and demand reduction measures in reducing Ireland's transport CO_2 emissions. The IPTEM model provides a novel structure with which to model passenger transport demand, developments in modal shift, and trip-purpose-based policy incentives for emission reduction scenario analysis. It determines why people travel, how they travel and how much they travel over the period of 2009 – 2019.

The IPTEM model includes information from the Irish Car Stock Model, the National Travel Survey and public transport provider's accounts. An overview of the IPTEM model and how the data sources relate to one another is shown in Figure 8.

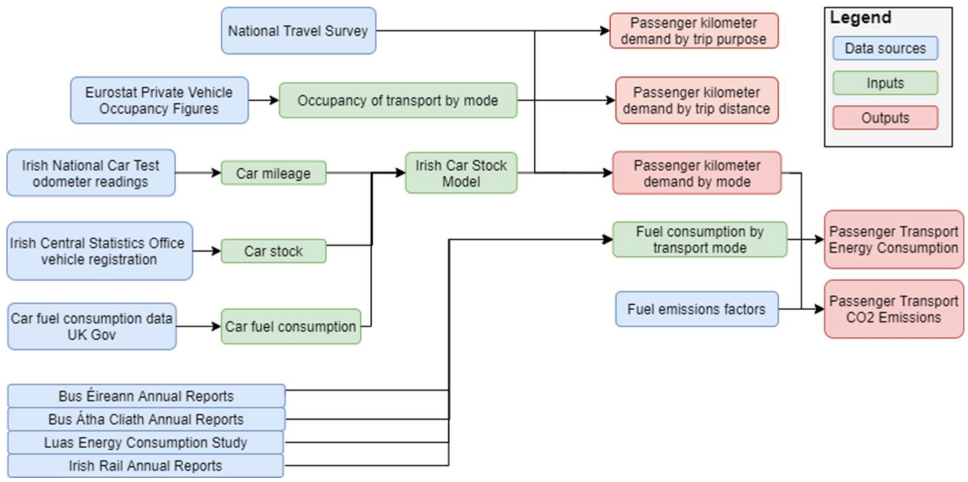

Figure 8: Overview of the Irish Passenger Transport Emissions and Mobility (IPTEM) Model

3.4.1. The Irish Car Stock Model

The Irish Car Stock Model as described in Daly and Ó Gallachóir develops a picture of private car energy demand in Ireland (H. Daly & Ó Gallachóir, 2011). The model used in this chapter is a technology stock simulation model, which relies on revealed preferences of car choice. This was selected over a cost optimisation model to estimate car choice, due to the unavailability and uncertainty associated with cost data on car private cars across various dealerships that is needed for a techno-economic optimisation model. The car stock and activity profile are disaggregated by car technology, engine class, fuel type and age (or car vintage) to produce a detailed look at private car activity and energy consumption over the period 2000 to 2008. The model has since been updated to include cars up to 2018. The model combines distance travelled, information on the fuel consumption performance with cars with the number of vehicle sales and survival rates of older cars in the Irish car stock. The

Irish Car Stock model is available on Zenodo (O'Riordan, Mulholland, et al., 2021). An overview of the Irish Car Stock Model is highlighted in Figure 9.

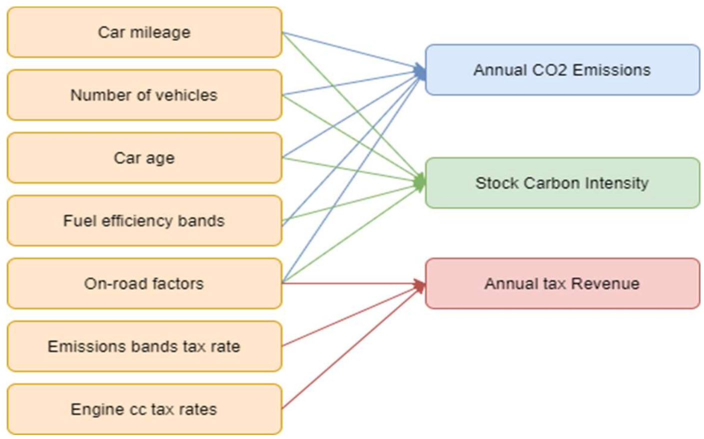

Figure 9: Overview of the Irish Car Stock Model

For the IPTEM Model, the total vehicle kilometres travelled by private cars is used. The total vehicle kilometres (Vkm) travelled by the private car fleet is calculated from the Irish Car Stock Model as described in Equation 5.

$$Vkm = Number\ of\ vehicles_{f,v,e} \times Average\ odometer\ reading\ (km)_{f,v,e} \quad (5)$$

where *f, v, e* represents the fuel type, vintage (age) of the vehicle and the engine cc of the vehicle, respectively. The results from the Irish Car Stock Model are highlighted in Data in Brief article included in Appendix B complimenting this chapter.

3.4.2. Public Transport modelling

Stock data on bus, train, and car energy consumptions and carbon dioxide emissions provide the basis for technical information for the IPTEM model and the opportunity to explore the underlying drivers of passenger transport demand in Ireland. The overall occupancy of public transport modes is also derived. This can be especially useful to determine the overall emissions intensity of modes of public transport. Public transport is not always more efficient than private car transport. If the occupancy of the private car in question is sufficiently high, or the occupancy of the public transport vehicle is sufficiently low, situations can arise where, on a per passenger kilometre basis, private car transport is more energy efficient and thus can have lower emissions per passenger kilometre assuming the fuel type across the modes is similar.

3.4.3. National Travel Survey

Responses from the 2009, 2012, 2013, 2014, 2016 and 2019 National Travel Survey were inputs to the IPTEM model's historical profile of passenger travel demand over the period of 2009 – 2019 (Central Statistics Office, 2020). Interpolation is used to supply estimates of passenger travel demand for the years that were not surveyed. Passenger kilometres for private vehicles were calculated by assuming the vehicle occupancy of private cars in Ireland was 1.5 persons. Studies for Ireland on private car occupancy are limited. The National Travel Survey from the United Kingdom determines an occupancy rate of 1.55 for England (UK Department for Transport, 2020), (European Environmental Agency, 2003). The occupancy rate of the most frequent car trips was recorded as 1.7 persons/car throughout the EU, ranging from a minimum of 1.4 in Denmark to 2.7 in Romania (Fiorello et al., 2016).

3.4.4. Passenger kilometres by Trip Distance

The passenger kilometres (Pkm) are calculated as shown in Equation 6.

$$Pkm = Vkm \times Occupancy \qquad (6)$$

Trip distance categories from the National Travel Survey were as follows:

- <2km
- 2 - 4km
- 4 - 6km
- 6 - 8km
- >8km

The average of each of the ranges is applied to the calculations for passenger kilometre demand. The figure for passenger kilometres for the >8-kilometre category was calculated through calibration with the Irish Car Stock Model, this was done by aligning the vehicle kilometres by car from the Irish Car Stock Model with the vehicle kilometres. The vehicle kilometres from the Irish Car Stock Model were then multiplied by an assumed occupancy rate of 1.5 people per vehicle to get passenger kilometres per car. The calculated passenger kilometres for the other categories were then subtracted from the total passenger kilometres to get the passenger kilometres for the >8km category.

The total number of journeys taken each year is calculated by extrapolating the number of daily journeys taken as stated by the respondents in the National Travel Survey across the entire Irish population for the year.

3.4.5. Passenger Kilometres by Mode Type

Passenger kilometres were calculated for the following modes of transport as specified in the National Travel Survey. The modes of transport are defined as follows (Table 5):

Table 5: Overview of transport modes

Mode	Description
Private Car – Driver	People travelling in a car as the main driver
Private Car – Passenger	People travelling in a car driven by another person
Walk	People walking, this is also categorized as an "active mode" of transport.
Bus	People taking the bus, there are two main bus transit providers in Ireland, Dublin Bus, which operates urban driving style city routes in Dublin, Ireland, and Bus Éireann, which provides a mix of urban and intercity driving. Private bus transport is assumed to be negligible.

Cycle	Includes the use of both mechanical bikes and e-bikes for cycling and is also categorized as an "active mode" of transport.
Rail/DART/Luas	This mode choice refers to the three rail providers in Ireland; Irish Rail - which operates long distance rail in Ireland, DART- the Dublin Area Rapid Transit, a commuter rail operating in the Greater Dublin area and Luas - a city light rail which operates in Dublin
Taxi/hackney	People travelling in a car operated by a registered taxi driver
Lorry/Motorcycle/Other	This mode includes lorries, motorcycles and any other mode choice not included in the preceding categories

A shortcoming of the distance categories is that it fails to account for mode types that typically service distances on the shorter end of the distance grouping. For example, cycling in the 4 – 6 km category is more likely to service journeys under 5km as the average journey distance for cycling trips is 3.5 km. To overcome this, weighting factors based on mode are calculated by applying the recorded average distance travelled by that mode and weighting this factor with respect to the "Private car – driver" mode as shown in Equation 7. Weighting factors account for the average distance for a given mode type being longer or shorter on average relative to private car – driver mode of transport.

$$Weighting\ factor_{mode,year} = \frac{Average\ distance\ of\ all\ journeys_{mode,year}}{Average\ distance\ for\ private\ car - driver_{year}} \quad (7)$$

The distribution of journeys by distance is recorded by the National Travel Survey over the period of 2009 – 2019. Total passenger kilometres for a given mode type and distance category is calculated by combining the percentage distribution of journey distance for all regions, weighting factors from Equation 7, the percentage of journeys by mode and distance category, and average distance by kilometre grouping for each mode type, extrapolating across the Irish population for the year. Weighting factors calculated by Equation 7 are included in Appendix B.

3.4.6. Passenger kilometres by trip purpose

Passenger kilometres by trip purpose were calculated by combining the percentage distribution of journey distances with the distribution of journeys by mode of travel and distance, extrapolating across the Irish population for the given survey year. The following trip purposes are covered in this study:

- Work
- Education
- Shopping
- To eat or drink
- Other
- Entertainment/Leisure/Sports
- Personal Business
- Companion/Escort Journey
- Visit family/friends

Weighting factors based on trip purpose are applied to adjust the average distance calculated to reflect the average journey lengths given for a given trip purpose. These weighting factors are based on the trip purpose and build on the weighting factors calculated by Equation 7 based on the mode type. As the average distance based on trip purpose is only calculated from the 2009 National Travel Survey, these figures are used for all journeys up to 2019. This is a data gap, and it is explored further in the uncertainty analysis.

3.4.7. Passenger Kilometres Serviced by Public Transport

Passenger kilometres, occupancy figures, energy, and carbon intensity per passenger kilometre serviced are determined for the following public transit providers in Ireland.

1. Bus Éireann – The intercity and nation-wide bus service in Ireland, and urban buses in Ireland's smaller cities
2. Dublin Bus – The urban bus service operating in Ireland's largest city, Dublin.
3. Irish Rail/DART – The heavy rail cross-country and commuter rail service operating in Ireland.
4. Luas – The light rail service in Dublin

There are two primary bus service providers in Ireland, Bus Éireann and Dublin Bus. Contributions from private bus travel is considered negligible. The respective share of passenger kilometres serviced by Dublin Bus and Bus Éireann are calculated as highlighted in Equation 8.

$$Share\ of\ Bus\ Pkm_{bus\ provider} = \frac{No.\ of\ Passengers_{bus\ provider} \times Vkm_{bus\ provider}}{\sum_{i=1}^{n} No.\ of\ Passengers \times Vkm} \quad (8)$$

Occupancy for the bus transport providers is derived from the passenger kilometres and vehicle kilometres, as illustrated earlier in Equation 6.

Vehicle kilometres for the bus service providers are given in the Dublin Bus (Dublin Bus, 2021) and Bus Éireann Annual Reports (Bus Éireann, 2021).

Estimates for passenger kilometres serviced by Irish Rail are calculated based on the passenger kilometres from journeys from Rail/DART/Luas. There are two primary rail service providers in Ireland, Irish Rail and Luas. The respective share of passenger kilometres serviced by Irish Rail and Luas are calculated as highlighted in Equation 9.

$$Share\ of\ Rail\ Pkm_{rail\ provider} = \frac{Passengers\ serviced_{rail\ provider} \times Vkm_{rail\ provider}}{Passenger\ serviced \times Vkm} \quad (9)$$

Occupancy is calculated in the same method as described for bus travel in Equation 6. Vehicle kilometres for the rail service providers are given in the Irish Rail (heavy rail) (Irish Rail, 2021) and Luas (light rail) Annual Reports (National Transport Authority, 2021).

Capacity rates of public transport are defined as the realised occupancy of public transport modes with respect to the maximum possible occupancy of the transport mode. The maximum possible occupancy is equivocated to the total seat vehicle kilometres as defined by the National Transport Authority in their reporting. Capacity factors are defined as described in Equation 10.

$$Capacity\ Factor = \frac{Total\ Vehicle\ Kilometres}{Vehicle\ Seat\ Kilometres} \times 100 \quad (10)$$

3.4.8. Energy Intensity and Carbon Intensity of Transport Modes

The energy intensity of each mode type per passenger kilometre (Pkm) was calculated as follows in Equation 11:

$$\text{Energy Intensity}\left(\frac{\text{kWh}}{\text{pkm}}\right) = \frac{Energy\ intensity\ per\ kW_{\ f,t} \times Energy\ consumption\ per\ year_{f,t}}{Pkm_t} \quad (11)$$

where *f* is the fuel type, and *t* represents the transit provider.

The carbon intensity of each mode type per passenger kilometre (Pkm) was then calculated as follows in Equation 12:

$$\text{Carbon Intensity}\left(\frac{\text{gCO2}}{\text{pkm}}\right) = \frac{Carbon\ intensity\ per\ kWh_{f,t} \times Energy\ consumption\ per\ year_{f,t}}{Pkm_t} \quad (12)$$

where *f* is the fuel type, and *t* represents the transit provider.

The carbon intensities of the energy sources are provided by the Sustainable Energy Authority of Ireland (Sustainable Energy Authority of Ireland, 2020).

Private vehicle carbon and energy intensity was calculated based on outputs from the Irish Car Stock Model (O'Riordan, Mulholland, et al., 2021). The model was updated to include figures up to 2019. The carbon and energy intensities of private vehicles are included to provide a comparison with public transit providers. The carbon intensity of electric vehicles is based on the electricity consumption of the Nissan Leaf, one of the most popular electric vehicle brands currently sold in Ireland (Green NCAP, 2019).

The proportion of passenger kilometres serviced by public transit to passenger transit has remained relatively stable over the period 2009 – 2019. The magnitude of passenger kilometres serviced by public transit decreased over the period of 2010 – 2012 due to the recession effect, which has been explored in (Whyte, Daly, & Ó Gallachóir, 2013), (Dineen et al., 2018).

3.5. Results

3.5.1. Passenger Kilometres by Trip Distance, Mode Type and Trip Purpose

Passenger kilometres by trip distance, mode type and trip purpose are shown in Figure 10. The private car is the mode type that services the greatest quantity of passenger kilometres, followed by the lorry/motorcycle/other choice group, rail transport, bus transport, cycling, and walking.

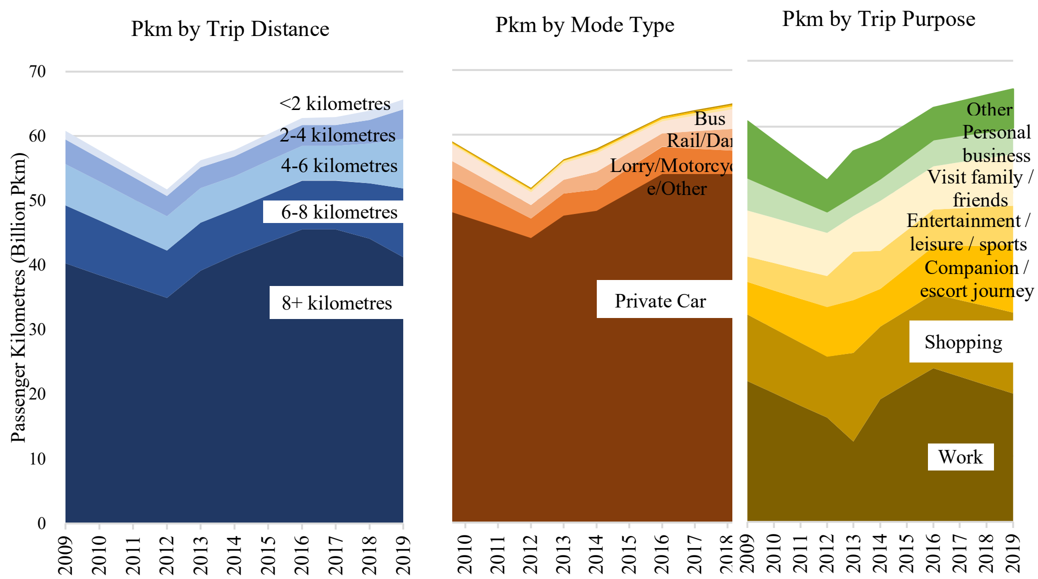

Figure 10: Passenger Kilometres by trip distance, mode type and trip purpose

Tabulated data can be found in the Data in Brief complementing this chapter (Appendix B; O'Riordan, Vera, Rogan, F., Uidhir, T. Mac, Ó Gallachóir, B., & Daly, H. 2022c), and calculations are available from the open-source repository of the IPTEM model on Zenodo (O'Riordan,et al,. 2022c). In 2019, travel for work purposes contributes the greatest to overall passenger transport demand (30% of all passenger kilometres) followed by shopping (19%) and companion journeys (16%).

3.5.2. Occupancy, Energy Consumption and Carbon Intensity of Passenger Transport

The average occupancy of each of the public transport mode types is highlighted in Table 6. The capacity of public transport modes in Ireland is derived from the seat vehicle kilometres divided by the total vehicle kilometres, as outline by Equation 10 in the Methods section.

Table 6: Average occupancy of public transport providers (people)

Transport Provider	2010	2011	2012	2013	2014	2015	2016	2017	2018
Dublin Bus (Urban Bus)	27	21	21	27	31	31	20	20	34
Bus Éireann (Intercity Bus)	7	5	5	7	8	8	5	5	9
Irish Rail (Long distance rail)	153	146	145	146	144	144	147	153	140
Luas (Light rail)	110	114	116	121	124	125	117	126	122

The capacity factors are summarized in Figure 11. The capacity factor for private cars is based on a 1.5 persons occupancy for a typical 5-seater car from information gathered from Eurostat (Eurostat, 2021a) and is included for illustrative purposes.

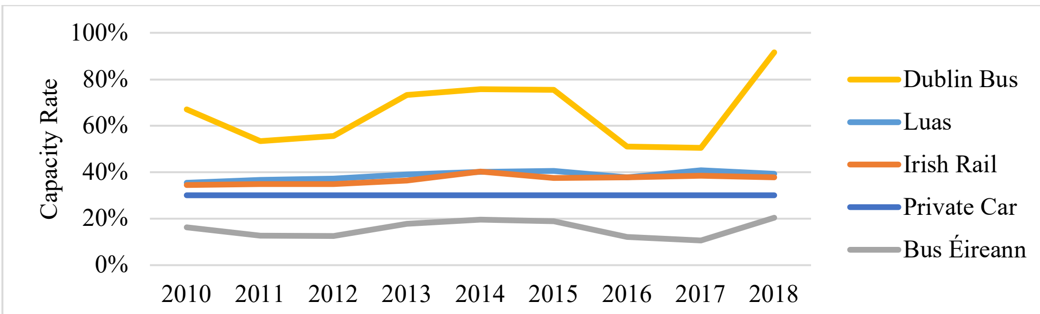

Figure 11: Capacity rates by transport mode

Energy consumption figures for 2019 are not yet available from public transport providers as of writing. For 2019 it is assumed energy consumption figures are equal to 2018 energy consumption figures. Carbon intensity by transport mode is calculated from the energy intensity by transport mode and applying carbon content factors specific to each fuel type as defined by the Sustainable Energy Authority of Ireland (Sustainable Energy Authority of Ireland, 2020). As mode shares by trip purpose are not specified in the National Travel Survey, specific carbon intensity by trip purpose is not disaggregated, calculations for emissions by trip purpose are based on overall mode shares for the given year and on passenger kilometre demand.

3.5.3. Total Emissions

The emissions intensity per passenger kilometres and total passenger kilometres recorded from the National Travel survey create a profile of emissions from transport over the past 10 years from all modes of transport in Ireland. The results of which are highlighted in Figure 12.

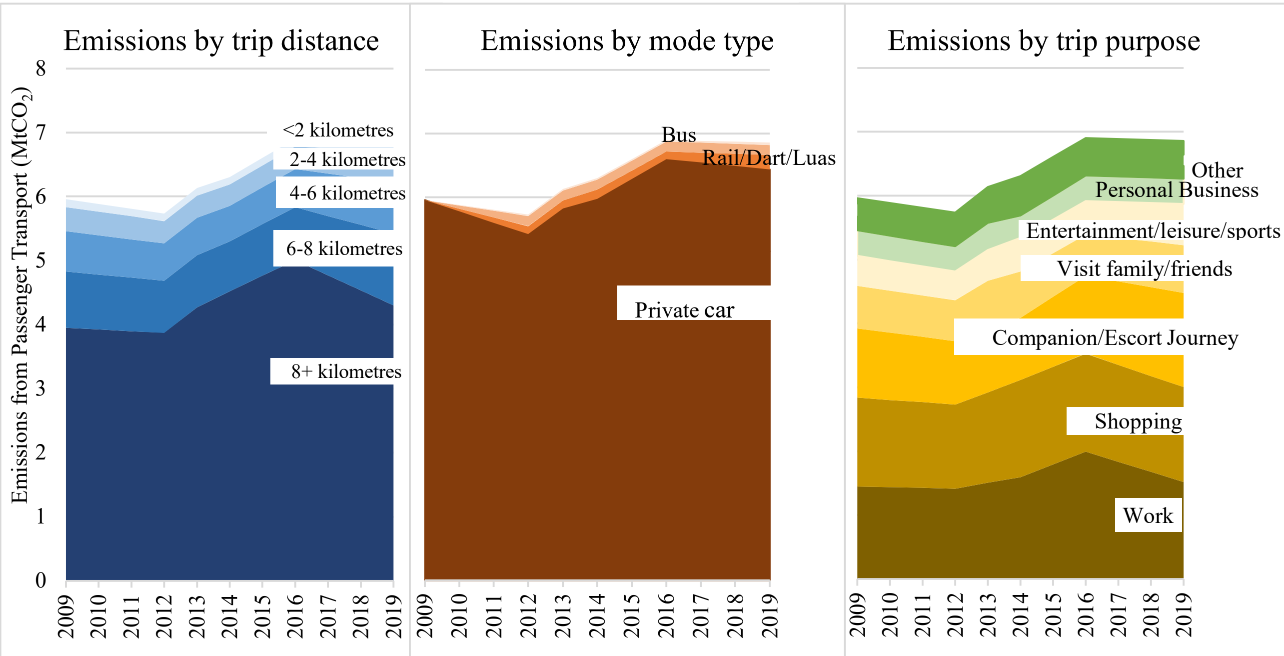

Figure 12: Carbon Dioxide Emissions from Passenger Transport by trip distance, mode type and trip purpose

Emissions intensity by mode type and trip purpose category is shown in Figure 13. This provides an insight into the grams of carbon dioxide (gCO_2) per passenger kilometre (pkm) serviced over the period of 2009 – 2019.

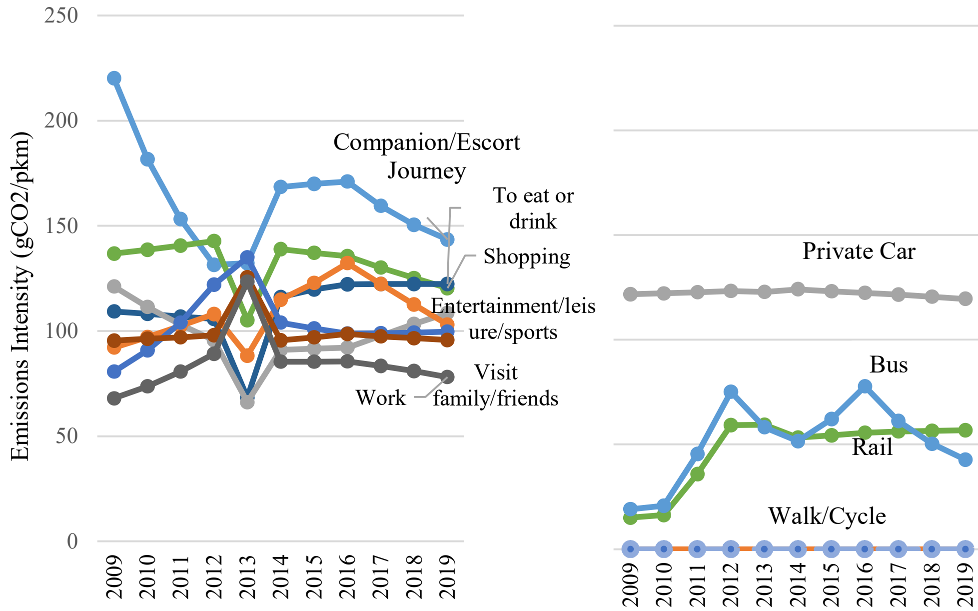

Figure 13: Emissions Intensity by trip purpose and mode type (gCO₂/pkm)

Emissions intensity by trip purpose notes that trips for companion/escort journeys are among the highest. While emissions by mode type are lower on average, higher occupancies skew on a trip-purpose basis. Walking and cycling passenger kilometres account for less than 1% of passenger kilometres (Figure 13), and the use of private car transport is widespread. Occupancy rates for companion/escort journeys may also be lower.

A breakdown of trip purpose and mode type from total passenger kilometres is shown in Figure 14 based on values from 2019.

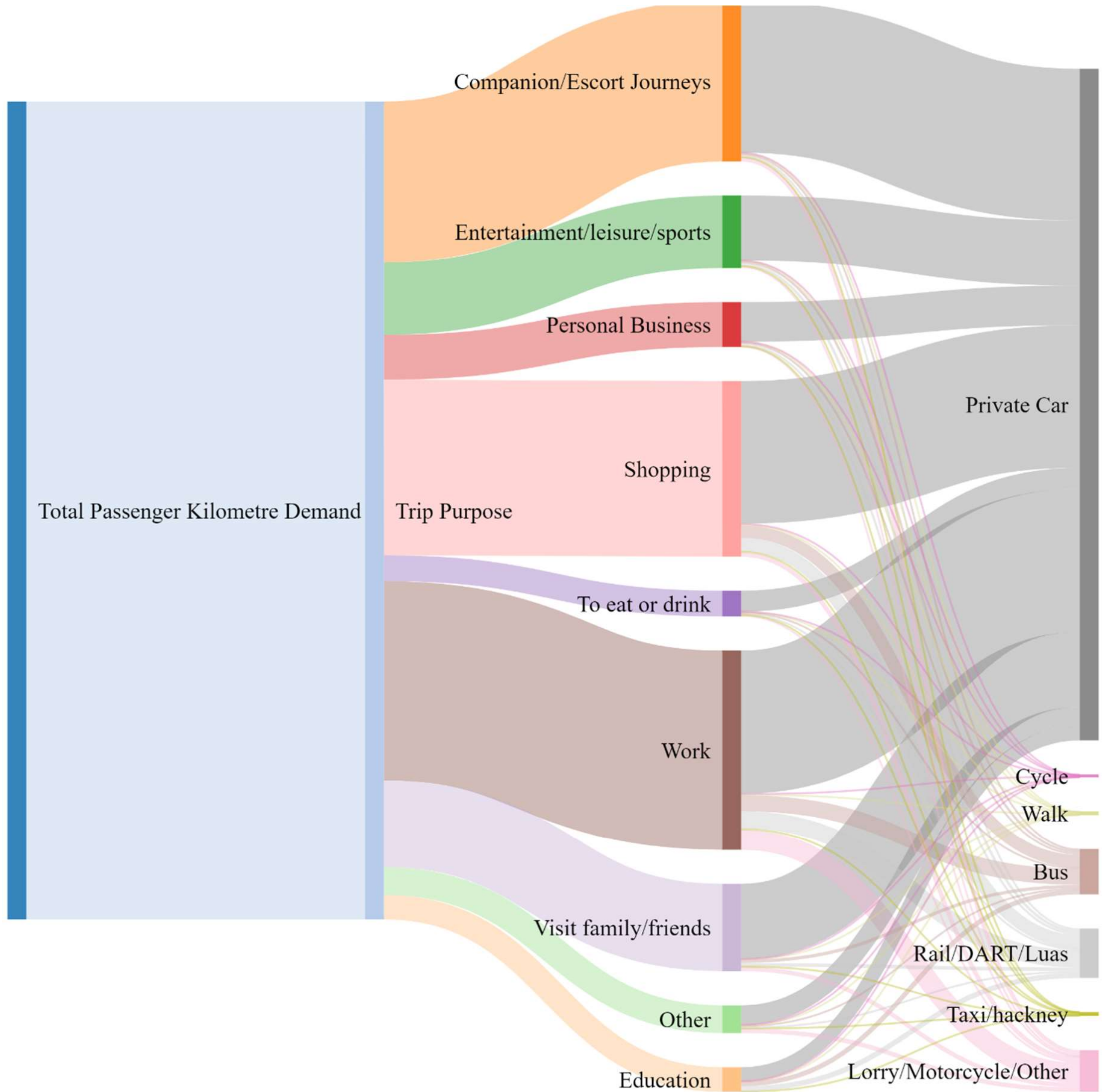

Figure 14: Breakdown of Passenger Kilometre trip purpose and mode type for 2019

A comparison of passenger kilometre demand and emissions for 2012 with 2019 is made by trip distance, trip purpose and mode type to highlight the changes in passenger kilometre demand (Table 5), and passenger transport emissions (Table 6) to highlight the kinds of insights and comparisons on passenger transport behaviour that can be derived from the IPTEM model. In Table 7, the relative shares of passenger kilometres for the given year with respect to another reference year (2012) are highlighted. This helps identify growth areas in passenger transport demand and emissions even if overall emissions are lower. Such is the case for 2012, as overall passenger kilometre demand is lower, however there are reductions in 2019 in the relative share of some journey types and Table 7 illustrates this.

Table 7: Comparison of passenger kilometre demand in 2019 with 2012 by mode type, trip purpose and trip distance

Comparison of passenger kilometre demand in 2019 to 2012 (%)	**Bus**	**Cycle**	**Private Car**	**Rail/Dart/Luas**	**Walk**	**Total**
Companion/Escort Journey	186	146	25	216	340	**55**
Education	44	-40	24	59	6	**-9**
Entertainment/leisure/sports	26	-29	29	39	27	**48**
Other	-39	45	23	-33	159	**-5**
Personal Business	-24	40	63	-16	150	**5**
Shopping	151	45	-7	178	158	**23**
To eat or drink	196	119	330	227	291	**187**
Visit family/friends	17	49	44	29	167	**22**
Work	109	64	87	131	193	**19**
Total	**70**	**38**	**-2**	**88**	**147**	**28**

Table 8: Comparison of passenger transport emissions in 2019 with 2012 by mode type, trip purpose and trip distance

Comparison of passenger transport emissions in 2019 to 2012	**Bus**	**Private Car**	**Rail/DART/Luas**	**Taxi/hackney**	**Total**
	%				
Companion/Escort Journey	62	48	203	145	**49**
Education	-19	-31	52	23	**-23**
Entertainment/leisure/sports	-29	46	33	8	**43**
Other	-66	-1	-36	-48	**-8**
Personal Business	-57	4	-20	-35	**1**
Shopping	43	8	166	115	**12**
To eat or drink	68	175	213	153	**172**
Visit family/friends	-34	18	23	0	**17**
Work	19	4	122	79	**8**
Total	**-3**	**19**	**80**	**46**	**20**

Table 8 illustrates a growth in travel for eating and drinking in passenger transport demand (+187%) and emissions (+172%), indicating a behavioural change with people eating out more, and this resulting in a greater transport demand and associated emissions. Growth in using rail, the DART or the Luas to travel can also be seen by 2019 (+88% overall) for all reasons of travel except for personal business and “other”. The relative share of private car emissions for education purposes as a driver has shrunk (-31%), indicating that adults travelling to education choose to do so by other modes of transport. The emissions from rail for education travel in 2019 compared to 2019, has increased (+52%), but emissions from the bus for education purposes has decreased (-19%), despite passenger kilometres travelled by bus increasing (+44%, Table 7). This indicates an increase in efficiency from bus transport. Figure 11 shows that the capacity rate of bus transport has increased from 2012 to 2019, which contributed to the overall efficiency increase in passenger transport. Overall, the passenger transport emissions in 2019 have increased for all mechanized modes of transport except for buses, which have reduced in emissions intensity per passenger kilometre serviced. Passenger kilometre demand across all mode types has increased, however, total emissions from bus transport has decreased (-3%) indicating a decoupling of passenger kilometre demand growth and emissions growth for bus transport.

3.6. Discussion

3.6.1. Uncertainty

Slight discrepancies occur due to the percentages not adding up to 100% for responses from the National Travel Survey. The National Travel Survey gathers data through travel diaries distributed to people living in the Republic of Ireland. In 2019, the statistical size was 3,690 people The reference population is all individuals living in private households in Ireland. All usual residents of the household are included. These survey results are then extrapolated by different demographic characteristics as per the Irish Census to capture a representative view of what aggregate values may be over entire regions. More information on the methods used in data collection for the National Travel Survey can be found on the Central Statistics Office website (Central Statistics Office, 2020). Interpolation of the unsurveyed years – 2010, 2011, 2014, 2015, 2017, and 2018, was required to compensate for the lack of survey data for those years. In addition, the National Travel Survey also only surveys adults in Ireland, and travel behaviours of children are not captured in the results.

The Irish Car Stock Model relies on external data sources from the National Car Testing Centre odometer readings which only record the mileage of cars greater than four years old. More information on the limitations and uncertainties in the Irish Car Stock model, which is used to calibrate the car passenger kilometres in the IPTEM model is discussed in Daly et al. (Daly and Ó Gallachóir, 2012), and Dennehy et al. (Dennehy & Ó Gallachóir, 2018).Occupancy rates for bus and rail transport are based on a combination of vehicle kilometres from the transport provider and the total passengers that pay a fee to board the public transport vehicle. A passenger is counted as a whole journey passenger despite some passengers only travelling a section of the journey route from which vehicle kilometres are calculated. This leads to an overestimation of occupancy and passenger kilometre figures as a passenger is considered an occupant even if their journey only forms part of the route. Figures underpinning the proportion of the journey route which occupants are "on-board" are not readily available and would enhance the accuracy o1f the calculations of occupancy and passenger kilometres on public transport.

There is a lack of empirical survey data on occupancy rates from private cars in Ireland. Observational surveys on private vehicle occupancies in Ireland is an area suitable for further study. The estimates are based on information gathered from Eurostat (Eurostat, 2021a). Future National Travel Surveys could include a question asking about the occupancy of private vehicle journeys to fill this gap. For example, the United Kingdom record the occupancy rates in private car transport for a given trip purpose.

The weighting factors used to calculate passenger kilometre demand are discussed in Section 3.4. For the calculation of passenger kilometres by trip purpose, there are only weighting factors from the 2009 National Travel Survey as information on average passenger kilometres by trip purpose is not openly available for subsequent years. These figures are applied to all years up to 2019 and are an example of a source of uncertainty in the model. The weighting factors by mode type and trip purpose are combined when calculating passenger kilometres from a given mode type and trip purpose.

Bus transport passenger numbers are not disaggregated by public and private bus transport. Private bus transport is included under the Bus Éireann or Dublin Bus sector, and future research can improve the resolution in this part of the model subject to better data. Commercial bus transport providers are a significant source of public transport vehicle kilometres in Ireland, with over 80 million vehicle kilometres being serviced by commercial bus in 2018 (National Transport Authority, 2019). Due to a lack of energy consumption and occupancy data for commercial bus operators, 100% of bus passenger kilometres is prescribed to either Bus Éireann or Dublin Bus. This is an overestimation of the prominence of both Bus Éireann and Dublin Bus in servicing passenger kilometre demand for bus transport. Future improvements to the model could involve obtaining occupancy and energy consumption figures from private bus/coach transport providers and include them in the IPTEM model. For private cars, disaggregated investigations into the technology types that make up the aggregated emissions intensity for car transport, greater detail on the fuel types of car transport in Ireland is explored within the Irish Car Stock Model (Daly & Ó Gallachóir, 2011; O'Riordan, Mulholland, et al., 2021).

3.6.2. Key Insights

This chapter calculates for the first time, passenger transport demand and carbon dioxide emissions by mode type, trip purpose and trip distance for Ireland. The novel IPTEM model combines energy consumption data with surveyed travel responses to construct a model of Irish passenger transport emissions over the past decade. Our findings build on the Irish Car Stock Model, and broadens the spectrum to include walking, cycling, bus, and rail transport technology options and disaggregates by trip purpose and trip distance. Passenger kilometres for passenger transport can be incorporated into energy systems models such as the LEAP Ireland 2050 model (Mac Uidhir et al., 2020c), and TIMES Ireland model (Balyk et al., 2021). Historical data on public transport and active modes of travel alongside understanding passenger kilometres is key to modelling the emissions reduction impacts of modal shift and passenger transport demand reduction.

Understanding the proportion of passenger transport demand met by sustainable modes of transport such as public transport and cycling, enables policy makers to set future targets and to track progress towards meeting targets. For example, in 2009, the Department of Transport issued a transport policy document entitled “Smarter Travel” which issued targets of 10% of journeys being completed by walking and cycling by 2020 (Department of Transport, 2009). While the IPTEM model emphasises share of passenger kilometres over the share of journeys, the IPTEM model does show that the proportion of cycling and walking passenger kilometres accounted for only 1% of all passenger kilometres.

The IPTEM model also enables international comparisons on cycling and public transport usage to be made. For example, in Ireland, ~1% of passenger kilometre demand is met by cycling, whereas in the Netherlands, 10% of passenger kilometre demand is met by cycling (Harms & Kansen, 2018). Public transport only accounts for 12% of all motorized passenger kilometres travelled in Ireland. International comparisons show both similar and much improved rates of public transport uptake when compared to Ireland. In the UK, public transport accounts for 17% of all motorized passenger kilometres travelled (Department for Transport, 2019). However, the UK also benefits from the economies of scale of having a larger share of public land and increased population density. This improves the feasibility of public transportation between and within its larger urban centres. Geographical comparisons between smaller island states in Europe such as Malta and Iceland can also been drawn. In Malta, public transport is less developed, with private car transport servicing 82% of passenger mode share (European Commission, n.d.). Calculations of passenger kilometres by mode type from Malta are not available for comparison. Another European Island state, Iceland, car ownership rates are high compared to Ireland, and bus is the only public transportation option, as opposed to Ireland's intercity and nationwide rail options. 86.4% of all passenger kilometre demand is met by cars, compared to Ireland's 81% as calculated from Eurostat (Eurostat, 2021a). Population settlement patterns in Ireland are dispersed and low density, a reason often cited for how difficult the transport transition will be for Ireland. Teasing out the implications of this, and any insights that IPTEM can provide could be useful additional discussion alongside the above-mentioned international comparisons.

The passenger transport demand (Figure 10) and emissions (Figure 12) are also quantified. Travel for work, companion/escort journeys and shopping were the top three sources of passenger transport demand in Ireland over the period of 2009 – 2019.

Work travel is responsible for the lowest emissions per passenger kilometre. Shopping journeys have twice as high an emissions per passenger kilometre – this could lead to developing emphasis or targeted policies focusing on certain trip journey types. Issues around carrying shopping and heavy goods raises the relevance of strategies such as cargo bikes and electrified delivery services to reduce the emissions intensity of shopping trips. Due to commuting trips needing less equipment to be carried and the often regularly scheduled pattern of commuting trips, switching to modes with lower emissions such as scheduled public transport or walking and cycling may be more widespread.

Companion/escort journeys cover journeys where the traveller is accompanying another person, and indicates journeys that may require supervision, such as those with young children, night-time journeys or journeys with people that have additional needs. It also could indicate car sharing, which is a potential energy efficiency measure to reduce additional passenger kilometres from individual car passenger kilometres and increase car occupancy. This indicates a demand for supervised, safe journeys and demand for companion/escort journeys could be reduced through the provision of transport modes that are safer, more accessible and supervised i.e., school buses, well-lit and public pedestrian and cycling routes, disability accessible public transport. It also may be an indicator of car sharing. Calculating the passenger kilometres that serve a particular purpose can provide a starting point for researchers to investigate the role of new social phenomena on future transport demands. Online shopping and remote working scenarios could be investigated using the data provided for passenger kilometres based on trip purpose from Figure 10.

Capacity rates are also quantified. Figure 11, which gives insights into the capacity rates of different modes of public transport, highlighted that it was the intercity buses (Bus Éireann) that had the lowest capacity over the observed period of 2009 – 2018, reaching a maximum of 22% in 2018. There are many reasons for this, many of which are currently poorly understood. The early results presented here indicate that better route planning and scheduling may be required for the routes serviced, to optimize capacity rates and uptake of the transport mode.

Total emissions by trip mode type, purpose, and distance category in Figure 12 provide helpful insights into what potential savings focusing on targeted categories can bring. For example, journeys under 8 kilometres are responsible for 37% of passenger transport related CO_2 emissions in 2019. Observations on emissions by trip distance can be particularly helpful in quantifying the possible returns of targeted low carbon policy packages focusing on trips of certain lengths.

Observations on the properties of different public transportation types are also evident. For example, from Figure 6, the emissions intensity per passenger kilometre from bus transport reduced below that of rail transport in 2019. From Figure 11, the capacity rate of Dublin Bus (city bus) increased simultaneously, while the capacity rate of rail transport over the period of 2009 – 2019 remained around 35%. The results of this chapter can usefully inform research on what public transport people use and where the opportunities for increased capacity lie. Initial findings from this chapter point to the capacity rates having a significant bearing on the respective environmental performance indicators of public transport. It is important to know the difference between vehicle kilometres and passenger kilometres when understanding how efficient a passenger transport mode is. Occupancy matters, as does fuel consumption.

The prevalence of car transport in 2019 can be seen in Figure 14, where private car transport is responsible for greater than four out of five passenger kilometres travelled by people in Ireland. The interlinkages between passenger kilometre demand by trip purpose and mode type are made visible, and the key characteristics of passenger transport demand in Ireland are quantified. Private car transport and travel for work, shopping, companion/escort journeys, and leisure journeys were among the most popular characteristics of passenger transport demand.

From Table 7, growing and declining areas in passenger transport demand can be identified on a national basis using the IPTEM model, and this can be useful for projecting future passenger transport demands by mode type, trip purpose and trip distance. Growing areas of emissions are identified in Table 8, and as efforts to reduce transport related CO_2 emissions continues, detailed monitoring of the reasons driving transport emissions and the profiles of journeys can help with policy planning by trip purpose, and trip distance tailored transitions from more polluting modes of transport such as fossil fuel cars of low occupancy, to more efficient ones (i.e. light rail, cycling and walking). It is important to note that Table 7 and Table 8 are developed with a reference to the 2012 year, and thus develop narratives with respect to the year 2012. For example, while Table 7 indicates an increase in passenger kilometres serviced by cycling (+38%) relative to 2012, cycling rates in 2019 were well below rates evident in the 1980's. This can be revealed when observing historical records on transport behaviour from the Central Statistics Office (Central Statistics Office, 2017a).

Emissions data from public transport providers and the Irish Car Stock Model allow for the calculation of passenger transport carbon dioxide emissions based on the passenger demand. The energy intensities and carbon intensities calculated are helpful in developing future projections for emissions from passenger transport in Ireland. Understanding energy intensity of fossil fuel transport is helpful to calculate the role of sustainable energy policy interventions such as biofuels in public transport and electrification of public transport. Historical snapshots of emissions from all modes of transport can be useful in developing modal-shift scenarios for future emissions and mobility models. The outputs from the IPTEM model could be used as inputs in energy system models. The purpose of the IPTEM Model is to improve the modelling landscape for the analysis of the carbon dioxide emission savings through modal shift and demand reduction in Ireland. As mentioned in the literature review, there is a pressing need for regionalized data and holistic representations of the causes of travel and the modes of travel chosen. I have developed an online repository for the IPTEM Model, which modelers can access, and use for their own transportation research purposes.

The limitations of the IPTEM Model were discussed in detail in Section 3.6.1, Uncertainty.

For future estimations of passenger kilometres, methods of combining passenger kilometre estimates with restriction occupancy guidelines for the period and traffic counter data combined with mobility data from network providers can provide insights for adjusting passenger kilometre demand for the 2020 – 2021 period [Appendix B]. Public transport usage is determined by a wide range of factors including socioeconomics, attitudes, social practices and combining passenger kilometre demand with trip purpose provides a useful mechanism for examining the role of purpose-based policy interventions on passenger transport demand and emissions. More in depth future work, focusing on a decomposition analysis on the changing contributions of occupancy, modal share, trip distance, trip purpose and fuel type is now possible with the information provided from the IPTEM model. Future work integrating observations on urban/rural shares could also guide the possibility of segregated policy packages based on spatial characteristics of densities, as public transport, and modal shift to walking and cycling has a greater feasibility in dense urban populations than rural ones, for example. This information is not available publicly from the Central Statistics office, with spatial information defined on a "Dublin" versus "Rest of Country" basis, as opposed an "Urban" versus "Rural" basis.

3.7. Conclusion

This study introduces the IPTEM model, which provides an estimate for total passenger kilometres across the entire country each year. The total passenger kilometre demand was between 50 – 65 billion passenger kilometres over the period of 2009 to 2019.

Work, shopping, and companion journeys are the primary reasons for passenger travel in Ireland. The IPTEM model provides a data basis to perform trip purpose-based demand reduction calculations which can help inform purpose-based policy incentives. Remote working schemes and school bus programs are just two examples of such policies that would draw on data from the IPTEM model to perform transport demand-based emissions reduction calculations.

Understanding the extent of active modes of travel such as walking and cycling in Ireland is important to provide greater context to sustainable transport targets that have been set and will be set by the Irish Government. Low uptake rates of active modes of travel in an Irish context is a persistent trend, and the data in the IPTEM model highlights this.

The IPTEM model calculates the total passenger kilometre demand by trip mode, trip purpose and trip distance. The IPTEM model helps modelers improve their representations of multiple modes of transport and purpose-based policy scenarios in energy systems models. The IPTEM model also provides a research base from which to set policy targets from and help policy makers understand the current passenger transport landscape in Ireland. As the Irish Government continues with their Climate Action Plan, which includes a multitude of transport related targets, there is a growing need for a research informed basis for sustainable transport targets that go beyond private car efficiency and fuel switching and for a systematic way of tracking progress for model shift to public transport and active modes of travel, which are lower in carbon intensity per passenger kilometre served when compared even to electric vehicles. The IPTEM model provides a basis for this analysis.

Further study on the occupancy rates and the reasons behind companion journeys would assist with purpose-based passenger kilometre estimates and with calculations. Future work incorporating the information from the IPTEM model could investigate the underlying drivers of passenger transport demand over the past 10 years and develop projections for future passenger transport demand by trip purpose, distance, and mode type. This would enable modelers to build more accurate pictures of future mobility and allow policy makers to broaden their horizons in developing low carbon, low demand transport policy that centres on what causes us to travel in the first place: to work, to shop, to eat, to learn, to have fun, and to visit loved ones.

Chapter 4. Avoid-Shift-Improve: Bottom-up simulation modelling of national policies for transport carbon budgets[4]

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4.1. Abstract

This chapter develops and applies a novel multi-mode and trip-purpose simulation-based model to analyse future transport policy and climate planning. This study models and quantifies the impact of avoiding and reducing demand for travel alongside policy measures drawn directly from national and regional low-carbon transition plans. A "business-as-usual" Reference scenario and an "Avoid-Shift-Improve" scenario based on national climate action plans is developed for Ireland using the Irish Passenger Transport Emissions and Mobility (IPTEM) and the LEAP Ireland ASI (Avoid-Shift-Improve) model. Several policy measures based on the Avoid-Shift-Improve Framework (such as reduced vehicle kilometre demand, working from home, more cycling, and increased public transport, increased electrification) highlight the impact of modal shift and demand reduction interventions on a country's transport CO_2 emissions profile. The results show how a combination of policies lead to cumulative emissions reductions over

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Carbon Budget 2 (2026 – 30) which results in net emission of 35 $MtCO_2$eq. from the transport sector over the period; 2 $MtCO_2$eq. lower than the legally required transport carbon budget for that period. The scale of the role of “Avoid”, “Shift”, and “Improve” measures for transport is assessed both individually and collectively. "Avoid" and "Improve" measures account for a greater share of emissions reductions than modal "Shift" measures. Private vehicle electrification and demand reduction targets have the greatest impact. The contribution of passenger transport measures outweighs freight transport measures.

4.2. Highlights

- Simulation methodology presented to model the Avoid-Shift-Improve framework in transport
- Improvement measures such as increased biofuel mixing, and private vehicle electrification deliver the greatest share of savings, followed by demand reduction measures ‘Avoid’, and modal ‘Shift’ policies
- The policy measures are projected to reduce transport emissions and be within carbon budget targets for the transport targets set in Ireland – provided the assumptions underpinned, and targets set out – are met in a timely manner

4.3. Introduction

4.3.1. Climate Action Context

According to the IPCC (Intergovernmental Panel on Climate Change), continuing growth in transport demand threatens to undo gains in energy efficiency (IPCC, 2014). Passenger and freight transport are responsible for approximately 24% of direct CO_2 emissions from fuel combustion globally, with passenger transport responsible for about half of these

(International Energy Agency, 2021). Transport, as a whole, is responsible for 17% of GHG (greenhouse gas) emissions globally (International Energy Agency (IEA), 2023a). Through the Paris Climate Agreement, 197 countries have agreed to a global commitment to reduce greenhouse gas emissions to maintain global average temperature rises to 1.5°C (UNFCCC (United Nations Framework Convention on Climate Change), 2021). Action is needed to reduce global GHG emissions and remain within a 1.5°C carbon budget.

Globally, a significant driver of the growth in transport demand and associated emissions has been adopting the private car as the primary mode of transport and the growing demand for goods for delivery via freight (Grubler, 1991; Peeters, 2004). Transport has also been identified as a sector more difficult to decarbonise than, for example, the electricity sector, due to its decentralised nature (Banister et al., 2011; Schäfer and Jacoby, 2006). Freight transport is 'not on track' regarding the net-zero energy transition (International Energy Agency (IEA), 2023b).

Ireland's share of the global carbon budget has been calculated as ranging between 128-223 $MtCO_2eq$. remaining before its carbon budget is exceeded (Glynn et al., 2019). Significant reductions in GHG emissions across all sectors, including transport, are required for Ireland to remain within a carbon budget consistent with 1.5°C.

Ireland has therefore set legally binding carbon budgets limiting cumulative GHG emissions over the first period, from 2021-25 (Carbon Budget 1, or CB1), and second period, from 2026-30 (Carbon Budget 2, or CB2). These economy-wide budgets have been allocated to sectors, including the transport sector, and sectoral emissions ceilings (SECs), with indicative targets set for 2025 and 2030 (Government of Ireland, 2022a). The transport SECs are 54 $MtCO_2eq$. for CB1 and 37 $MtCO_2eq$ for CB2.

In Ireland, transport GHG emissions grew at an annual average rate of nearly 1.7% from 1990 to 2021, faster than any other end-use sector (Environmental Protection Agency, 2023).The Government publishes annual Climate Action Plans (CAPs) to set out measures necessary to meet the legally-binding carbon budgets. The most recent CAP set out measures for the transport sector, to reduce private car vehicle kilometres, increase walking and cycling rates, add additional routes and capacity for public transport, and electrify private cars and public transport (Government of Ireland, 2023). In 2022 transport emissions increased by 6% due to the rebound in transport demand following travel disruptions from the COVID-19 pandemic (Environmental Protection Agency, 2023), further emphasising the difficulties Ireland is experiencing in decarbonising this sector.

In June 2023, the Irish Environmental Protection Agency (EPA) released an emissions inventory and projections based on the suite of policy measures included in the latest CAP (Environmental Protection Agency, 2023). Under the "With Additional Measures" scenario, transport emissions decrease by 35% (from 10.9 to 7.2 $MtCO_2eq.$) between 2021 and 2030.

4.3.2. The Avoid-Shift-Improve Framework

In this study, I apply the Avoid-Shift-Improve (ASI) Framework to a transport energy and emissions simulation model. The ASI Framework was introduced by the German Parliament's Enquète Commission in the 1990s (Schipper, 2002). It is based on a three-pillar approach – first, to advocate reducing the need to travel in the first instance through addressing demand drivers and reducing the travel requirements to service the transport of people and goods ("Avoid"). Secondly, it recommends that for the travel demand that remains after demand reduction measures are implemented, modal shift away from private cars is encouraged, towards centralised public or mass transport or active modes of travel such as walking and cycling ("Shift"). Then as a final step in the sustainable transport policy-making process, it advocates for decarbonising transport vehicles and fuels ("Improve"). The framework serves to structure policy-making decisions. While its emphasis is largely centred on urban areas, it can also be applied to policy at a national level – as done in this study. A recent report on sustainable transport in Ireland from the OECD recommended adopting the ASI framework when planning the deep decarbonisation of passenger transport (OECD, 2022). In this study, the ASI framework is used to model the decarbonisation of both passenger and freight transport sectors. In this next section, I discuss previous studies on transport emissions mitigation and how they relate to the ASI framework.

4.3.3. Previous Studies on Transport Emissions Mitigation

Up until now, a great deal of emphasis in the Irish transport modelling community has focused on techno-economic, fuel efficiency and technology switching "Improve" based measures, such as the role of biofuels in transport (Czyrnek-dele et al., 2020; Harvey, 2013; Mulholland et al., 2016), the role of electrification (Calnan et al., 2020; Smith, 2010; Sun et al., 2020), and the role of new car purchases and energy efficiency incentives and taxes based on emissions (Dineen et al., 2018; Hennessy and Tol, 2011; O'Riordan et al., 2021a; Ryan et al., 2009). However, there is a growing need to factor in the impacts of demand drivers in policies, models, and analyses to explore the possible impacts of model shift, cycling, walking and public transport uptake as part of a low-carbon transition and demand reduction for transport in general (Cuenot et al., 2012; Mulholland et al., 2014). For example, it has been acknowledged that EVs alone will not achieve the CO_2 emissions reductions required from transport to meet climate targets (Milovanoff et al., 2020), and, given supply constraints with biofuels (Government of

Ireland, 2022b), and there is a high cost per tonne of CO_2 abated with internal combustion engine car efficiency measures such as emissions-based car taxes (Hennessy and Tol, 2011;; Rogan et al., 2011, Chapter 2).

A previous study looked at the emissions reductions from active travel replacing motorised travel in isolation (Brand et al., 2021), which draws on information from national travel surveys to incorporate trip purpose (focusing on commuter trips), trip distance and trip mode type to contextualise the substitutions of these modal choices. Active travel studies are often based on analyses of the potential for emissions mitigation (Yang et al., 2018), generating scenarios or smaller-scale studies focusing on a single city, region, or country (Neves & Brand, 2019). Another policy study examined how sustainable school travel for pupils provides a tangible opportunity for emissions reductions (Bearman and Singleton, 2014).

While individual studies are instructive on the effectiveness of policies in isolation and provide greater detail on the specific policy intervention, quantifying sector-wide emissions requires an understanding of policy interactions. Modelling multiple policy measures and how they work and fit within a carbon budget can advance system-wide thinking on national transport carbon budget planning.

There have been examples of multi-policy transport decarbonisation policy models, such as the International Energy Agency's (IEA) MoMo (Mobility Model). MoMo includes a broad range of demand ("Avoid") and supply side ("Shift" and "Improve") measures in modal shift and ultra-low energy scenarios up to 2050 (IEA 2012). The study applies top-down assumptions that start with an improvement in carbon intensity and fuel efficiency measure, which is an avoid/shift measure, assuming passenger kilometres of travel grow by 25% less in the 2°C scenario than in the 4°C scenario. The UK Transport Carbon Model (UKTCM), a life-cycle energy, emissions, and environmental impacts model, was used to model transport energy demand with a socio-technical approach and delves into the role of demand reduction alongside technological fixes (Brand et al., 2012). It applies modal shift penetration rates using a top-down "lifestyle" adjustment approach, thus covering the "Shift" and "Improve" aspects of the ASI Framework from a top-down modal shift and bottom-up technology penetration perspective (Anable et al., 2012). For Ireland, scenarios investigating growth in transport demand and increased renewables for electric vehicles, increased electric vehicles, increased CNG vehicles, flattened travel demand, new efficient cars, and eco-driving measures being introduced have been modelled (Daly,. and Ó Gallachóir, B.P., 2012) The current study builds on methods first developed in Daly et al., with the inclusion of the Irish Car Stock Model, the modelling of the impacts of eco-driving, and increased electric vehicles among those included in the decarbonisation scenario presented in this study.

Top-down modelling methods have applied the ASI framework without directly referencing national policy (Fulton et al., 2013). Furthermore, modelling focussed on decarbonisation can downplay the value of “Avoid” and “Shift” measures. A multi-modal, low-carbon transport sector aiming to manage travel demand and increase access to public transport and active travel yield benefits in air quality, traffic congestion, safety and overall societal mobility and transport justice for those who cannot travel by car (OECD, 2022). To do so, energy systems and transport models should consider demand reduction options in policy interventions, otherwise demand reduction (“Avoid”) policy interventions will remain overlooked and excluded, and the expectations for technological innovation and uptake (“Improve”) will become increasingly unrealistic and unachievable (Grubler et al., 2018).

To address this gap, I develop the LEAP Ireland ASI model. The LEAP Ireland ASI model is built on an energy systems simulation platform called ‘LEAP’, which is the

Low Emissions Analysis Platform. It provides tools to develop an emissions inventory of a country or region, and then the capability to simulation scenarios based on changes made to future projections in the model. This study's purpose, aim and scope are outlined in the next section.

4.3.4. Purpose, Aims, and Scope of this Study

For Ireland, a national approach can provide insights into the national realities uncaptured by models developed globally or with other regions in mind. Cuenot et al. also stated a need to disaggregate global and large-scale models to gain regional insights where local conditions vary from the aggregated picture (Cuenot et al., 2012). Local studies often show that behavioural and infrastructure policy interventions impacting modal shift, distance travelled, and technological change could effectively decrease emissions (Creutzig et al., 2018; Pye and Daly, 2015).

Blending the methods and insights from these approaches to studying transport decarbonisation, in this study, I combine a) assumptions and studies on regional and specific transport targets across the ASI framework with b) bottom-up national data on passenger and freight transport and c) scenarios based on national climate policy plans.

The aims of the study are as follows:

1. To develop a methodology for modelling scenarios based on the ASI framework
2. To model the impacts of national climate plans and regional transport strategies on achieving transport carbon budgets
3. To assess the policy insights from adopting the ASI framework and the transport sector’s role in deep decarbonisation.

The chapter's layout is as follows: the chapter's topic has been introduced here in Section 4.3, "Introduction"; Section 4.4, “Methods", will briefly cover the background to the

IPTEM Model (Section 4.4.2) used to inform the historical data in this chapter, and the LEAP Ireland ASI model (Section 4.4.3), which handles the scenario analysis simulations, and the application of the scenarios and how they interact with one another is covered in Section 4.4.8. Section 4.5, "Results", will cover the insights from modelling the ASI measures. Section 4.6, "Discussion", analyses results, including the methodological advancements (Section 4.4) and policy implications arising from the results (Section 4.6.2). The results are also compared with the Irish Environmental Protection Agency's "With Additional Measures" scenario (Section 4.6.3). Then, uncertainties associated with the results and methodology are discussed (Section 4.6.4). Section 4.7, "Conclusions", summarises and highlights the key findings of the study.

4.4. Methods

4.4.1. Background

This case study uses the Irish LEAP model, which intakes demand and final energy intensity values from the IPTEM (Irish Passenger Transport Emissions and Mobility) model, developed and discussed in Chapter 3, and provides an application using the overarching LEAP software program to handle scenario comparisons (Heaps, 2021; Mac Uidhir et al., 2020).

Simulation modelling compares alternate "scenarios" with a business-as-usual case, defined by the modeller, referred to as the "Reference" scenario. Emissions savings are calculated as CO_2 emissions reductions of a stated scenario relative to the reference. Simulation modelling is particularly useful as it can be easily reused and communicated for custom purposes (Robinson et al., 2004). The Low Emissions Analysis Platform (LEAP) provides a basis for developing a reference scenario for transport and combination scenarios with variations that can be compared. Energy consumption rates and net CO_2 emissions are handled within the platform by combining stocks and stated energy demands with the associated fuel demands per unit of demand and the carbon intensity of the fuels (Heaps, 2021).

4.4.2. The IPTEM model

The Irish Passenger Transport Emissions and Mobility (IPTEM) model provides a snapshot of passenger kilometres by trip purpose, trip distance and trip mode type throughout 2009 – 2019 (O'Riordan et al., 2022a). It also contains information on fuel consumption and associated CO_2 emissions from passenger transport by trip purpose, distance, and mode type. The IPTEM model is an Excel-based spreadsheet available on an open-source repository (O'Riordan et al., 2021b) and data in brief article (O'Riordan et al., 2022b). An overview of the data sources, inputs, and outputs for the IPTEM model is highlighted in Figure 15.

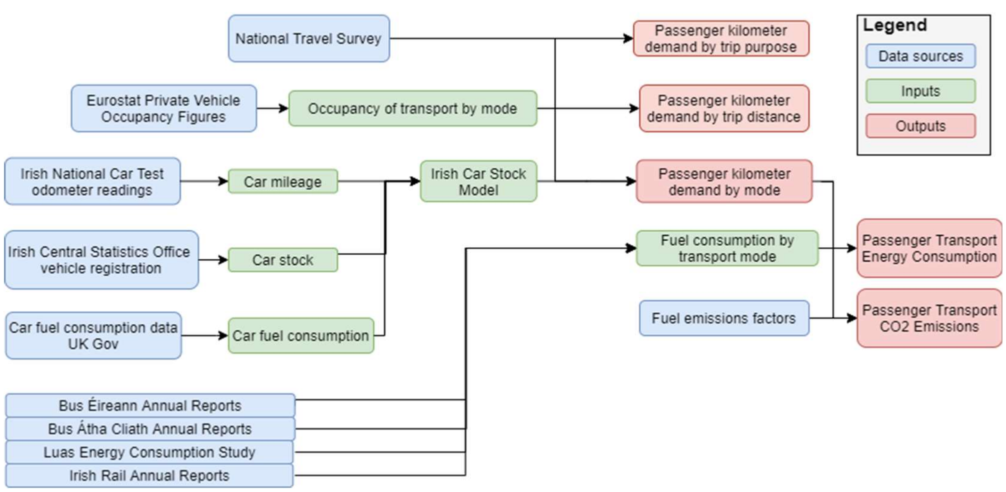


Figure 15: Overview of the Irish Passenger Transport Emissions and Mobility (IPTEM) Model (source: O'Riordan et al., 2022a)

4.4.3. LEAP Ireland ASI model

LEAP, the Low Emissions Analysis Platform, is a greenhouse gas (GHG) accountancy-based policy analysis platform encompassing the Economy, Energy and Environment aspects of Transport, Heating and Electricity demands (Manfren et al., 2011).

LEAP is a scenario-based simulation tool which provides a basis for comparison against a 'no-policy' scenario. The relative difference between the reference scenario and the scenario with a simulated target or policy can be used in an advisory capacity to highlight the scale and success of different interventions. "What-if" analyses are exploratory and easy to communicate with policymakers. In the absence of cost data, which is required for optimisation models, simulation models can provide a helpful first step in identifying what policy targets, demand-side measures, and technologies are impactful in reducing transport-related CO_2 emissions.

LEAP has been used previously to develop a multi-sector simulation model modelling scenarios in the LEAP Ireland model (O'Riordan et al., 2023a). The model presented in this study, the LEAP Ireland ASI model, is a transport-only model that develops a wider range of transport scenarios closely aligned with regional and national climate plans.

By developing alternative passenger and freight transport demand scenarios and modal shares based on policy targets and interventions, LEAP highlights the relative reductions in transport CO_2 emissions based on these interventions up to 2030. The LEAP Ireland ASI model and the associated IPTEM model are openly available, using the proprietary LEAP software (O'Riordan et al., 2023b, O'Riordan et al., 2021b).

The method involves using inputs from spreadsheet models based on national data (Irish Car Stock Model, IPTEM Model) to feed into an energy and emissions inventory tool (LEAP) as outlined in a review of models by Kooshian et al, (2017).

A visual summary of classes of available methods and associated tools for modelling emissions reductions for climate action is shown in Kooshian et al., (2017) is highlighted in Figure 16.

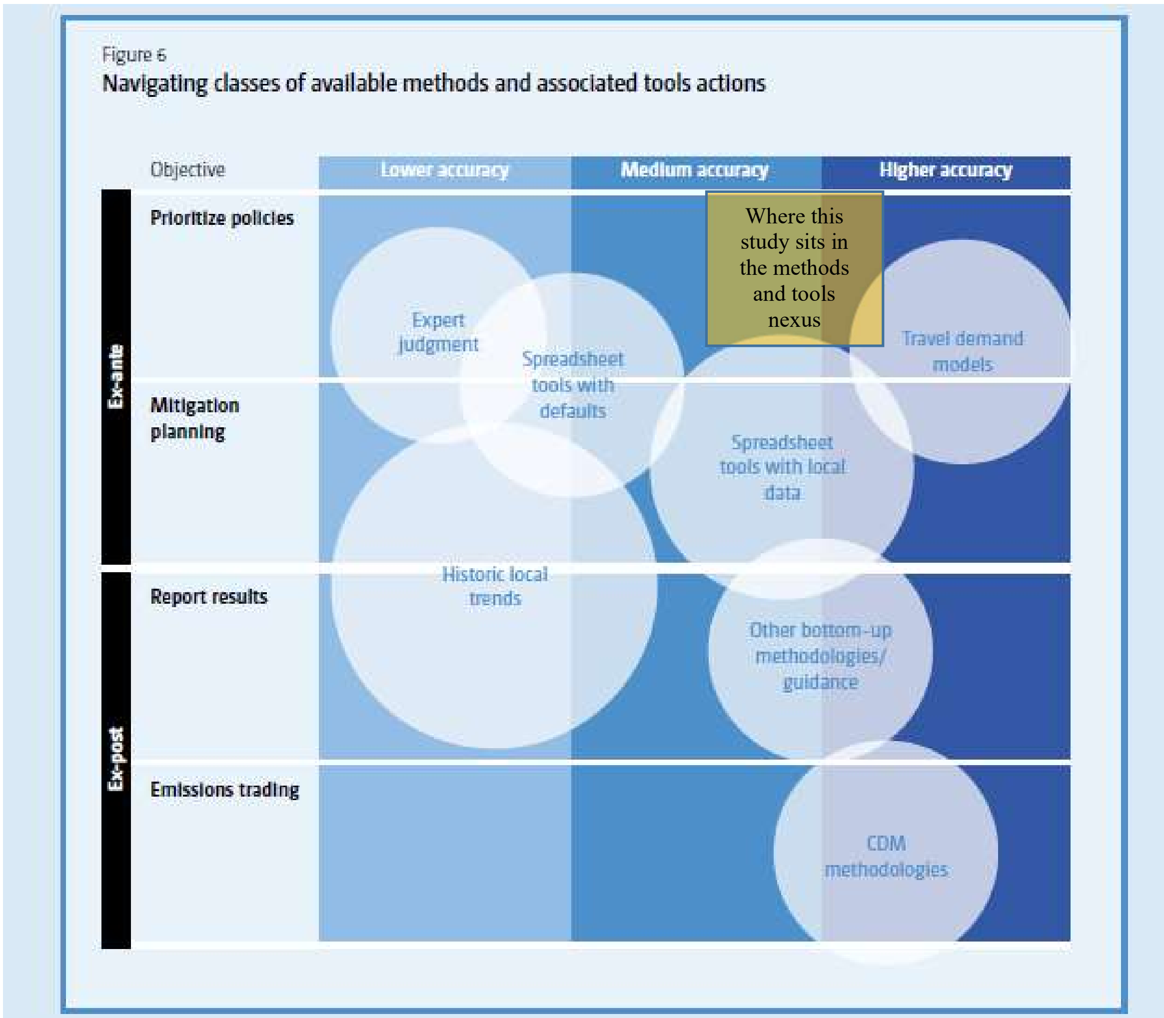


Figure 16: Navigating classes of available methods and associated tools actions (Source: Kooshian et al., 2017) and where this study sits in the methods and tools nexus. Note: CDM methodologies refer to the set of rules and procedures set out under the UNFCCC's Clean Development Mechanism

4.4.4. Simulation Modelling

The process for simulation scenario modelling with the IPTEM and LEAP Ireland ASI model is as follows:

1. Identify transport decarbonisation and energy transition targets from national climate policy plans and regional transport strategies (refer to Table 9)
2. Gather transport data from the CSO, the Irish Car Stock and IPTEM models.
3. Develop scenario parameters and assumptions for introducing policy targets for Avoid targets (Table 10), Shift targets (Table 11), and Improve targets (Table 12) based on demand-side changes in passenger and freight kilometres (Avoid scenarios), mode share rates (Shift scenarios), and vehicle/fuel shares and intensity values (Improve scenarios).
4. Compare the reference scenario with an alternative scenario and combine multiple scenarios in a scenario package to observe the combination interaction effect between multiple targets and scenarios in LEAP.
5. Quantify each scenario's cumulative and annual CO_2 emissions savings relative to the references to inform the planning of carbon budgets and CO_2 emissions reduction policy.

A graphical overview of the data collection – modelling – simulation – interpretation framework is illustrated in Figure 17.

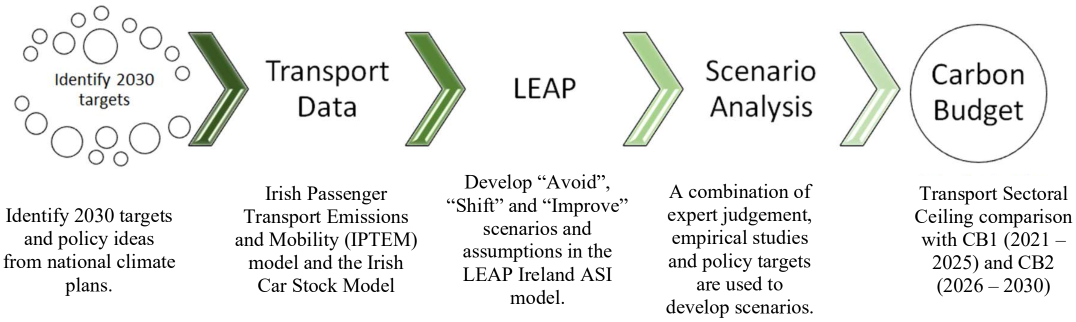


Figure 17: Overview of the IPTEM, LEAP Ireland ASI model, and carbon budgeting process

Each scenario that makes up the LEAP Ireland ASI modelled scenario is based on references to policy objectives in CAP 2023 for Ireland (Government of Ireland, 2022a). The scenarios are denoted ASI 1 – 23, and a summary of the link between each of these targets from CAP 2023, where they come from, and where they are represented in the LEAP Ireland ASI scenarios is shown in Table 9 below. The spreadsheet inputs, which feed into the LEAP Ireland ASI model, use input data from the IPTEM, Irish Car Stock model and inputs from assumptions as outlined in, Table 10, Table 11, Table 12 and Appendix C.

Table 9: Scenarios in LEAP Ireland ASI model

Measure	Scenario reference	Sub-Sector (Passenger/ Freight/Both)	Policy Plan Reference
Working from Home	ASI 1	Passenger	Section 10.3.2: Reduce Your Use Campaign – mention of promoting remote work to reduce demand (Climate Action Plan 2023)
20% Reduction of total vehicle kilometres by 2030	ASI 2	Both	Table 15.6 – Key Metrics to Deliver Abatement in the Transport Sector (Climate Action Plan 2023)
20% Reduction of total car kilometres by 2030	ASI 3	Passenger	Table 15.6 – Key Metrics to Deliver Abatement in the Transport Sector (Climate Action Plan 2023)

20% Reduction of total car commuting km by 2030	ASI 4	Passenger	Table 15.6 – Key Metrics to Deliver Abatement in the Transport Sector (Climate Action Plan 2023)
Remote working hubs	ASI 5	Passenger	Section 11.2.4 Digital Transformation (Climate Action Plan 2023)
Park and Ride provisions	ASI 6	Passenger	Cork/Dublin Metropolitan Area Strategies (Climate Action Plan 2023, Cork Metropolitan Area Transport Strategy, 2020, Greater Dublin Area Transport Strategy, 2022)
125,000 Sustainable Journeys per day	ASI 7	Passenger	Table 15.6 – Key Metrics to Deliver Abatement in the Transport Sector (Climate Action Plan, 2023)
Additional 300 buses added to the Public Service Fleet	ASI 8	Passenger	Table 15.5 Potential Metrics to Deliver Further Abatement in Transport (Climate Action Plan, 2021)
Additional electric bikes	ASI 9	Passenger	Table 15.4 Actions - Action 237 (Climate Action Plan, 2021) Section 15.3.4 Shift (Climate Action Plan, 2023)
Additional 1000km of walking and cycling infrastructure	ASI 10	Passenger	Table 15.4 Actions - Action 233 (Climate Action Plan, 2021)
Bus Connects - 5 cities (Cork, Limerick, Waterford, Galway, Dublin)	ASI 11	Passenger	Cork Metropolitan Area Transport Strategy (CMATS, 2020), Dublin Metropolitan Area Transport Strategy, 20, Limerick Metropolitan Area Transport Strategy (LMTAS, 2022), Climate Action Plan 2021 Action 240 – 244 (Climate Action Plan, 2021)
Metrolink	ASI 12	Passenger	Action 247 Commence delivery of MetroLink (Climate Action Plan, 2021)
DART+ West Program	ASI 13	Passenger	Table 15.7 – Key Actions to Deliver Abatement in Transport for the Period 2023-2025: Advance DART+ programme (Climate Action Plan, 2023) 246 Commence delivery of DART+ Programme and continue heavy rail fleet investment (Climate Action Plan, 2021)

School Transport Scheme	ASI 14	Passenger	Section 15.3.4 Shift Escort to Education Journeys (Climate Action Plan, 2023)
Bike Share Schemes	ASI 15	Passenger	Cork Metropolitan Area Transport Strategy (CMATS, 2020), Dublin Metropolitan Area Transport Strategy, 2020, Limerick Metropolitan Area Transport Strategy (National Transport Authority, 2023), Climate Action Plan 2021 Action 240 – 244 (Climate Action Plan, 2021), Climate Action Plan 2023
Rural Transport System - Connecting Ireland's rural mobility plan	ASI 16	Passenger	Climate Action Plan 2021 Action 245 (Climate Action Plan, 2021), "Delivering a Just Transition in the Midlands Region" JM/23/9 Support the decarbonisation of public and private local rural bus routes, Section 3, Chapter 8 (Climate Action Plan 2023)
Luas extension - Cork, Limerick, Galway	ASI 17	Passenger	Section 15.3.4 Shift - Cork Area Commuter Rail Programme (Climate Action Plan, 2023)
Electric Vehicle Uptake	ASI 18	Passenger	Section 5.2 Key Measures and Shifts Required (Climate Action Plan 2023) The uptake of electric vehicles will also require a step change, with 30% of the private car fleet to be electrified by 2030 and all new car registrations to be electric for subsequent years
20,000 EV commercial vans by 2030	ASI 19	Freight	Section 15.3.5 Improve - Special Focus: Haulage and Heavy Goods Road Freight Sector p. 201 (Climate Action Plan, 2023)
Electrification of rail	ASI 20	Passenger	Table 15.6 – Key Metrics to Deliver Abatement in the Transport Sector (Climate Action Plan, 2023), Section 15.3.1 Sustainable Mobility (Climate Action Plan, 2021)
Electrification of 1,500 Buses	ASI 21	Passenger	Table 15.7 – Key Actions to Deliver Abatement in Transport for the Period 2023-2025 (Climate Action Plan, 2023)

			Section 15.2 Targets (Climate Action Plan, 2021)
Biofuel mixing	ASI 22	Both	Table 15.6 – Key Metrics to Deliver Abatement in the Transport Sector p. 193 (Climate Action Plan, 2023)
Speed management	ASI 23	Both	Table 15.7 – Key Actions to Deliver Abatement in Transport for the Period 2023-2025 (Climate Action Plan, 2023) "TR/23/20 Advance Speed Management and Enforcement work programme."

4.4.5. Avoid Scenarios (ASI 1 – ASI 5)

Demand reduction scenarios are a key first part of the ASI framework. Demand reduction scenarios focus on interventions that result in the overall reduction of passenger and freight kilometres travelled (Avoid). A description of the "Avoid" scenarios is given in Table 10.

Table 10: Assumptions and methodology for "Avoid" scenarios in LEAP Ireland ASI model

	Measure/Target	Assumptions and methodology
ASI 1	Working from home 2 days per week	Based on the remote working potential recorded by Crowley and Dornan. (2020) for each economic sector and applying for 2019 work numbers by economic sector, a potential of 55% full-time equivalent (FTE) was calculated, which was calculated based on the remote working potential of workers by sector in Ireland (Central Statistics Office, 2021; Crowley et al., 2021) and the number of people working in these sectors. An uptake of 2 days working from home is assumed.
ASI 2	20% reduction in vehicle kilometres by 2030	20% reduction in total vehicle kilometres by 2030 – this includes HGV (Heavy Goods Vehicles), LGV (Light Goods Vehicles) and private car transport
ASI 3	20% reduction in car kilometres by 2030	20% reduction in total car kilometres by 2030 – this measure includes private car transport only
ASI 4	20% reduction in the total car commuting kilometres by 2030	20% reduction in total car commuting kilometres by 2030

ASI 5	Remote working hubs	55% of people could work from Remote working hubs, and 18% of those people would use remote working hubs.

4.4.6. Shift scenarios (ASI 6 – ASI 17)

Modal shift scenarios in the LEAP Ireland ASI model are based on calculations derived from the IPTEM model and bottom-up assumptions based on expert judgement and empirical studies which measures the potential of modal shift measures. A summary of the scenarios and their descriptions is included in Table 11, and numerical calculations and assumptions are in Appendix C.

Model shift for the ASI scenario was made up of the net impact of the individual scenarios ASI 6 – ASI 17. The model shift rates were calculated by adjusting the mode of one transport type downward and increasing the passenger kilometres of the new mode type by the same amount. In some cases, the changes in passenger kilometres were split across several modes. The adjustments were made such that the total number of passenger kilometres was not changed, unlike the calculations made in the 'Avoid' scenarios. The impact of the modal shift measures in combination were additive in the ASI Scenario.

Table 11: Assumptions and methodology for "Shift" scenarios in LEAP Ireland ASI model

Scenario Code	Scenario	Description
ASI 6	Additional Park and ride provisions for Cork and Dublin	The provision of additional park-and-ride spaces is based on Dublin's Greater Dublin Area Transport Strategy (GDATs) (National Transport Authority, 2022) and Cork's Metropolitan Area Transport Strategy (CMATS) (Creegan et al., 2020). It assumes that an average of 3 km of car travel per trip would switch to bus travel and that the occupancy rate of the park-and-ride would serve an average of 1.3 cars per day.
ASI 7	125,000 sustainable journeys per day	Assumes an increase of sustainable journeys for bus, rail, cycling and walking proportional to their current shares. The number of journeys met by these modes is increased to meet the 125,000 journeys per day target.
ASI 8	Additional 300 Buses	Passenger kilometres for bus transport are increased by 25% as an increase in the bus fleet by 300 vehicles would represent an approximate 25% increase in bus vehicles. It assumes the occupancy of buses stays the same. A modal shift from car to bus transport is assumed for these journeys.

ASI 9	E-bikes	It is assumed that 5% of the population will get an e-bike; while specific targets are not set, e-bikes are mentioned in the Climate Action Plan 2023 as an area for future targets to be set (Government of Ireland, 2022a, p.32)
ASI 10	Additional walking and cycling infrastructure	3000km of cycling infrastructure is added, and cycling is increased proportionately to the added cycling infrastructure. There are 500 kilometres of cycling infrastructure and cycling accounts for 0.35% of the mode share. An increase to 3,500 kilometres is a seven-fold increase. An assumption is made that the increase in cycling passenger mode share would also increase seven-fold, and the use rates of the cycling infrastructure would be the same as the current cycling infrastructure.
ASI 11	Bus Connects – 5 cities in Ireland: Cork, Galway, Waterford, Limerick, Dublin.	This scenario is based on CAP Action No. 88 – "Implementation of Bus Connects services network" (Department of Communications Climate Action and Environment, 2019) Bus Rapid Transit for Dublin - assuming 20% of car ridership in Dublin switches from car to bus, based on studies from the past success of mode switching with BRT from studies, which indicate

		mode shift potential of between 5 - 70% from car to bus following the introduction of a Bus Rapid Transit system (Satiennam et al., 2016). This scenario suggests a 25% switch from current private car use to bus in the Dublin area. Based on the medium success of car-to-bus switchover, 25% of car-passenger kilometres in Cork, Galway, Limerick, and Waterford cities would switch to bus-passenger kilometres. The passenger kilometres in Cork, Galway, Limerick, and Waterford are proportional to the population, as data specific to passenger kilometres in those cities have yet to be available.
ASI 12	Metrolink in Dublin	This scenario is based on the increase in passenger kilometres in rail equals the number of anticipated passengers per year (50 million) multiplied by the average distance travelled along the 19-kilometre line (8 kilometres) (Transport Infrastructure Ireland, 2022b)
ASI 13	Extension of the DART (Dublin Area Rapid Transit) from 50	Increase of rail passenger kilometres in proportion to the 100-kilometre increase in rail infrastructure (Transport Infrastructure Ireland, 2022b).

	kilometres to 150 kilometres	
ASI 14	Sustainable school transport	The increase share targets are based on the historical walking rates of children to school in 1996 and 1986. Current cycling and walking rates are based on passenger kilometre demand from the IPTEM model and census data on how children get to school from the CSO (Central Statistics Office, 2017a)
ASI 15	Bike share scheme	The scenario assumes the number of bikes in bike share schemes in Ireland would increase from 1,020 to 20,000 and the average journey is 2 kilometres, and each share bike is used 2 times per day (RTÉ, 2019).
ASI 16	Rural Mobility Plan - increased bus services for Carlow, Mullingar, Portlaoise, Leitrim	The modal shift towards the bus from car transport is determined based on the population of these towns, the average passenger kilometre demand per person and a 10% modal shift from car passenger transport to bus transport.
ASI 17	Luas extension of Cork, Galway, and Limerick	This scenario assumes the introduction of light rail to Cork Limerick and Galway by 2027. The uptake of light rail is the same as in Dublin, and passenger kilometres in these cities are

		proportional to the population of each of the cities (Government of Ireland, 2022a). It assumes a 50% mode shift from car to light rail, 25% from bus to light rail and 25% from bike to light rail.

4.4.7. Improve Scenarios (ASI 18 – ASI 23)

“Improve” refers to updating the performance, introducing eco-driving measures, and changing the fuel type of the choice of mode to a less carbon-intensive one. The "Improve" scenarios are based on a combination of interventions inspired by CAP 23 by the Government of Ireland and ambitions set by the Biofuel Obligations Scheme in Ireland and from Biofuel policy in the EU (European Union) (National Oil Reserves Agency, 2020).

Table 12: Assumptions and methodology for "Improve" scenarios in LEAP Ireland ASI model

Scenario Code	Scenario	Description
ASI 18	840,000 EVs by 2030	This scenario is based on Climate Action Plan No. 72, which sets the target of 840,000 EV (Electric Vehicle) sales by 2030 (Department of Communications Climate Action and Environment, 2019). EVs were assumed to replace newer cars in the car stock model, and are

		typically driven further than the average car (which is about 7 years old in the Irish Car Stock). The mileage is assumed to be the same as other new electric vehicle mileages recorded from the Irish Car Stock Model.
ASI 19	20,000 commercial Electric Vehicles by 2030	20,000 commercial electric vehicles by 2030 corresponds with 78% of all commercial light goods vehicles in Ireland being electric by 2030.
ASI 20	Electrification of Rail	Electrification of all railway lines in Ireland by 2030
ASI 21	1,500 Electric buses	Currently, there are just over 1,600 public transport buses. Up to 87% of buses are modelled as electric in this scenario by 2030.
ASI 22	10% Biofuels in Petrol, and 20% Biofuels in Diesel by 2030.	Increase biofuel mixing up to 10% biofuels in gasoline cars and 20% biodiesel for diesel cars.
ASI 23	Speed management program to reduce speeds on national roads and motorways	Assumes a speed reduction coincides with a reduction in fuel consumption of 0.7%. This reduction is based on a study that would see fast driving emissions reductions of 0.7% fuel savings if speed limits were reduced on national roads across the country from a 10 kph reduction on motorways (Transport Infrastructure Ireland, 2022c). This scenario was based on a

		recommendation for a review under CAP 2023 and may or may not be implemented.

Additional details on the calculations associated with all scenarios and related calculations can be found in Appendix C and within the LEAP_IE_TRA.xlsx spreadsheet within the LEAP Ireland ASI model provided (O'Riordan et al., 2023b).

4.4.8. Interaction and application of scenarios

The scenarios in the LEAP Ireland ASI model are based on adjusting the activity, mode share, and fuel type for each of the scenarios, and how each of the scenarios are developed is outlined in Figure 18.

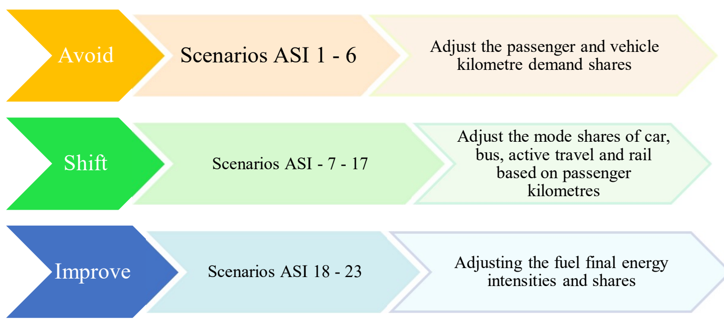


Figure 18: Overview of how the scenarios is adjusted within the LEAP Ireland ASI model for the ASI interaction scenario.

When modelling the combined impact of a relatively large number of policy measures (as undertaken here) careful preparation of each scenario set of equations is required to ensure the interaction between each policy measure is accounted for rather than one scenario inadvertently 'overwriting' another. This will ensure consistency in the combined impact of all policy measures. In addition, when analysing results (e.g., on CO_2 emissions) a comparison can be made between the *combined modelled impact* of a suite of policy measures with the *sum of the individually modelled impact* of each policy measure; in this way, the interaction effect or double-counting potential for any given set of policy measures can be calculated. Lastly, to integrate the impact of the interaction effect associated with an individual policy measure, a scenario ensemble approach is devised as follows: the combined impact of all scenarios is compared with a scenario ensemble of all scenarios *except* the individual policy measure scenario in question. This process of elimination is repeated for all the individual scenarios.

Detailed calculations on the interaction effect between scenario combinations and individual scenarios are not covered in this study, but the general approach applied to calculate the interaction effect in the context of these 23 scenarios in combination is calculated as follows in Equation 13:

$$Interaction\ effect = Emissions[(REF - Scenario_x) - (ALL\ except\ Scenario_x - ALL\ Scenarios)] \quad (13)$$

In this equation, REF refers to the reference scenario, and specifically the emissions coming from that sector, the difference between the reference scenario and a given scenario x is calculated. This gives the individual emissions reduction from scenario x. This value is then compared with a combination scenario that includes the emissions from all scenarios except the individual scenario (All except , and the difference between that collection from when all scenarios are included. The difference between these two values is the interaction effect, showing the difference in modelled emissions reductions when the scenario acts alone, to when the adjustments in the individual measure/scenario acts alongside other measures.

In the instance of ASI 2, 20% reduction in vehicle kilometres by 2030 and ASI 3 for instance, a 20% reduction in car kilometres by 2030; there is a complete overlap in interaction as a 20% reduction in car kilometres by 2030 (ASI 3) as stated in the Climate

Action Plan would feature in a scenario where there is a 20% reduction in vehicle kilometres in general by 2030 (ASI 2).

The interaction effect is first introduced in a study on a multi-sector model, the LEAP Ireland model, where the interaction effect in the context of passenger transport is explored (O'Riordan et al., 2023).

Table 13: Key parameter changes for scenarios in LEAP Ireland ASI model (2030 values shown)

Scenario	Total Passenger Billion Pkm	Freight Billion Tkm	Mode share – Active Modes (%)	Mode share – Buses (%)	Mode share – Passenger Rail (%)	Mode Share – Road Private Cars (%)	Mode Share – Taxis (%0	Biodiesel mix (%)	Bioethanol in ethanol mix share (%0	Share of cars that are electric (%)	Share of electrified rail (%)	Share of electrified buses (%)	Share of electrified LGVs (%)
Reference	74.3	17.1	0.44	3.00	7.58	88.74	0.25	0.06	0.03	1.47	12	2	0
ASI 1	69.4	17.1	0.44	3.00	7.58	88.74	0.25	0.06	0.03	1.47	12	2	0
ASI 2	61.6	17.1	0.54	3.64	9.21	86.30	0.30	0.06	0.03	1.47	12	2	0
ASI 3	61.6	17.1	0.54	3.64	9.21	86.30	0.30	0.06	0.03	1.47	12	2	0
ASI 4	74.3	17.1	0.44	3.00	7.58	88.73	0.25	0.06	0.03	1.47	12	2	0
ASI 5	74.3[5]	17.1	0.44	3.00	7.58	88.74	0.25	0.06	0.03	1.47	12	2	0
ASI 6	74.3	17.1	0.44	3.00	7.58	88.73	0.25	0.06	0.03	1.47	12	2	0
ASI 7	71.9	17.1	0.46	3.14	7.90	88.25	0.26	0.06	0.03	1.47	12	2	0
ASI 8	74.6	17.1	0.44	3.76	7.61	87.94	0.25	0.06	0.03	1.47	12	2	0
ASI 9	74.3	17.1	1.10	2.98	7.54	88.14	0.25	0.06	0.03	1.47	12	2	0
ASI 10	74.5	17.1	1.48	2.90	7.37	88.01	0.25	0.06	0.03	1.47	12	2	0
ASI 11	74.6	13.7	0.45	6.55	7.81	84.93	0.26	0.06	0.03	1.47	12	2	0
ASI 12	74.4	17.1	0.43	2.74	8.11	88.47	0.25	0.06	0.03	1.47	12	2	0
ASI 13	74.3	17.1	0.44	3.00	7.58	88.73	0.25	0.06	0.03	1.47	12	2	0
ASI 14	74.3	17.1	0.75	3.15	7.61	88.24	0.25	0.06	0.07	1.47	12	2	0
ASI 15	74.3	17.1	0.44	3.00	7.58	88.73	0.25	0.06	0.03	1.47	12	2	0
ASI 16	74.3	17.1	0.45	3.12	7.68	88.49	0.25	0.06	0.03	1.47	12	2	0

[5] Note: Due to the change in passenger kilometres from the uptake of remote working hubs contributing a small share to overall passenger kilometre reduction, the reduction is not captured in the passenger kilometre values rounded to one decimal place

ASI 17	74.3	17.1	0.44	2.97	7.69	88.66	0.25	0.06	0.03	1.47	12	2	0
ASI 18	74.3	17.1	0.44	3.00	7.58	88.74	0.25	0.06	0.03	37.1	12	2	0
ASI 19	74.3	17.1	0.44	3.00	7.58	88.74	0.25	0.06	0.03	1.47	12	2	78
ASI 20	74.3	17.1	0.44	3.00	7.58	88.74	0.25	0.06	0.03	1.47	98	2	0
ASI 21	74.3	17.1	0.44	3.00	7.58	88.74	0.25	0.06	0.03	1.47	12	87	0
ASI 22	74.3	17.1	0.44	3.00	7.58	88.74	0.25	0.20	0.03	1.47	12	2	0
ASI 23	74.3	17.1	0.44	3.00	7.58	88.74	0.25	0.06	0.03	1.47	12	2	0
ASI Scenario (ALL)	62.0	13.7	6.84	9.11	9.95	73.80	0.30	0.21	0.07	37.1	98	87	78

4.5. Results

Emissions in the reference scenario for Carbon Budget 1 (2021 – 2025) are projected to be 55 $MtCO_2eq$, above the 54 $MtCO_2eq$. sectoral emission ceiling for transport. In CB2 (2026 – 2030), the reference transport emissions are projected to be 60 $MtCO_2eq$., above the transport sectoral emission ceiling of 37 $MtCO_2eq$., (Figure 19).

Implementing the measures outlined in the CAP 2023 and the interventions ASI 1 through to ASI 23 resulted in an emissions reduction throughout 2021 – 2030 compared to the reference scenario without those actions. The combination of these interventions is captured in the "ASI scenario", which quantifies the cumulative impact of these scenarios, accounting for the interaction between the individual transport decarbonisation measures. In this scenario, where the targets outlined in CAP are met on time, the ASI Scenario emissions for Carbon Budget 1 (2021 – 2025) are 46 $MtCO_2eq$., well below the 54 $MtCO_2eq$. budget for transport. Emissions for the ASI scenario is projected to come at 35 $MtCO_2eq$. in CB, 2 $MtCO_2eq$. below the transport sectoral emissions ceiling of 37 $MtCO_2eq$.

Without the modelled interventions of CAP 2023, emissions for Carbon Budget 1 (2021 – 2025) is modelled as 55 $MtCO_2eq$., 9 $MtCO_2eq$. (20%) higher than the ASI Scenario. For CB2, the difference between the intervention ASI scenario and the reference 'donothing' scenario grows. The reference scenario cumulative emissions of 60 $MtCO_2eq$. exceeds the CB2 (2026 – 2030) transport sectoral emissions ceiling of 37 $MtCO_2eq$.

Figure 19 (a) shows the annual and cumulative avoided emissions from the ASI Scenario relative to the reference scenario and the Sectoral Emissions Ceiling allotted to the transport sector under CAP 2023.

The cumulative carbon budget comparisons for CB1 (Carbon Budget 1, 2021 – 2025) and CB2 (Carbon Budget 2, 2026 – 2030) between the reference and the ASI Scenario are shown in Figure 19 (b).

The annual reductions in emissions in the ASI scenario relative to the Reference scenario accumulate. As a result, the gap between the "business as usual" Reference scenario transport emissions for CB2 (2026 -2030) and the ASI Scenario increases in CB2.

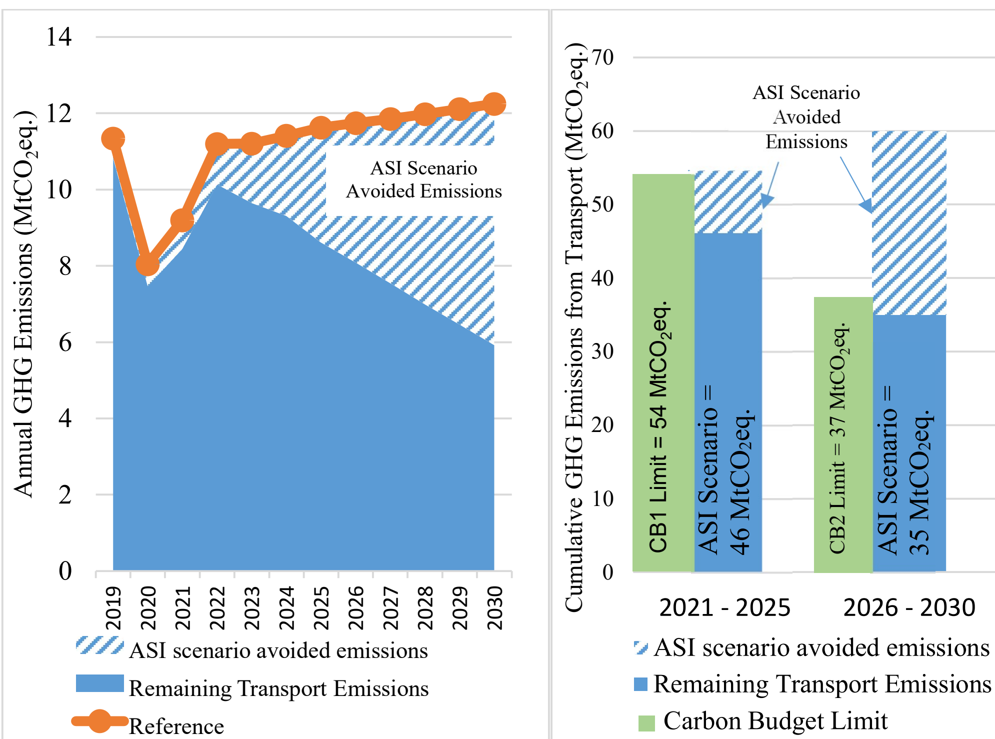


Figure 19 a) ASI scenario Carbon Budget vs. Carbon Budget and reference scenario Carbon Budget and b) the LEAP Ireland ASI scenario and the reference scenario for GHG emissions

The contribution of the top 6 contributing individual scenarios is shown in Figure 20. "Improve" based scenarios contributed the greatest share of emissions reductions – the target of 845,000 electric vehicles by 2030 contributed the greatest share (ASI 18), followed by biofuel mixing (ASI 22).

Demand reduction from passenger transport has a sustained and significant impact on emissions (ASI 2).

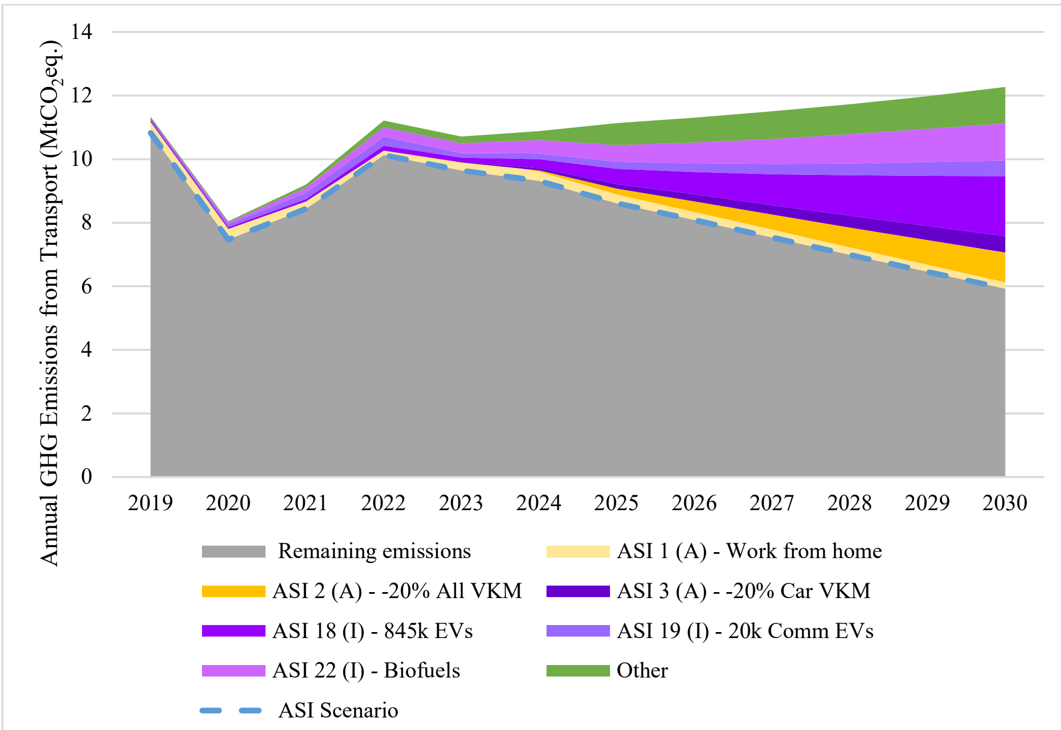


Figure 20: Impact of individual measures (emissions avoided from the measures) in the LEAP Ireland ASI scenario

For the ASI scenario, the contribution of the passenger transport sub-sector and the freight transport sub-sector was determined.

Passenger transport scenarios contributed 4.04 $MtCO_2eq.$ reduction by 2030, while freight transport scenarios contributed 0.57 $MtCO_2eq.$ of reductions. Biofuel mixing and transport demand reductions, encompassing both sectors, accounted for 4.04 $MtCO_2eq.$ of reductions. Then there was an interaction of 0.58 $MtCO_2eq.$ of double counting emissions targeting the same sectors – i.e., electrification of cars and modal shift of passenger transport. This results in the ASI scenario in 2030, having net annual emissions from the transport sector of 5.92 MtCO_2eq. in 2030 - a reduction of 48% compared to transport emissions in 2019. The reduction in transport emissions is short of the 51% overall emissions reduction target for all sectors. A waterfall chart of the contributions of the passenger and freight sectors and the interaction between the scenarios is shown in Figure 21 (a).

In the reference scenario, transport emissions in 2030 are 12.27 MtCO_2eq. “Avoid” interventions were responsible for 3.77 MtCO_2eq. emissions reductions by 2030 in this scenario, whereas “Shift” interventions had the smallest effect on emissions reductions, at 0.66 MtCO_2eq. “Improve” interventions had the greatest effect on emissions reductions at 5.97 MtCO_2eq. Overall, the interaction between all these scenarios had a 4.06 MtCO_2eq. overlap. A waterfall comparison chart for the contribution of ASI scenarios is shown in Figure 21 (b).

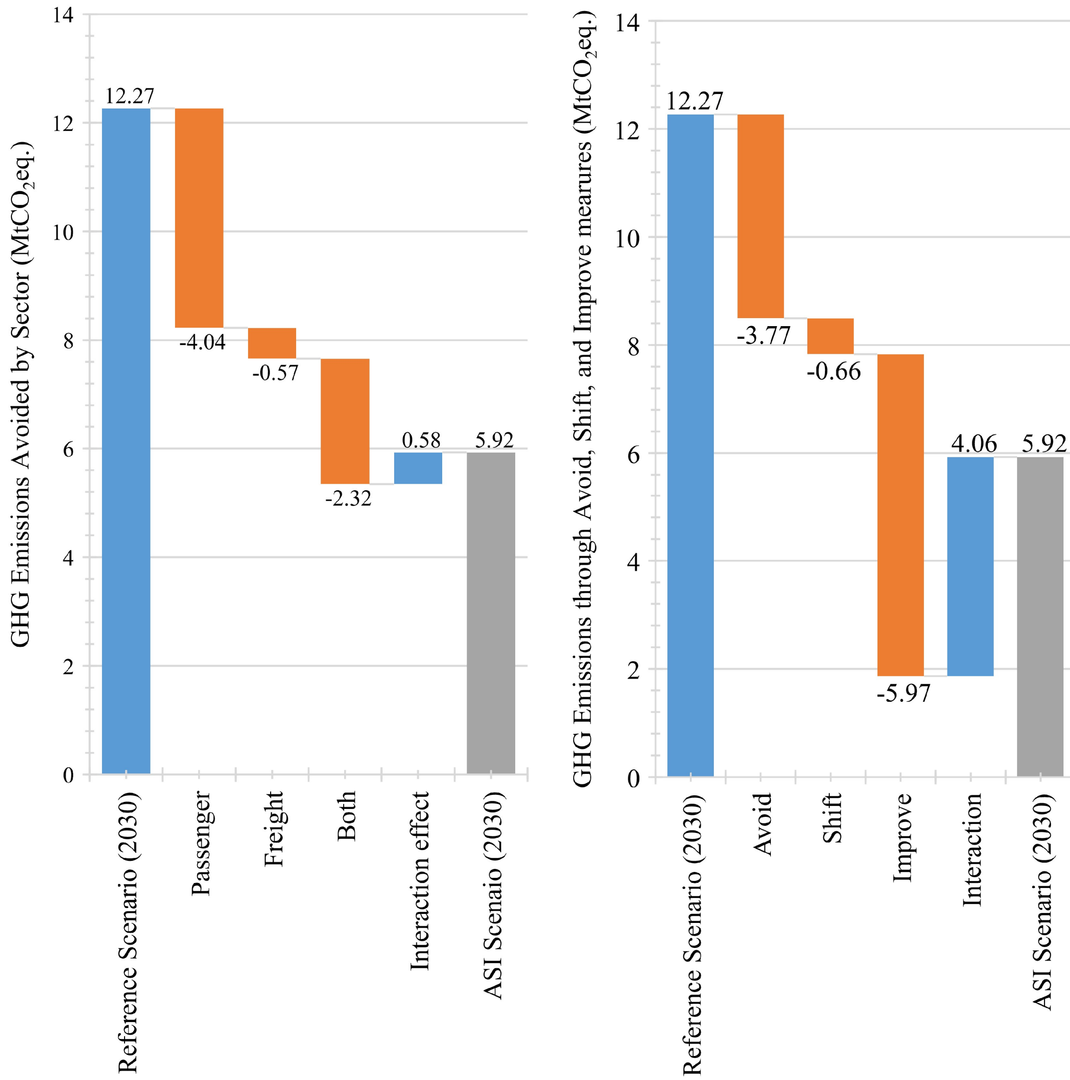


Figure 21: Comparison of the a) contributions of the passenger transport and freight transport sectors and b) of the Avoid, Shift, and Improve categorised scenarios to transport emissions reductions in the LEAP Ireland ASI scenario compared to the reference in 2030.

Figure 22 shows the annual and cumulative contributions of emissions reductions from passenger transport and freight transport throughout 2019 – 2030. Passenger transport interventions contribute to a cumulative reduction of 5.53 $MtCO_2eq.$ in CB1 2021 – 2025, and 15.65 $MtCO_2eq.$ in CB2, 2026 – 2030. Freight transport contributes a cumulative reduction of 1.24 $MtCO_2eq.$ in CB1 2021 – 2025, and 2.24 $MtCO_2eq.$ in CB2, 2026 – 2030. Cross-sector (both freight and passenger transport measures – biofuel mixing and vehicle kilometre reduction) measures contribute to a cumulative reduction of 1.91 $MtCO_2eq$. in CB1 2021 – 2025, and 8.82 $MtCO_2eq$. in CB2, 2026 – 2030.

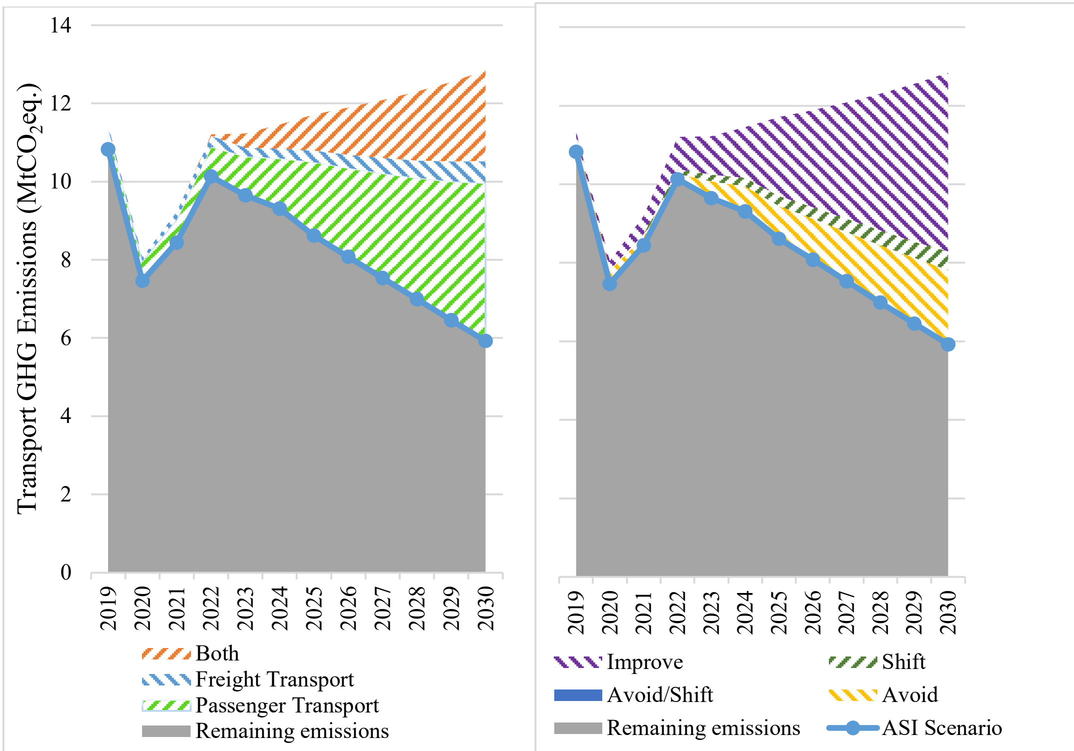


Figure 22: Contributions of the passenger transport and freight transport sector-based scenarios to overall emissions avoided in the transport sector for the LEAP Ireland ASI scenario compared to the reference (2019 – 2030), Contributions of the "Avoid," "Shift", and "Improve" based scenarios to overall emissions reductions in the transport sector for the LEAP Ireland ASI scenario compared to the reference (2019 – 2030)

4.6. Discussion

4.6.1. Methodological Advancements

Policy-defined transport measures for a country were simulated in the context of a carbon budget for the first time. Methods, models, data, and assumptions are made openly available. The relative contribution of "Avoid," "Shift," and "Improve" measures are quantified. The contribution of passenger versus freight transport is also discussed. Here, the Irish Passenger Transport Emissions and Mobility (IPTEM) model is coupled with LEAP to develop the LEAP Ireland ASI model. A key methodological advancement shown in the study meant that it is now possible to quantify and compare measures that target specific travel purposes or cohorts of travellers (e.g., commuters, school pupils) with measures that target specific technologies, mode types, trip purposes, and fuels.

The LEAP Ireland ASI model is openly available (O'Riordan et al., 2023b), and the assumptions for the 23 Avoid, Shift, and Improve scenarios are included in Appendix C. Technology fuel consumptions, energy and emissions intensities, mode share rates are provided for each scenario. This allows for open interrogation of the assumptions made and further exploration of passenger and freight transport scenarios.

The methods in this study also include the interaction between transport measures and account for the double-counting effect between measures. The novelty in this study is in the combination of the following three features: 1) bottom-up national data and scenario development on passenger and freight transport, 2) the application of the ASI framework to simulation modelling, and 3) the evaluation of emissions reductions from transport in the context of national policy and cumulative carbon budgets.

4.6.2. Policy Implications

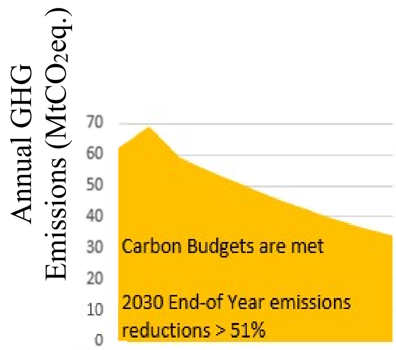
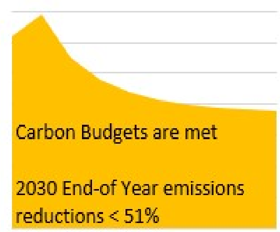
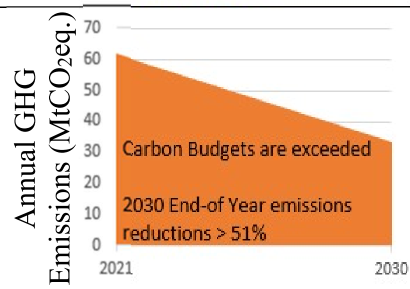
Carbon Budgets and Sectoral Ceilings

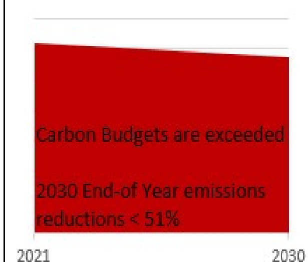
The results from the ASI scenario show that meeting CAP targets on time would help the transport sector stay within its sectoral ceiling emissions target.

Savings accumulate as the decade continues, provided action occurs during the first budget period. As the reductions of the first budget continue in the second budget period, there is an additional benefit. Thus, early, and sustained emissions reductions are critical to accumulate carbon budget savings in the transport sector.

The modelled scenario shows that the transport sector achieves its sectoral emissions ceiling, and by implementing the measures outlined in CAP 2023 on time, there is evidence to support that carbon budgets could be met, though this also depends on the performance of other GHG emitting sectors (predominantly the agriculture, electricity, residential, industry, and services and land-use, land-use change, and forestry sectors) Despite the end-of-year 51% reduction target for the transport sector not being achieved, the overall sectoral emissions ceiling for the ASI Scenario is met for CB1 and CB2. The cumulative emissions are more important than the end-of-year emissions targets, as reducing carbon budgets and having a deep decarbonisation pathway over several years results in lower carbon emissions going into the atmosphere. The relationship between carbon budgets and end-of-year emissions reduction targets is highlighted in Table 14.

Table 14: Carbon Budgets versus End-Of-Year Sectoral Ceilings performance matrix

<table>
<tr><td></td><td></td><td colspan="2">Meeting the End of Year Sectoral Ceiling targets</td></tr>
<tr><td></td><td></td><td>✓</td><td>✗</td></tr>
<tr><td rowspan="2">Meeting the cumulative Carbon Budgets over the specified time</td><td>✓</td><td>*Early and sustained action*

</td><td>*Early action, insufficient continual cumulative reductions*

</td></tr>
<tr><td>✗</td><td>

Delayed action, end-of year 2030 target met but interim emissions too high to meet cumulative target</td><td>

Business as usual
Insufficient action</td></tr>
</table>

Insights on the ASI Framework

On an individual basis – the most successful measures were as follows – ASI 18 (840,000 EVs by 2030), ASI 22 (10% Biofuels in Petrol, and 20% Biofuels in Diesel by 2030), ASI 2 (20% reduction in all vehicle kilometres by 2030), ASI 3 (20% reduction in car kilometres by 2030), ASI 19 (20,000 commercial EVs by 2030), and ASI 1 (Working from home 2 days per week). The individual "Shift" measures were not as impactful but collectively account for 0.82 $MtCO_2eq$. cumulative emissions reductions in Carbon Budget 1 (9.5% of total emissions avoided in ASI scenario for CB 1) and 1.9 $MtCO_2eq$. cumulative emissions reductions in CB2 (7% of total emissions avoided in the ASI scenario for CB 2). The low impact from “Shift” measures could be related to a relatively low ambition in projects instigating modal shift compared to the “Avoid” and “Improve” measures set by the CAP 2023.

Though the scenarios focusing on demand reduction of 20% for car, commuting, and commercial transport are modelled to show significant reductions (ASI 2, ASI 3, ASI 4), the specifics behind such a measure and *how* this target could be met are unclear. It is critical to specify what options and methods are possible to reduce the demand for freight transport beyond the modelled target of a reduction of 20% of commercial vehicle kilometres. Over-reliance on emissions reductions on a handful of key policies is a high-risk strategy, should one of those targets not be met, and increasing ambition with modal shift targets can diversify reliance on “Avoid” and “Improve” type interventions.

To avoid double counting policy achievements and associated emissions savings, policies can address the existing overlaps in regional and national Action Plans and co-ordinate funding for these interlinked policy areas. Analysts planning for decarbonisation need to be aware of both regional and national transport plans when assessing the possibilities for model shift and demand reduction, and view cities as part of a wider national strategy for decarbonisation under the Climate Action Plan.. A solution would involve establishing tighter linkages in policy plans with regional plans and explicitly referencing how these policies align. CAP's success hinges on the concurrent development of regional transport strategies like CMATS, LMATS, and GMATS, complementing each other effectively. These strategies should align with CAP targets, with a particular emphasis on using the ASI framework to achieve the emissions reductions required.

Freight Transport versus Passenger transport

The number of measures outlined in CAP for passenger transport far outnumbered the number of freight transport measures. This was also reflected in the number of scenarios modelled that were exclusively freight transport-related (2 scenarios) versus exclusively passenger transport-related (19 scenarios). As there is a lack of detail on the specific policy measures and options available for freight transport decarbonisation, the solution space and, thus, the modelled scenarios for freight shifting and load shifting from HGV transport is not shown, and the possibilities for HGV decarbonisation may be overlooked as a result. Exploring such possibilities could bring about greater decarbonisation in the freight transport sector and contribute to necessary reductions in the transport carbon budget. Specific targets such as – targets for fleet switching numbers, records of the number of heavy goods vehicles, rather than just the tonne-kilometres of carried transport, and greater research on the possibilities for load shifting to smaller electrified vehicles in city areas in Ireland and what tonne kilometres would be suitable for such switching could be a possible target in the context of climate action plans and then modellable under the LEAP Ireland ASI model.

Interaction Effect between Policies

An ensemble approach to calculating the interaction effect and account for double counting for all scenarios is shown in Figure 20. For each of the scenarios, the impact of all measures is compared to the impact of the measures without a particular scenario, as described in Equation 13.

The interaction effect between groups of certain policies is shown in the waterfall chart (Figure 21 (a). That interaction is calculated by comparing the modelled combined impact with the sum of the separately calculated individual impact. The interaction between the group of passenger transport policies, freight transport policies, and the combination of both policies was determined. The interaction of 0.58MtCO_2 reduces the net emissions reduction figure of the combination of policy scenarios and accounts for double counting and overlapping impacts – one such example is that if biofuel mixing is introduced in the freight transport, the decarbonisation impact of electrification of light goods vehicles is reduced, as the fossil fuel fleet would be partially decarbonised from the biofuel policy (that impacts both passenger and freight transport).

4.6.3. Comparison with the Environmental Protection Agency Projections

In June 2023, the Irish Environmental Protection Agency released an emissions projections inventory, with top-down calculations on emissions based on improvements from CAP 2023 through their "With Additional Measures" scenario (Environmental Protection Agency, 2023). Under the "With Additional Measures" scenario, transport emissions are projected to decrease by 35% (from 10.9 MtCO_2eq. to 7.2 MtCO_2eq.) between 2021 and 2030. This reduction is driven by incremental increases in the Biofuel Obligations Scheme, widespread adoption of electric vehicles (943,500 EVs by 2030), and a 20% reduction in total vehicle kilometres through sustainable policies. The scenario also considers the impact of transport infrastructure projects like DART

Expansion and Bus Connects. The significant impact of COVID restrictions on transport emissions in 2020 and the rebound in 2021 are evident in the projections also.

In these projections, the transport sector is expected to overshoot the sectoral emissions ceiling for both CB1 and CB2. In the case of the LEAP Ireland ASI model, a decrease of 35.6% over the period up to 2030 is projected compared to 2022. The key differences between the assumptions outlined in the EPA's "With Additional Measures" scenario for transport and LEAP Ireland's ASI scenario are outlined in Table 15.

Table 15: Key differences between the EPA With Additional Measures projections and the LEAP Ireland ASI mode approach

Key difference	EPA With Additional Measures (WAM) model	LEAP Ireland ASI model
Approach	Top-down	Bottom-up
Commercial vehicles	95,000 commercial electric vehicles	20,000 commercial electric vehicles (ASI 19)
Increase in daily public transport journeys	The passenger kilometres are increased to have 50% increase in daily active travel journeys by 2030 and a 130% increase in daily public transport journey by 2030	Journeys are increased to 125,000 per day from the current rates, and typical journey distances for these active journeys apply. The journeys modes are shifted from other mode types, the reduction in private car travel, taxis, cycling, and walking is such that it is in proportion to their percentage mode shares and reduced by the same amount as the public transport modes – bus and rail - are increased (ASI 7).
E-bikes	Not explicitly mentioned	E-bike uptake is included as a modal shift measure (ASI 9)
Additional cycling infrastructure	Not explicitly mentioned	Additional cycling infrastructure is included as a measure that would encourage a modal shift from public transport and car transport to active travel (ASI 10)
Rural buses	Not explicitly mentioned	Rural bus connect schemes are included (ASI 16)
School Sustainable Transport	Not explicitly mentioned	Increased public transport and active travel for schools are included (ASI 14)
Speed reduction	Not explicitly mentioned	Speed reductions on national roads are included (ASI 23)

4.6.4. Uncertainty

Translating policy measures to modelling insights requires insights and assumptions on the modeller's behalf. This model is openly available to further the deliberation process, with assumptions about the modelled passenger kilometres, modal shift rates, and uptake rates included in Appendix C.

As many scenarios target the same sectors – e.g., train and bus transport compete for public transport modal shift- a limitation of the model is that it is unclear how each policy measure interacts in the real world. Real-world conditions and calibrations can be helpful in the case of an ex-post evaluation of the success and implementation of these policies. As the policies are introduced, passenger kilometres, modal shares, and emissions from transport can be monitored to see to what extent models need adjustment variables or confounding variables based on real-world calibration.

Modal shift

Compared to the “Avoid” and “Improve" transport measures, the modal "Shift" does not contribute as much to overall GHG emissions reduction. These scenarios must explore possibilities for radical public transport infrastructure rollout in the short term. They are based on the CAP 2023, as shown in Table 9. Whether other opportunities lie for a modal shift with national rollouts or restrictions on private vehicle use remains to be seen. Additional research is needed on the potential of electric bikes and mass public transport infrastructure developments and specifically on how they impact passenger transport demand by mode type, so their role in the decarbonisation transition can be more clearly calculated and understood. More ambition with public transport plans and timeliness is critical with these plans to encourage a radical modal shift, unlike the modal shift in these scenarios. An area for future work is to examine the possibilities of modal shifts based on micro-mobility rollout. Micro-mobility could further the role of "Shift" based policies for transport decarbonisation.

Time delays and target achievement risks

Delays in achieving targets such as the 845,000 electric vehicles rely on the private market and supply chains and reasonable pricing for mass market adoption. Metrolink and light rail extension projects are pending reviews, and these projects being delivered before 2030 is unlikely. Therefore, as future work, applying probabilities and risk factors to emissions savings and project implementation is an area for future work stemming from this study.

4.6.5. Future Work

In this study, I cover the individual impacts of the ASI interventions, demonstrate the utility of bottom-up simulation modelling in highlighting the individual impacts of these policy measures and provide a comparison and analysis of the most impactful strategies and the variety of strategies available to policymakers and planners. The individual comparisons provide context to the relative impact of each intervention and ensure a wide range of policy measures across the ASI framework.

Future work could focus on the combinations of policy measures that can be implemented and the costs associated with the policy interventions. Various policy combinations or packages can create synergies or result in a net sum of less than or greater than its parts. For example, a bus electrification scheme combined with an increased modal shift away from private car use to using buses would result in energy savings greater than the sum of the individual parts. The bonus effect is due to the positive interaction between bus electrification (i.e., an "Improve" based policy measure) and increased bus use (i.e., a "Shift" based policy measure). On the other hand, a bus electrification scheme ("Improve" measure) combined with a reduced bus occupancy due to an increase in the use of active modes of travel ("Shift" measure) and more commuters working from home (an "Avoid" measure), would result in a reduced overall emissions savings when compared to the sum of the individual parts. The reduction is due to the measures targeting the same passenger kilometres.

Future research needs could include investigating the role of micro-mobility in the context of freight and passenger decarbonisation. As findings from empirical studies inform scenarios for the decarbonisation of transport, more information on technological advancements and progress in the freight transport sector, and in micro-mobility can inform decarbonisation scenario development for these technologies and policies. Modelling over longer periods beyond 2030 could include technologies not yet commercially available or in the policy sphere, as targets are typically not set for technologies that aren't available yet (e.g., hydrogen in the freight sector). A greater understanding of the electric Heavy Goods Vehicle market can also inform whether targets for the electrification of heavy goods in Ireland are feasible and inform scenarios focusing on this issue.

Currently, aviation and maritime transport emissions are not included in emissions modelling or legislation in Ireland. Aviation is included in UK emissions balances (United Kingdom HM Government, 2023). Transport sectoral ceiling emission targets in future carbon budgets could be adjusted to factor in aviation and maritime transport that originates or refuels in Ireland. Modelling aviation and maritime transport could enable deeper analysis and regulation of the fuels used for aviation and maritime transport linked to Ireland. The modelling scope could be expanded to include maritime and aviation in the emissions calculations, and scenarios for the decarbonisation of these sectors could be explored.

Modelling risk and cones of uncertainty for each of the scenarios is an area for future work. Quantifying and applying risk factors for decarbonisation scenarios and assigning these probabilities to emissions reductions can also inform policymakers on the policy measures that have the greatest potential to deliver savings. Combining emissions savings quantity with emissions savings likelihood can contextualise the policy measures with the greatest certainty with their emissions savings and reduce uncertainties around carbon budget target achievement.

4.7. Conclusions

In this chapter, tangible climate policy initiatives based on national climate policy plans were integrated into a simulation model to compute annual transportation emissions. This allows for comparing policy-defined transport actions within a carbon budget framework. The study quantifies the effectiveness of "Avoid," "Shift," and "Improve" (ASI) measures in reducing emissions. This helps provide insights into the effectiveness of transport policy interventions.

Using detailed national data and scenario construction for passenger and freight transportation coupled with the ASI paradigm, an exhaustive analysis of emission reductions can be conducted in the context of national policy and cumulative carbon budgets. Incorporating interactions among transport measures and measures to prevent the double counting multiple and concurrent transport decarbonisation measures results in a more robust appraisal of policy impacts.

The outcomes demonstrate that by implementing Climate Action Plans alongside ASI interventions, the transport sector can meet its emission targets for both Carbon Budgets 1 and 2. The assessment evaluates the impact of 19 passenger transport measures, 2 freight transport measures, and 3 cross-cutting transport sector measures. Synergies among these policies are considered, and their cumulative effect upon implementation is assessed. The projected total carbon budget for Carbon Budget 1 (2021 – 2025) under the ASI Scenario is 46 $MtCO_2eq$, significantly below the sector's emission cap of 54 $MtCO_2eq$. Comparable reductions are anticipated for Carbon Budget 2 (2026 – 2030), with a projected reduction of 2 $MtCO_2eq$. below the 37 $MtCO_2eq$. sectoral emission cap. These cumulative emission savings highlight the importance of early and sustained emissions mitigation, as savings accumulate over time and increases the likelihood of staying within carbon budgets.

Chapter 5. Policy Simulation Modelling to inform National Carbon Budget Pathways[6]

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5.1. Abstract

Carbon budgets are emerging as a key policy tool to set cumulative targets on greenhouse gas emissions at a national and international level. In this chapter, I develop a methodology for simulation modelling of energy demand and carbon dioxide (CO_2) emissions to assess the implication of different scenarios on sectoral emissions ceilings and carbon budgets. I demonstrate how this simulation modelling approach to carbon budgets applies to Ireland's Climate Action Bill, which sets a legal obligation to keep within defined sectoral emission ceilings. The transport, residential, industry, and electricity sectors meet Carbon Budget 1 (2021 – 2025), and the residential and services sector meets Carbon Budget 2 (2026-2030) sectoral ceilings in the scenario presented. This chapter also examines the interaction effect between these policy scenarios. The interaction effect between public transport and modal shift shows an additional emissions savings of 0.1 $MtCO_2$. The interaction effect also highlights a 'double counting' effect between the uptake of Electric Vehicles (EVs) and increased biofuel mixing for private car transport of 0.3 $MtCO_2$, and for EVs and passenger transport modal shift of 0.2 $MtCO_2$.

[6] Based on the publication: O'Riordan, V., Mac Uidhir, T., Rogan, F., "Policy Simulation Modelling to Inform National Carbon Budget Pathways". Available at https://doi.org/10.1016/j.esr.2023.101237

5.2. Highlights

- Multi-sector energy and emissions simulation model methodology with carbon budget analysis is presented
- Interaction effect between public transport and modal shift showing additional savings of 0.1 $MtCO_2$
- Interaction effect showing emissions savings overlap and 'double counting' effect between EVs uptake and biofuel blending of 0.3 $MtCO_2$, and EVs and modal shift 0.2 $MtCO_2$
- Discrepancies in past GHGs accounting adds uncertainty to carbon budget scenarios
- Policy interaction effect analysis finds cases of synergies and diminishing returns

5.3. Introduction

5.3.1. Top-down and Bottom-up Target Setting

The 2015 Paris Agreement brought about the use of country-level emission reduction pledges (nationally determined contributions (NDCs) to underpin the achievement of a global temperature target. However, since 2015, there has been growing misalignment between NDCs and the required reductions in global greenhouse gases (GHG) to achieve the global targets of limiting global warming to 1.5°C. The 2019 UNEP (United National Environmental Program) Emissions Gap Report, which addressed this gap, noted the need for global GHG emissions to reduce by 7.6% per annum for the 1.5°C target to be achievable. If sufficient climate action begun in 2010, average annual reductions of GHG emissions of just 3.3% would have been required (United Nations Environmental Program, 2019). These top-down calculations by the UNEP (United National Environmental Program) have been used to guide updated country-level targets, which represents a departure from the Paris Agreement emphasis on bottom-up NDCs.

An example of this comes from the case of Ireland which ratified the Paris Agreement in 2016. Following a general election in 2020, prospective government parties engaged in extensive political negotiations on future climate mitigation targets that were strongly influenced by the 2019 UNEP Emissions Gap report figure of 7.6% p/a reduction. A reduction in GHGs of 7% p/a was proposed *prior* to any detailed analysis on the technological and policy feasibility of this pathway and was the basis for the final agreement of the new Irish government. Preliminary analysis using the TIMES Ireland Model did provide an early indication that the 7% target was technically feasible (Daly et al., 2021).

The process of updating NDCs represents a negotiation between top-down global analysis of the necessary scale in GHG emissions reductions and a bottom-up country-specific analysis of what is feasible. Given the global authority of UNEP, it is possible that many countries will use UNEP type global analysis to align their national targets to the scale of global change required. However, global targets do not convert simply into national targets due to – in the words of the UNFCCC - "differentiated responsibilities and respective capabilities, in the light of different national circumstances" (The Paris Agreement, 2015). Feasible deep decarbonisation pathways – at a national level - require detailed national analysis of all GHG producing activities (energy, transport, agriculture, land-use).

5.3.2. Carbon Budgets: from Global to National

Global temperature change is driven by cumulative GHG emissions (Rogelj et al., 2019). A global carbon budget both aligns with best practice in climate science and the need to effectively communicate the importance of limiting cumulative GHG emissions rather than single-year GHG emissions (Glynn, 2021). Carbon budget governance is emerging as a method to align national climate policy with global climate action targets. However, while there has been growth in countries adopting net zero emission targets, recent reviews have noted just 4 countries with a carbon budget governance approach in legislation (A. Z. Smith, 2021). This is despite net-zero targets not being equivalent to a carbon budget approach and therefore less consistent with climate science (Mc Guire et al., 2020).

In 2021, Ireland passed climate legislation to reduce GHG emissions by 51% by 2030 (compared to 2018) and be climate neutral by 2050; crucially these new targets must be rendered into 5-year carbon budgets and sectoral emission ceilings (Government of Ireland, 2022a). The first carbon budget (2021 – 2025) of 295 $MtCO_2eq$. represents an average annual reduction in emissions of 4.8% per annum; the second carbon budget (2026 – 2030) of 200 $MtCO_2eq$. is equivalent to an 8.3% average annual reduction. These targets are some of the most ambitious mitigation targets in the world and are particularly challenging for Ireland, which in 2020 reduced non-Emission Trading Sector (ETS) GHG emissions by just 7% compared to a 20% target (Environmental Protection Agency, 2021a). By changing its climate governance approach to carbon budgets for 2021-2030, there comes a need to continually update and assess annual emissions and monitor the cumulative emissions over carbon budget periods.

5.3.3. Modelling to Inform Climate Policy

Like many countries, Ireland has used a range of energy system models to inform various aspects of energy and climate policy for over a decade. The TIMES Ireland Model has recently been used to contribute to calculating carbon budgets at a national level. However, the challenges of modelling near-term deep decarbonisation policy pathways and tracking their performance over the lifetime of a single carbon budget presents a new set of challenges that haven't been faced before (Balyk et al., 2021; Chiodi et al., 2013;

Glynn et al., 2019; Rogan, Cahill, Daly, Dineen, Deane, Heaps, Welsch, Welsch, et al., 2014).

This chapter presents a case study of an energy system simulation model – the LEAP Ireland model – developed to explore pathways and combinations of policy measures to achieve carbon budget deep decarbonisation targets arising from a global benchmark from the UNEP. The scale of change required by deep decarbonisation necessitates multiple policy measures, which makes interaction effects between policy measures unavoidable. The LEAP Ireland model incorporates many scenarios that can account for and quantify these complexities for the first time to support analysis on the range of policy options required to achieve deep decarbonisation.

5.3.4. Simulation Modelling of Policy Measures

The increasing need to focus on deep decarbonisation pathways has presented new demands on the capabilities of energy system models to understand complex interaction effects across different sectors at a national and international scale. For example, in the context of modelling net-zero emission pathways, Pye et al. (2021) describe three main challenges: (1) the need to represent new mitigation options especially on the demand-side, (2) the need for enhanced model functionality, and (3) the need for modelling practice to adapt to new policy contexts. Pfenninger et al. (Pfenninger et al., 2014) and Wiese et al., (Wiese et al., 2018) describe five main challenges including: (1) growing energy system complexity, (2) a need for interdisciplinarity, (3) model utilization, (4) uncertainty in modelling results, and (5) the need for models to be transparent, methodologically sound, and reproducible.

Simulation models are particularly primed for communication and interaction with stakeholders, as the operation of the simulation model and the user interface can be particularly transparent. The importance of simulation modelling to educate on climate related policy decisions is notable (Rooney-Varga et al., 2020) and is also a key objective in developing the LEAP Ireland model. While optimisation modelling is based on the theory that one solution is optimal, simulation modelling is not as prescriptive, responding to the input parameters and calculating a projection of what could happen, rather than suggest what should happen. As noted in Lund et al. (2017), as simulation modelling is not deterministic and is exploratory, it leaves more space for political and societal decisions. It does not base decision making on a single set of economic efficiency values, rather it generates a range of developmental pathways. This provides the benefit of allowing politicians and society to decide what they value and have a wider discussion about the range of developmental pathways they choose. It is for these reasons that a simulation model is chosen to explore a carbon budget pathway scenario, and the methodology is demonstrated in this chapter to show how it could be used for other policy scenarios under consideration by stakeholders. For example, Fleiter et al. (Fleiter et al., 2018), focused on the energy transition for the industry sector, and this simulation model seeks to develop multi-sector scenarios including the industry sector in the context of a deep decarbonisation transition that determines whether the energy emissions from these sectors align with carbon budget targets up to 2030.

Optimisation models have progressed to develop ‘second-best’ (Strachan & Usher, 2012), near-optimal (Price & Keppo, 2017), or ranges of solutions from optimisation models (Yue et al., 2020). These modelling approaches have been developed to overcome the assumption that least-cost optimisation is the best option for decarbonisation. Adapting a hybrid modelling approach to difficult policy questions such as what carbon budgets should be set and how can these carbon budget be met is helpful to bolster the evidence base and sense-check model outputs. For example, Mulholland et al. (Mulholland et al., 2017a) employed a simulation and optimisation dual approach to developing scenarios for the freight transport sector. The authors show how analysis from a simulation model can enhance robustness of constraints set in optimisation models such and complement the optimisation models' results.

A review of LEAP literature identified 61 examples of journal articles, technical reports, books, and applications developed using the LEAP framework at national, sub-national, and regional levels. Approximately half (30) of the LEAP models reviewed are supply-side only analyses and the remainder examine energy supply and demand. LEAP is freely available for non-commercial purposes.

5.3.5. Modelling to Inform Climate Policy in Ireland

A range of energy system modelling tools have been developed in Ireland, in response to the need for more integrated climate planning and evidence-based policy support. These tools include macroeconomic models, energy system optimisation models (ESOM), integrated dispatch models, and simulation modelling tools.

A suite of macroeconomic models underpin national economic forecasting, these include the HERMES (Harmonised Econometric Research for Modelling Economic System) model (Bergin et al., 2013), COSMO (Core Structural Model) (Bergin, Conroy, Rodriguez, Holland, Mcinerney, et al., 2017), and the Ireland Environment, Energy and Economy (I3E) model (Bruin et al., 2020), a computable general equilibrium (CGE) model. The EMPowER model (UCD Energy Institute, 2019) considers system cost and carbon emissions associated with building energy, consumer behaviour, electricity networks, and the climate. The TIMES (The Integrated MARKAL-EFOM System) Ireland Model (TIM) (Balyk et al., 2021) is a least-cost energy system optimisation model which provides future decarbonisation pathways for the Irish energy system. TIM has been used in the development of the Low Carbon Energy Roadmap (P. Deane et al., 2013) and supported the development of Ireland's first set of carbon budgets.

A LEAP model of the Irish energy system as described in (Rogan, Cahill, Daly, Dineen, Deane, Heaps, Welsch, Welsch, et al., 2014) modelled energy supply and demand for the period of 2009-2020. Scenarios representing both individual policy measures and packages of policy measures quantified the impact on energy demand, but not on energy related emissions. The analysis also described a methodology for accounting the double counting effect but didn't allocate this to individual policy measures. The LEAP Ireland 2050 model improved disaggregation of the residential and transport sectors for national emissions. The model included scenarios which examine the large-scale deployment of electric vehicles and residential retrofitting in Ireland (Mac Uidhir et al., 2020a). The LEAP Dingle model supports the evidence base for the complete electrification of the Dingle peninsula, a small rural village with a population of about 3,000 people, with a primary focus on the deployment of electric vehicles, retrofitting, decarbonisation of agricultural activity, and the deployment of renewable electricity generation (McGookin et al., 2022).

5.4. Methodology

In this section, I describe the overall LEAP Ireland model architecture, including the external primary data sources and spreadsheet models which feed into the LEAP Ireland model. The assumptions which underpin the Reference scenario with which the UCC Sectoral Ceilings Scenario is compared are outlined. The UCC Sectoral Ceiling Scenario – named after the university of the research group conducting the study, University College Cork, is based on a series of scenarios simulated based on actions outlined in the Government of Ireland's Climate Action Plan. The scenarios covered do not cover all aspects of the Climate Action Plan but do cover some of the key policy targets currently being implemented that are central to Ireland's low carbon transition.

5.4.1. The Low Emissions Analysis Platform

The Low Emissions Analysis Platform (LEAP) is a modelling tool developed and maintained by the Stockholm Environment Institute (SEI). LEAP can be used for energy and emissions systems simulation modelling. The software is available to download online (Heaps, 2022) and is made freely available to academic organisations, non-governmental organisations, not-for-profit government agencies, and World Bank-tier 1 (WBT-1) economies. It is user friendly and has low data requirements due to the built-in environmental and technology/environmental database (TED).

5.4.2. LEAP Ireland Model Architecture

The LEAP Ireland model contains national demand figures for residential, transport, services, agriculture, and industry sectors. It also contains energy intensity values and, when combined with fuel types, accounts for the carbon dioxide and other pollutant information from each of the sectors. An overview of the model architecture to include the external input models soft-linked and hard-linked to the LEAP Ireland model and the sectors covered within the LEAP Ireland model is illustrated in Figure 23.

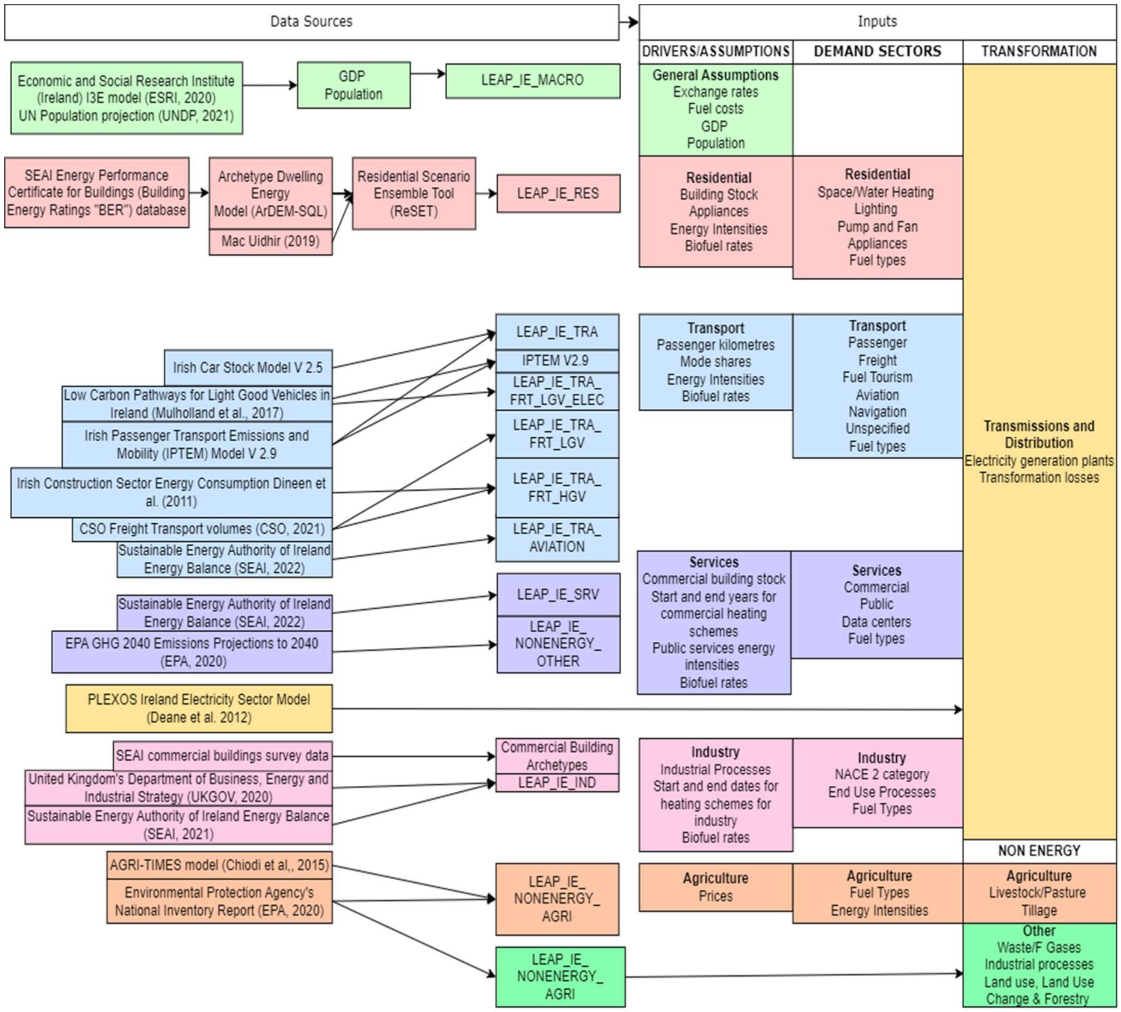

Figure 23: Overview of the LEAP Ireland model data sources, inputs, and sectors

5.4.3. External Models and Data Sources

The following external models are incorporated into the LEAP Ireland Model.

Irish Car Stock Model V 2.5: The Irish Car Stock model is provided in the supporting folder file accompanying the LEAP Ireland model. The Irish Car Stock model is a bottom-up technology stock model initially developed by Daly et al. (Daly & Ó Gallachóir, 2011) that also includes future projections for energy consumption based on fleet ageing, biofuel mixing and improvements in energy efficiency. The latest version of the Irish Car Stock Model is available from an open-source repository (O'Riordan, Mulholland, et al., 2021).

Irish Passenger Transport Emissions and Mobility Model: The Irish Passenger Transport Emissions and Mobility Model is a passenger transport spreadsheet model developed by O'Riordan et al. (O'Riordan, Rogan, Ó Gallachóir, Mac Uidhir, et al., 2020c; O'Riordan, Rogan, Uidhir, et al., 2022).

Archetype Dwelling Energy Model-SQL*:* The Archetype Dwelling Energy Model SQL (ArDEM-SQL) is a modelling tool initially developed by Dineen et al (D. Dineen et al., 2015), and Mac Uidhir et al. (Mac Uidhir, Rogan, Collins, Curtis, & Gallachóir, 2020a, b). The ArDEM-SQL model is a simulation tool based on the Dwelling Energy Assessment Protocol (DEAP) and has information relating to residential households. Other data sources that inform the LEAP Ireland model are included in Appendix D..

5.4.4. LEAP Ireland Model Structure

Key Assumptions

Key assumptions provide projections for fuel price, GDP, and population. These key assumptions are required to calculate future transport and residential stock requirements and outputs. As increased stock and output leads to greater activity, the relationship between fuel price, GDP, and population and activity is key to modelling future energy demand. For the sectors of transport, residential, services, industry, agriculture, the LEAP Ireland model relies on projections that uses econometric equations based on the relationship between fuel price, population, GDP, and activity demand. GDP and population projections for the reference scenario are included in Appendix D..

Sectors

Transport

Scenarios for transport can broadly be defined under the five main demand categories of transport:

Passenger Transport: Passenger Transport is defined in terms of total passenger kilometres is divided into 6 “modes” (Private Cars, Bus, Rail/DART/Luas, Cycling/Walking and Taxis). Assumptions for passenger transport are listed in Appendix D..

Freight Transport: Freight data includes the total tonne-km activity of vehicles, subdivided in weight classes and economic sectors. Freight in the LEAP Ireland model is subdivided into Light Good Vehicles (LGVs) and Heavy Good Vehicles (HGVs). LGVs are grouped by fuel type, weight class and age and HGVs are grouped by NST categories (Appendix D.), weight class and fuel type.

Aviation: Aviation activity and energy consumption is subdivided into domestic travel and international travel. Domestic and international aviation fuel consumption projections are included in Appendix D.G. For the sectoral ceilings and carbon budget analyses, international aviation is not included, and thus the energy consumption and associated emissions are excluded from the total emission calculations.

Navigation: Navigation data is provided as total energy consumption in kilotonnes of oil equivalent. The energy consumption values for navigation are based on annual emissions accounts from the EPA (Environmental Protection Agency, 2022). Energy consumption projections for Navigation sector are provided in Appendix D..

Fuel tourism: Fuel tourism is defined by the ratio of the pound to the euro as this was found to be a strong driver of cross-border fuel consumption and purchasing (Kennedy et al., 2018). Energy consumption figures relating to cross border tourism are included in Appendix D..

A summary of the transport model activity and intensity units is included in Table 16.

Table 16: Summary of Transport activity and intensity measurements

Sub sector	Activity measurement	Intensity measurement
Road private cars	Passenger-km (Pkm)	MJ/Pkm
Buses	Passenger-km	MJ/Pkm
Walking/Cycling	Passenger-km	MJ/Pkm
Passenger Rail	Passenger-km	MJ/Pkm
Heavy goods vehicles (HGVs)	Tonne-km	MJ/Tkm
Light good vehicles (LGVs)	Vehicle-km	MJ/Vkm
Rail Freight	Tonne-km	MJ/Tkm
Fuel Tourism	N/A	kToe
Navigation	N/A	kToe
Aviation	N/A	kToe

Residential

The residential sector demand is defined by three end uses a) Space heating, b) Water heating and c) Lighting and Appliances. The types of dwellings are defined by whether the dwelling is new or existing, by the type of housing (detached, terrace or apartment) and by energy rating. Fuels delivering space and water heating include electric heat pumps, coal, natural gas, solid fuels, and kerosene. A summary of the residential activity and intensity units is included in Table 17.

Table 17: Overview of residential energy end use activity and intensity measurement units

Residential Energy End Use	Activity measurement	Intensity measurement
Main Space Heating	Number of households	kWh per household
Secondary Space Heating	Number of households	kWh per household
Main Water Heating	Number of households	kWh per household
Secondary Water Heating	Number of households	kWh per household
Lighting, Pumps and Fans	Number of households	kWh per household
Appliances – White Goods	Share of all households	kWh per household
Appliances – Cooking	Share of all households	GJ OR kWh per household

Industry

The industry sector's data is provided by the Environmental Protection Agency's Energy Balance, which adapts the NACE (European standardized economic classifications – Appendix D.) convention in reporting its energy consumption. Fuel consumption is defined per share of economic output (which is defined in Euros). A summary of industry activity and intensity units is included in Table 18. The fuel types included are electricity, natural gas, oil, coal, and biomass energy.

Table 18: Summary of industry activity and intensity units

Industry Energy End Use by NACE category	Activity measurement	Intensity measurement
High Heat Treatment Processes (HTP)	% Share of Euros	kT of Oil Equivalent per Euro
Low Heat Treatment Processes (LTP)	% Share of Euros	kT of Oil Equivalent per Euro
Motors	% Share of Euros	kT of Oil Equivalent per Euro
Compressed Air	% Share of Euros	kT of Oil Equivalent per Euro
Lighting	% Share of Euros	kT of Oil Equivalent per Euro
Refrigeration	% Share of Euros	kT of Oil Equivalent per Euro
Space Heating	% Share of Euros	kT of Oil Equivalent per Euro
Other	% Share of Euros	kT of Oil Equivalent per Euro

Services

Data for the services sector can be broadly defined in three sub-sectors.

Public sector: Total energy demand from the entire public sector based on the SEAI energy balance (SEAI, 2021). Recent economic activity is from the Central Statistics Office (CSO) and is measured as gross value added (million euros). The relative spending activity of each of the public sectors is then used to infer the share of energy consumption from each sector.

Commercial sector: Energy intensities and fuel types for the commercial services sector is based on classifications by service types. Fuel intensities by service, building type and building insulation quality. The classification is based on a survey commissioned by the Sustainable Energy Authority of Ireland. The buildings are defined by building type, size, by heating fuel and by building fabric condition (Appendix D.). The data is based on the "Commercial Building Archetypes" spreadsheet.

Data Centres: Data Centre information is from the National Transmission Systems operators capacity statements (EirGrid Group & SONI Ltd, 2021). The data centre electricity demand for the reference scenario is listed in Appendix D..

A summary of the activity and intensity measurements for the services subsector used is in Table 19.

Table 19: Overview of activity and intensity measurements for the services subsectors

Services Subsector	Activity measurement	Intensity measurement
Public Sector	Billion Euro	MJ per Euro
Commercial Sector	Percent share of Buildings by Commercial business type	MWH per building
Data Centres	n/a	TWH

Electricity

The electricity sector is represented in an aggregated form whereby powerplants of similar fuel and efficiency are grouped together into a single generation unit (measured by plant heat rate GJ/MWh). Variable renewable electricity is modelled at a national scale based on total capacity (onshore wind, *offshore, solar). Natural gas Carbon Capture and Storage (CCS) is modelled as a future technology option. Modelled electricity sector units are listed in*

Appendix D. Base year data for generation capacity and modelled electricity demand comes from the national Transmission System Operator, EirGrid (EirGrid Group & SONI Ltd, 2021). Baseline data for other factors (heat rate, availability, fixed & variable O&M costs) are supplied from the PLEXOS Ireland model and the Commission for Regulation of Utilities (CRU, 2020) and is summarized in Table 20.

Table 20: Electricity sector modelled units (capacity, efficiency, availability)

Generation Type	Fuel	MW (2018)	Heat rate GJ/MWh	Availability
Condensing Steam Cycle	Coal	855	9.92	90.9%
Steam Turbine Lignite	Peat	300	9.57	92%
Combined Cycle Gas Turbine	Natural Gas	1537	5.95	93%
Combined Cycle Gas Turbine	Natural Gas	460	6.18	93%
Gas Turbine	Natural Gas	1756	7.12	93%
Open Cycle Gas Turbine	Natural Gas	326	6.5	97.6%
Wind (onshore)	Wind	3475	3.6	Availability Curve
Wind (offshore)	Wind	25	3.6	Availability Curve
Hydro	Water	238	3.6	50%

Solar	Sun	10	3.6	Availability Curve
Biomass	Biomass	114	10.91	92%
Carbon Capture & Storage (in combination with natural gas fired power generation)	Natural Gas	-	7.2	93%

Agriculture

Agriculture's GHG emissions in LEAP are subdivided into energy-based emissions sources and non-energy-based emissions sources. Energy-related demand is defined by electricity and oil consumption, with activity measured by agricultural output at basic prices (million euros) from the Central Statistics Office (Central Statistics Office, 2023). The energy intensity of which is defined as energy consumption per euro of agricultural output from the "LEAP_IE_AGRI" file as highlighted in Figure 23. A summary of energy-related activity and intensity measurements for the agriculture sector is included in Table 21.

Table 21: Energy related activity and intensity measurements for the agriculture sector

Agriculture Sector (Energy related)	Activity measurement	Intensity measurement
All	Euro	Million Euro per TJ

Non-energy-based sources come from biological sources of greenhouse gas emissions, and are typically methane, or nitrogen based. This primarily comes from livestock followed by pasture, tillage, and fertilizer sources. The energy intensity and activity figures for livestock/tillage are provided exogenously from the AGRI-TIMES model (Chiodi et al., 2016). Livestock activity is measured as total number of each livestock category. The methane and nitrous oxide emission intensity for each type of animal is estimated. Non-energy measurements are listed in Table 22.

Table 22: Non-energy GHG emissions measurements for the agriculture sector

Livestock and Tillage Type	Effect	Emissions
Livestock	Methane (Biogenic)	$kTCH_4$
Waste	CO_2	$kTCO_2$
F Gases	CO_2	$kTCO_2$
Industrial Processes	CO_2	$kTCO_2$
Land use change (LULUCF)	CO_2	$kTCO_2$

Scenarios

Reference Scenario

The reference scenario is the "Business as Usual" case with which the UCC Sectoral Ceiling Scenario is compared against. The reference scenario develops projections based on input parameters up to the year 2030. An overview of the reference scenario assumptions is included in Table 23.

Table 23: Reference Scenario in LEAP Ireland

Sector	Sub-Sector	Driver	2018	2030	Source
Transport	Passenger Transport	Activity: Passenger Kilometres	64.7 billion	77.5 billion	(O'Riordan, Rogan, Ó Gallachóir, & Daly, 2022)
	Passenger Transport	Mode share %: Private Cars Passenger Rail Buses Active Modes Taxis	82.1% 6.0% 4.8% 0.8% 0.5%	81.4% 5.9% 5.3% 1.9% 0.5%	(O'Riordan, Rogan, Uidhir, et al., 2022)
	Freight Transport – HGV	Activity: Million Tonne Kilometres	11,538	17,085	(Mulholland et al., 2014; Whyte, Daly, & Gallachóir, 2013)
	Freight Transport – Rail	Activity: Million Tonne Kilometres	103.7	110.3	(Mulholland et al., 2014; Whyte, Daly, &

					Gallachóir, 2013)
	Freight Transport – LGV	Activity: Million Vehicle Kilometres	6,035.05	9,278.20	(Mulholland et al., 2016)
	Passenger Transport/ Freight Transport	Biofuel mixing %: Biodiesel Bioethanol	4.976% 3.33%	6.295% 3.3%	(National Oil Reserves Agency, 2020)
Residential	Space/Water Heating Lighting, Pumps, and Fans Appliances	Activity: Number of households (thousands)	1,707	1,959	(Uidhir, Rogan, Collins, Curtis, & Gallachóir, 2020; Uidhir, Rogan, Collins, Curtis, & Ó Gallachóir, 2020)
	Space/Water Heating Lighting, Pumps, and Fans	EPC distribution % : A B1 B2 B3	5.3 0.8 1.8 6.1 37	20.1 0.7 1.5 5.3 31.1	(Uidhir, Rogan, Collins, Curtis, & Gallachóir, 2020; Uidhir, Rogan, Collins, Curtis, & Ó

	Appliances	C D E F G	23.9 12.2 5.5 7.4	20.1 10.3 4.7 6.3	Gallachóir, 2020)
Commercial	Hotel Office Restaurant & Pub Retail Warehouse	Activity: Number of buildings	5.7 41.8 20.8 50.1 6.7	15.5 37.3 32.6 99 1.8	(Sustainable Energy Authority of Ireland, 2015, 2021)
Public		Activity: Billion European Euro	32.5	49.91	(Environmental Protection Agency, 2022)
Data Centres		TWh	2.2	11.2	(CRU, 2020)
Agriculture		Activity: Million European Euro	7,443.8	8,899.9	(Environmental Protection Agency, 2022)
Electricity		Activity: Electricity	See Appendix D.	Merit order dispatch approach	(CRU, 2020; Government of Ireland, 2022a)

				using 2030 capacity values	

COVID-19 impacts

Public health measures in response to the COVID-19 pandemic led to the wide-scale disruption of social and economic activity in 2020 and 2021. To account for this, a range of adjustments were applied to each sub-sector for these two years. These adjustments are detailed in Table 24.

Table 24: Modelling COVID-19 Impacts in the LEAP Ireland model

Sector	Accounting Method	Source
Transport		
Passenger transport		
Road Private Cars	Private passenger traffic volume used for 2020/21 to adjust for lower private passenger transport.	(Transport Infrastructure Ireland, 2022a)
Passenger Rail	Passenger volumes are adjusted based on government issued travel advisories which enforced lower passenger capacities.	(Irish Rail, 2020, 2021)
Buses	Passenger volumes are adjusted based on government issued travel advisories which enforced lower passenger capacities.	(Bus Éireann, 2020, 2021)

Active Modes	Active modes are reduced in response to the increase of other modes of transport, following COVID adjustments and passenger transport information.	N/A
Taxis	Private passenger traffic volume used for 2020/21 to adjust for lower private passenger transport.	(Transport Infrastructure Ireland, 2022a)
Freight		
LGV	There are decreases in LGV activity for 2020 based on traffic volumes. In 2021 and 2022, there are increases in LGV traffic volumes with respect to pre-COVID 2019 traffic volumes	(Transport Infrastructure Ireland, 2022a)
HGV	Increased freight activity is recorded in tonne-km.	(Central Statistics Office, 2022b)
Fuel Tourism	Updated recorded fuel tourism activity for period 2020/21.	
Navigation	Updated recorded navigation related activity for period 2020/21.	(SEAI, 2021)
Aviation	Change in passenger numbers as reported by Aviation authorities	(Central Statistics Office, 2018; Irish Aviation Authority, 2023)
Residential	Energy per dwelling increased by 9% across all dwellings to adjust for known increased emissions.	(Environmental Protection Agency, 2022)
F-gases	F-gas emissions fell by 14.4% in 2020	(Environmental Protection Agency, 2022)

Waste	Waste emissions fell by 0.8% in 2020	(Environmental Protection Agency, 2022)
Industrial Processes	Industrial process emissions fell by 7% in 2020	(Environmental Protection Agency, 2022)
Industry	Industrial manufacturing emissions fell by 1.5% in 2020	(Environmental Protection Agency, 2022)
Services/ Commercial	Commercial service emissions fell by 0.3% in 2020	(Environmental Protection Agency, 2022)
Services/ Public	Public service emissions increased by 1% in 2020	(Environmental Protection Agency, 2022)

UCC Sectoral Ceilings Scenario

The UCC Sectoral Ceilings scenario contains a combination of scenarios based on Ireland's Climate Action Plan 2021 and 2023 (Government of Ireland, 2022a). A list of scenarios and the assumptions which inform the UCC Sectoral Ceilings Scenario are included below (Table 25).

Table 25 – Policy Measures from UCC Sectoral Ceiling Scenario as included in LEAP Ireland Model

Scenario	Sector	Policy Measure	Target	LEAP Ireland Model
TR_PAS7	Passenger Transport	Light rail (Luas) extended to Finglas	+0.4% increase for passenger kilometre share of Luas	CAP2019, extension of Luas to Finglas
TR_PAS14	Transport – Rail	Low-carbon transport modes	Expansion of electrified rail services	Electrification of all rail lines
TR_PAS34	Passenger Transport	Demand reduction from Working from Home for the Civil Service (Civil Service)	2 days' work-from-home for 20% of the Civil Service	Program for Government reference to 2-day work from home for civil service

TR_PAS35	Passenger Transport	Demand reduction from Working from Home	2 days' work-from-home per week for all professions/job (~55%) that can do so	CAP2021 reference to encouraging working from home
TR_PAS37	Passenger Transport	Increased cycling passenger kilometres (due in infrastructure improvements)	10% increase in cycling passenger kilometres	CAP2021, reference to walking and cycling infrastructure improvements
TR_PAS38	Passenger Transport	Demand reduction from School Sustainable Transport	0.28% increase in passenger kilometre share for walking 0.28% increase in passenger kilometre share for cycling 0.26% increase in passenger kilometre share for bus transport	CAP2021, reference to sustainable travel plans for schools – no specific targets
TR_PAS39	Passenger Transport	Bus Connects for Cork, Limerick, Galway & Waterford	1.3% increase in passenger kilometre share for bus transport	CAP2021, Bus Connects for Cork, Limerick, Galway, Waterford
TR_PAS40	Passenger Transport	Light rail for Cork, Galway, Limerick	+0.005% increase in passenger kilometre share for Rail/DART/Luas transport	CAP2021, light rail transport expansion programs
TR_PAS45	Passenger Trips	Demand shifts	500,000 additional public transport & active travel journeys per day	500K trips per day
TR_PAS46	Transport – Private Cars	Passenger EVs, #	845,000 vehicles with a focus on BEVs	845K vehicles (80/20 for BEV/PHEV)
TR_PAS47	Transport – Buses	Low-carbon transport modes	1,500 EV buses	1.5k EV buses
TR_FR1	Transport – Light Good Vehicles	Zero emissions vans	~95,000 vans	95K vans
TR_FR3	Transport – Heavy Goods Vehicles	Eco Driving for Heavy Goods Vehicles	10% improvement in driving efficiency	UCC analysis
TR_FR4	Transport – Heavy Good Vehicles	Heavy goods vehicles, #	~3.5k heavy goods vehicles	3.5K
TR_BLN5	Road Transport	Bioethanol blend, Vol%	E10	E10

TR_BLN5	Road Transport	Biodiesel blend, Vol%	B20	B20
ELC_5	Renewable Electricity	Onshore wind, GW	Up to ~8 GW	8GW
ELC_5	Renewable Electricity	Offshore wind, GW	~5 GW	5GW
ELC_5	Renewable Electricity	Solar PV, GW	~1.5-2.5	2.5GW
RES_2.3	Residential	Retrofit residential dwellings	500K (B2 BER /cost optimal equivalent or carbon equivalent)	500K B2 retrofits
RES_2.3	Residential	Zero-emission heating in existing homes	400,000 homes with zero-emissions heating	400,000 heat pumps
RES_2.3	Residential & Services	District heating demand, TWh	~2.7 TWh (2.12 residential only)	1.8 TWh (residential only)
RES_8	Residential	Ban on fossil fuel boilers on new builds	0% fossil fuel by 2030	0% fossil fuel by 2030
RES_10	Residential	New homes with zero-emission heating	250K-280K	222K (65% of new dwellings)
BLD_BLN1	Residential/Services/Industry	HVO in heating oil	20% blend	UCC analysis
BLD_BLN2	Residential/Services/Industry	Biogas in natural gas	20% blend	CAP2021
SRV_PUB1	Public Services	Emission abatement from public buildings	50%	50% emissions reduction
SRV_COM3	Commercial Services	Commercial buildings with zero-emission heating, # buildings	50,000 - 55,000 commercial buildings with zero emissions heating	50,000 buildings with electrified heating
IND_ELC2	Industry	Share of carbon neutral heating in total fuel demand	~50-60% of industry energy demand electrified	50% electrified
NEE2	Industry – F-Gases	Emission reduction vs 2014	80% reduction in emissions	80% reduction in F-Gas emissions
SRV_COM2	Commercial Services	Deep Retrofit Commercial Buildings	70,000 buildings (approximately 64% of total stock)	70,000 buildings retrofitted, with heating type electrified

5.5. Results

5.5.1. Energy

Energy demand for the agriculture, industry, transport, services, residential, electricity sectors are included in Figure 24. Even with policy interventions, energy demand for the UCC Sectoral Ceiling scenario is projected to grow (+2.35 TWH, +1.8%) compared to 2018. When compared to the reference scenario in 2030, however, the UCC Sectoral Ceiling scenario energy demand is projected as 36.6 TWH lower (or 16% lower) than the reference scenario. This shows that the policy interventions simulated in the UCC Sectoral Ceilings scenario curb the growth in energy demand relative to the reference scenario and shows an improvement in energy efficiency for the UCC Sectoral Ceilings scenario relative to the reference scenario in 2030.

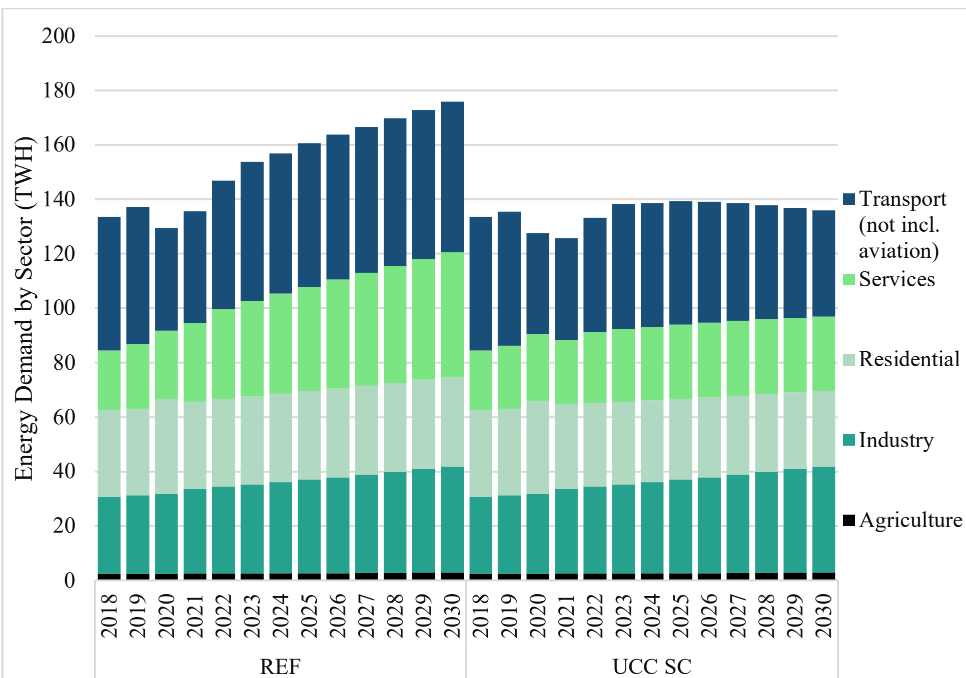

Figure 24: Energy demand by sector for the Reference and UCC Sectoral Ceilings Scenarios (2018 – 2030)

5.5.2. Emissions

In 2022, energy-related emissions were responsible for 52% of Ireland's GHG emissions. Agriculture, F-gases, waste, and industrial processes taking up the remaining 48% in

2022 (Table 26). In Figure 24, energy related CO_2 emissions for both the reference scenario and UCC Sectoral Ceiling scenario are shown. There is a 21% reduction in annual GHG emissions from the UCC Sectoral Ceiling Scenario by 2030, compared to the 2018 baseline, when both energy and non-energy related emissions are included. The Climate Action Plan 2021 sets out the targets for a 51% reduction in annual CO_2 equivalent emissions by 2030 relative to 2018, and thus the UCC Sectoral Ceiling Scenario does not meet this 51% target. The UCC Sectoral Ceilings Scenario *energy*-related emissions have a 46% reduction in annual CO_2 equivalent emissions by 2030. This shows that slow progress in the non-energy related sectors impedes the ability of the scenario to reach its overall 51% reduction target, as once non-energy emissions are included, a reduction of 21% by 2030 compared to 2018 is achieved.

The decoupling of energy demand from CO_2 emissions is also evident. Despite energy demand increasing for the UCC Sectoral Ceilings scenario in 2030 compared to 2018 (Figure 24), the energy related CO_2 emissions associated with these growing demands is projected to fall by 16.4 $MtCO_2eq.$ in 2030 when compared to 2018 (-46%).

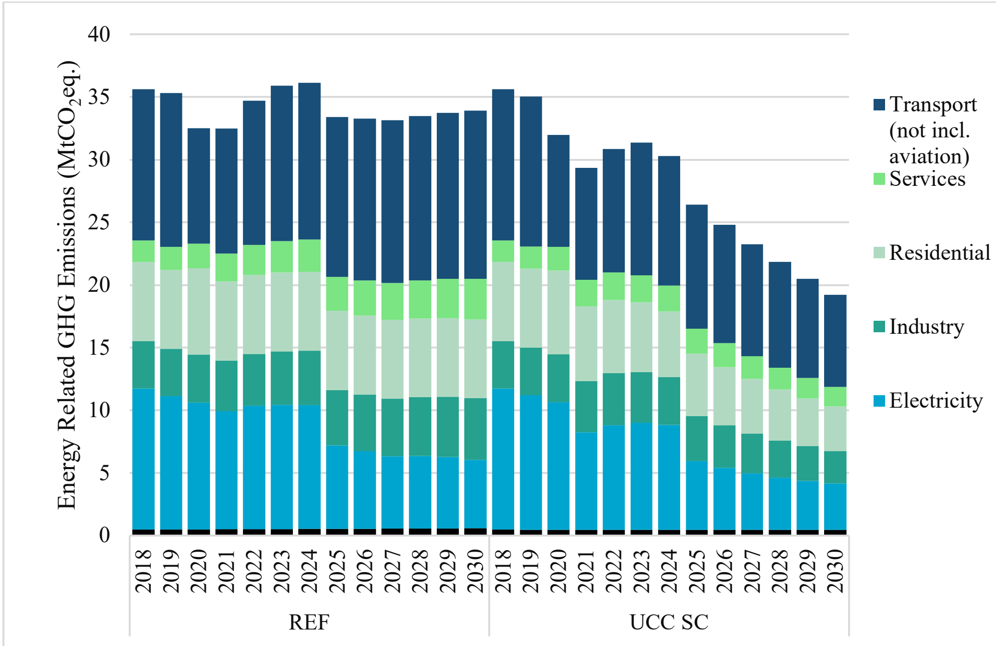

Figure 25: Energy-related CO_2 Emissions by sector for the Reference and UCC Sectoral Ceilings Scenarios (2018 - 2030)

An overview table of emissions projections by scenario is included in Table 26. In the reference scenario, energy related emissions account for 50% of the total GHG emissions by 2030, whereas in the UCC Sectoral Ceilings scenario, energy related emissions account for only 37% of all GHG emissions. This shows that as energy related interventions take hold in the UCC Sectoral Ceilings scenario, the relative share of the non-energy emissions sector increases and makes it the largest source of GHG emissions. The relative importance of emissions from the non-energy sector, the majority of which are agriculture and land-use related emissions, increases significantly, from 46% of GHG emissions to 63% of total GHG emissions.

Table 26: Emissions projections by scenario ($MtCO_2eq.$) for Ireland (2018 - 2030)

	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
	$MtCO_2eq.$												
Reference	65.7	65.1	62.2	62.7	65.2	68.4	67.9	65.6	64.7	65.1	65.6	66.2	67.2
Energy	35.6	35.3	32.5	32.5	34.7	35.9	36.1	33.4	33.3	33.1	33.5	33.7	33.9
Non-Energy	30.1	29.8	29.7	30.2	30.5	32.5	31.8	32.2	31.5	32.0	32.1	32.4	33.3
Energy (%)	54%	54%	52%	52%	53%	52%	53%	51%	51%	51%	51%	51%	50%
Non-Energy (%)	46%	46%	48%	48%	47%	48%	47%	49%	49%	49%	49%	49%	50%
UCC Sectoral Ceilings	65.7	64.8	61.7	59.5	61.3	63.7	61.9	58.4	56.0	54.9	53.6	52.5	52.1
Energy	35.6	34.7	31.7	29.4	30.9	31.4	30.3	26.4	24.8	23.3	21.8	20.5	19.2
Non-Energy	30.1	29.8	29.7	30.2	30.4	32.4	31.6	32.0	31.2	31.6	31.7	32.0	32.9
Energy (%)	54%	54%	51%	49%	50%	49%	49%	45%	44%	42%	41%	39%	37%
Non-Energy (%)	46%	46%	48%	51%	50%	51%	51%	55%	56%	58%	59%	61%	63%

For the demand sectors of transport, residential, industry, and services, Figure 26 shows the cumulative and avoided emissions for 2018-2030. Apart from the residential sector, emissions in all sectors in 2030 are higher than in 2018.

The transport sector has the largest cumulative reduction in GHG emission (8.8 $MtCO_2eq.$ over CB1 of 2021 – 2025, and 22.2 $MtCO_2eq.$ over the CB2 period of 2026 – 2030). Even with these cumulative reductions compared to the reference scenario for the UCC Sectoral Ceiling Scenario, the transport sector exceeds its emission ceiling by 5 $MtCO_2eq.$ in CB2 (2026 – 2030 inclusive). The services sector undertakes the largest percentage reduction with a 32% reduction in annual emissions by 2030 compared to 2021 (the beginning of the carbon budgeting time periods). That said, the emissions ceilings place an importance on the cumulative emissions, not just the net reductions at the end of the budgeting period, and the services sector exceeds its emission ceiling by 4 $MtCO_2eq.$ in CB1 and another 4 $MtCO_2eq.$ in CB2. The electricity sector wedge emissions reductions are shown in Figure 27.

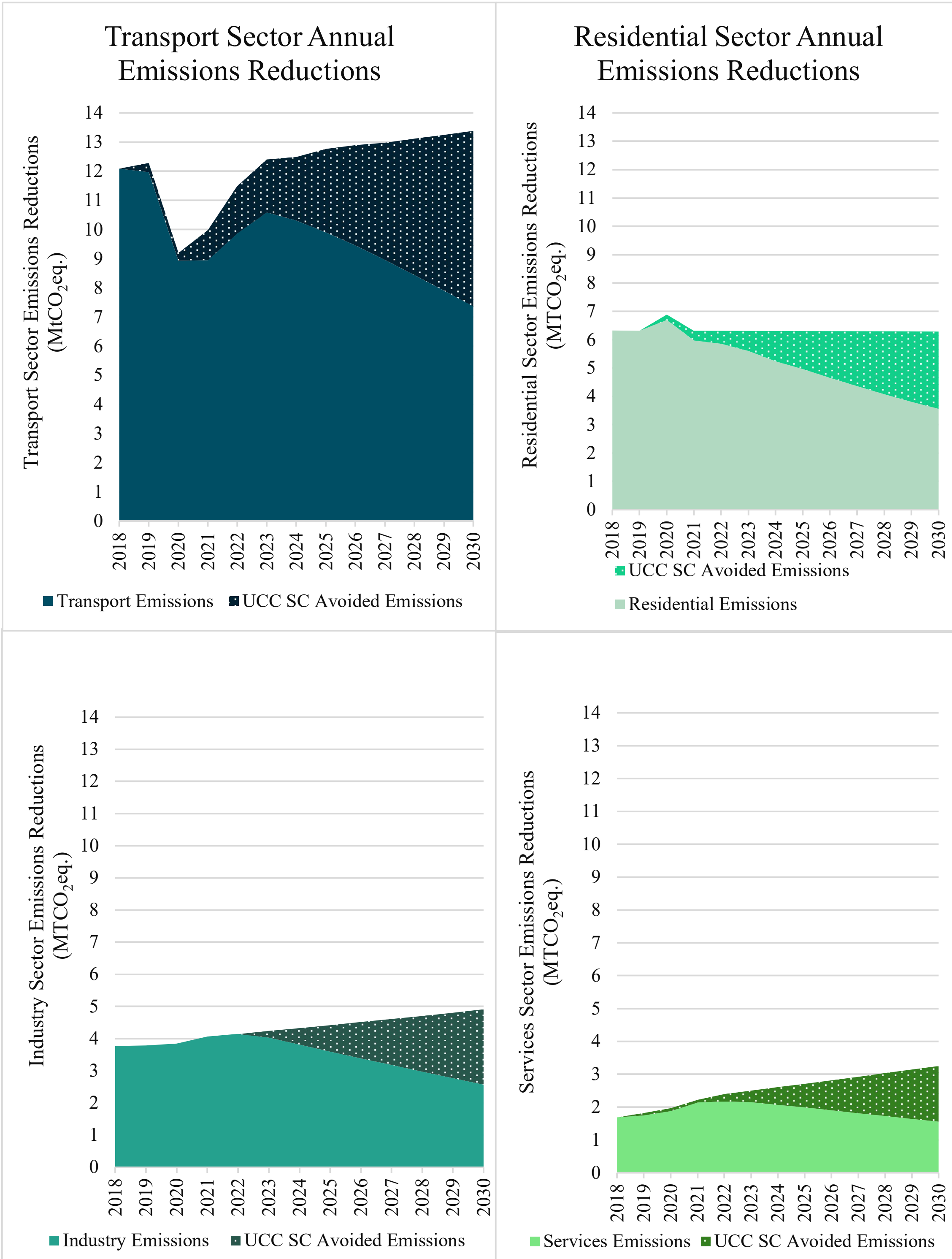

Figure 26: Sectoral Emissions reductions for UCC Sectoral Ceilings Scenario versus Reference scenario

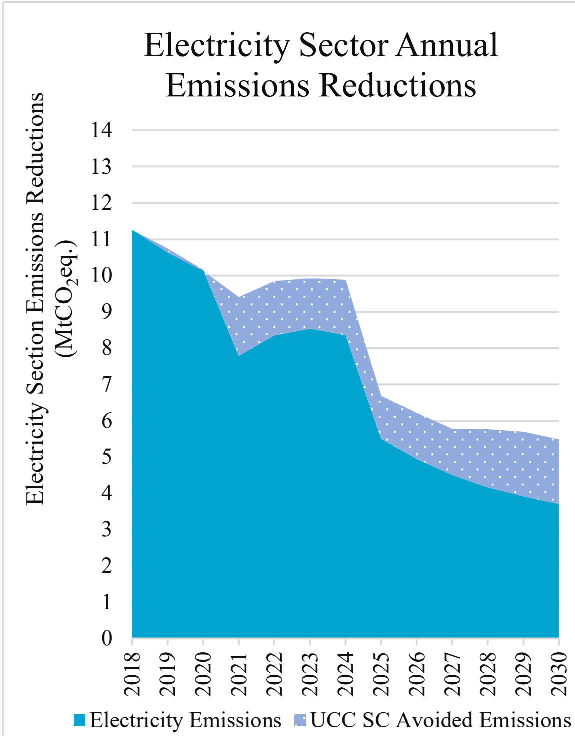

Figure 27: Electricity Sector Annual Emissions reductions for UCC Sectoral Ceilings Scenario versus Reference scenario

5.5.3. Carbon Budgets and Sectoral Emissions Ceilings

Meeting the 51% target as set out in the Climate Action Plan 2021 does not necessarily mean that legally binding sectoral emission ceilings and carbon budget targets in the Climate Action Plan 2023 will be met, as the carbon budgets are not calculated based on an end year target but are based on cumulative emissions over the period of 2021 – 2030. The UCC Sectoral Ceilings scenario shows a cumulative reduction of 23.36 $MtCO_2eq.$ in the CB1 period (2021 – 2025) compared to the reference scenario, and 56.13 $MtCO_2eq.$ in the CB2 period (2026 – 2030). Despite the improvements relative to the 'business as usual' case, the UCC Sectoral Ceilings scenario policy measures do not keep within all the sectoral emissions ceilings limits.

Table 27 shows the net annual contribution of each sector (Transport, Residential, Electricity Generation, Industry, Services, F Gases) to the first Carbon Budget, CB1 (2021 – 2025), and the second carbon budget, CB2 (2026 - 2030) based on the UCC

Sectoral Ceilings Scenario. The UCC Sectoral Ceiling Scenario stays within the electricity, transport, and residential and industry carbon budgets in the first carbon budget period (CB1). However, only the industry and residential sectors are within the sectoral emissions ceilings limits for the UCC Sectoral Ceilings Scenario in the second carbon budget period (CB2).

The industry sector is the only sector to meet or exceed the sectoral emissions ceilings for both scenarios – the reference and the UCC Sectoral Ceiling scenario - in CB1 and CB2.

Table 27: Reference and UCC SC Scenario sectoral performance with Climate Action Bill's Carbon Budgets 1 & 2

	Carbon Budget 1 2021-2025			Carbon Budget 2 2026-2030		
	Sector Emission Ceiling	Reference Scenario	UCC SC Scenario	Sector Emission Ceiling	Reference Scenario	UCC SC Scenario
	$MtCO_2eq.$					
Electricity	40	46	39	20	29	21
Transport	54	59	50	37	66	42
Residential	29	32	28	23	31	20
Services	7	12	11	5	15	9
Industry	30	21	20	24	24	15
Other (F gases & Petroleum refining)	9	19	19	8	19	17
Agriculture	106	124	121	96	123	123

The annual GHG emissions and avoided emissions ($MtCO_2eq.$) for the UCC Sectoral Ceilings Scenario by sector are shown in Figure 28.

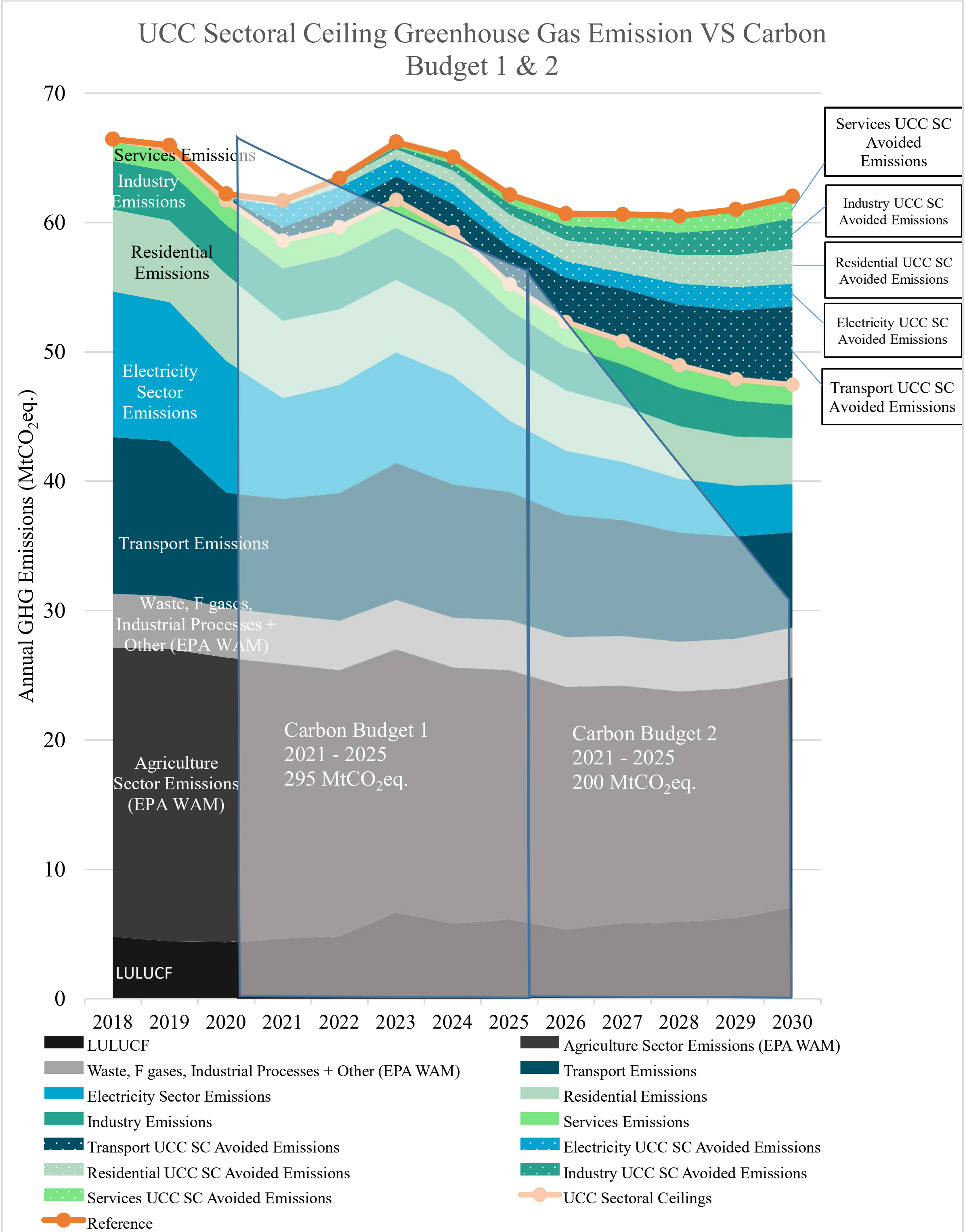

Figure 28: Annual GHG emissions and avoided emissions for the UCC Sectoral Ceilings Scenario by sector from 2018 - 2030 (MtCO$_2$eq.)

A comparison of a) the UCC Sectoral Ceiling emissions changes each year and b) the approximate year-on-year emissions reductions required to meet the net emissions ceilings of Carbon Budget 1 and Carbon Budget 2 is shown in Table 28. Apart from 2025, the year-on-year emission reductions for the UCC Sectoral Ceiling Scenario are not in line with the yearly emission reductions that would be expected to meet the overall CB1 (2021 – 2025) and CB2 (2026 – 2030) Carbon Budgets.

Table 28: Comparison of UCC Sectoral Ceilings Emissions changes and year-on-year emissions targets

Scenario	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
UCC Sectoral Ceilings Emissions	59.5	61.3	63.7	61.9	58.4	56.0	54.9	53.6	52.5	52.1
Year on year emissions change (UCC SC)	-3%	3%	4%	-3%	-6%	-4%	-2%	-2%	-2%	-1%
Year-on-year approximate target	-4.8%	-4.8%	-4.8%	-4.8%	-4.8%	-8.3%	-8.3%	-8.3%	-8.3%	-8.3%

The sectors that avoid emissions and the quantities of emissions that are avoided are shown in Figure 29.

The Climate Action Plan's legally binding Carbon Budget across all sectors for CB1 from 2021 - 2025 (inclusive) is 295 $MtCO_2eq$. The UCC Sectoral Ceilings Scenario total carbon budget across all sectors for that time comes in at 294 $MtCO_2eq$. The overall carbon budget for the CB1 period is met, even if the sectoral ceiling emissions limits for the services sector and agriculture sector is not met in the case of the UCC Sectoral Ceilings scenario (Table 27).

Without the policy interventions in the UCC Sectoral Ceiling Scenario, the modelled carbon budget for CB1 exceeds the first carbon budget (CB1) as the reference scenario's total emissions of 319 $MtCO_2eq$. surpasses the 295 $MtCO_2eq$. Carbon Budget target by 24 $MtCO_2eq$. For CB2, the second Carbon Budget period from 2026 – 2030 (inclusive), the UCC Sectoral Ceilings Scenario exceeds the budget of 200 $MtCO_2eq$. by 48 $MtCO_2eq$., at a total of 248 $MtCO_2eq$. Without the policy interventions as modelled in the UCC Sectoral Ceiling Scenario, the carbon budget would have exceeded the budget of 200 $MtCO_2eq$. by 105 $MtCO_2eq$., at a total of 305 $MtCO_2eq$.

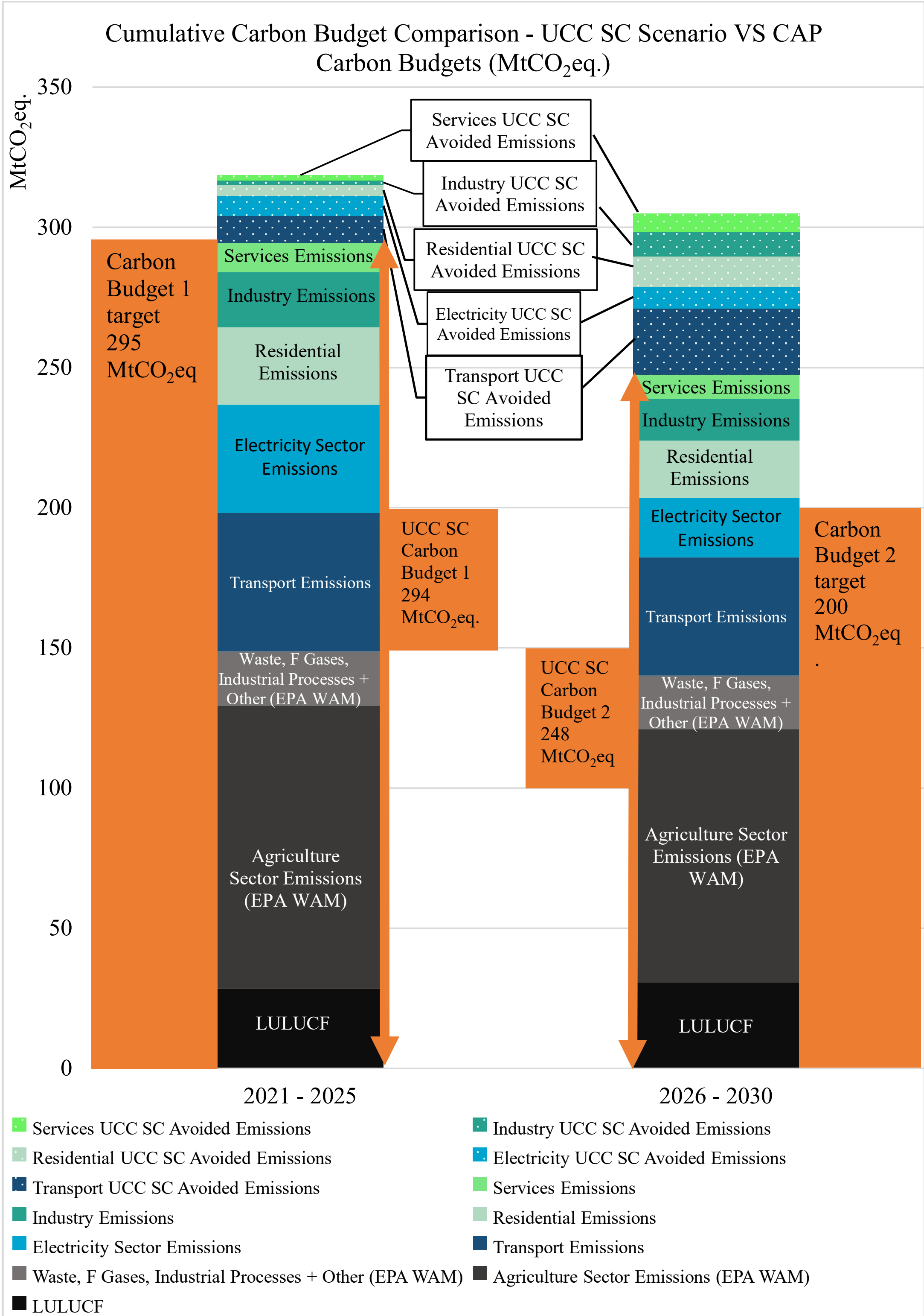

Figure 29: Cumulative carbon budget comparisons by sector for CB1 (2021 - 2025) and CB2 (2026 - 2030) and UCC Sectoral Ceiling Scenario

5.5.4. Interaction Effect of Policy Measures

As outlined in Table 25, many scenarios are included to represent the many policy measures across all sectors. For passenger transport alone, there are 13 policy measure scenarios. Analysis to quantify the interaction between these passenger transport policy measures is presented in Figure 30. The 13 policy measures were grouped into the following 5 categories: Electric Vehicles (EVs); Biofuel Blending (E10/B20); Modal Shift to walking, cycling and public transport; Working from Home (WFH); & Electrification of Public Transport (Public T ELC). For the year 2030, Figure 30 shows the avoided emissions and the impact on emissions arising from the *interaction* of two policy measure combinations. In most cases, the interaction results in lower overall emission reductions, e.g., EVs + Biofuel Blending have 5% less CO_2 (0.2 $MtCO_2eq.$) savings when combined. An exception to these diminishing returns is the interaction between modal shift and public transport electrification which results in 9% higher savings CO_2 (0.1 $MtCO_2eq.$). This type of analysis could be applied to all sectors to determine synergies and the potential for accelerated CO_2 emission reductions.

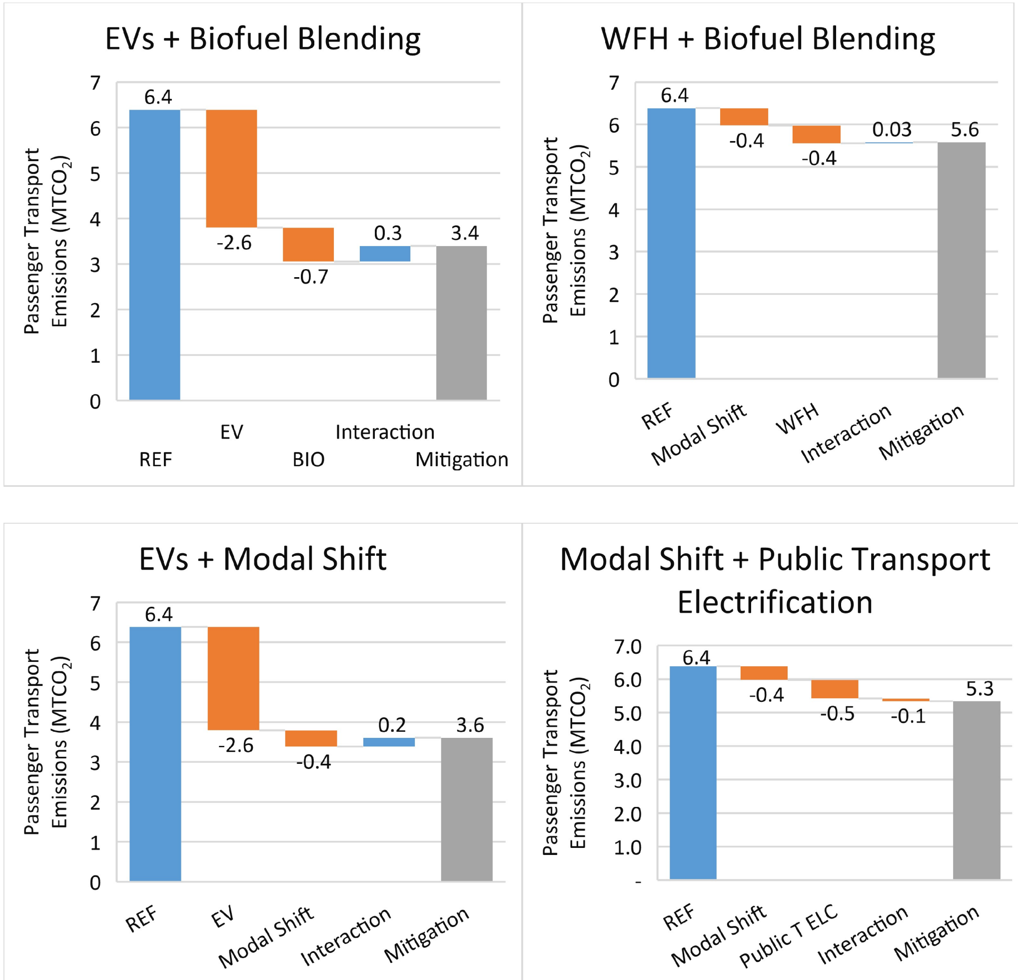

Figure 30: Passenger Transport Emissions in 2030: Interaction Effect Analysis

5.6. Discussion

The LEAP Ireland model developed in this chapter meets the need for enhanced sectoral detail and simplicity for communication, accessibility, and transparency for modelling deep decarbonisation that was envisioned by Pye et al. (2021) for the case of net-zero emissions ambition. The LEAP Ireland model also addresses the need for transparent simulation models that investigate individual policy measures for decarbonisation at national scale, and it is openly available (O'Riordan et al., 2023). The LEAP Ireland model facilitates the examination of scenario uncertainty, implications for deep decarbonisation scenarios, and informs the evidence base underpinning policy insights and recommendations. While the analysis and results presented in this chapter relate primarily to energy sectors, the LEAP Ireland model also presents a platform for future detailed policy analyses relating to non-energy sectors.

5.6.1. Carbon Budgets

Carbon budgets provide a means of bridging the gap between long-term policy targets and near-term policy interventions which can deliver those targets. They can function as a useful communication tool which can highlight the difference between annual and cumulative emissions reductions over time. They can provide insight into emission reduction pathways which are consistent over a complete time horizon.

The pathway, rather than the end point at year X, is what matters for compliance with Carbon Budgets, as it is the aggregate emissions over the period of 2021 – 2025 and 2026 – 2030 (inclusive) that are legally binding targets in the Climate Action Bill. The UCC Sectoral Ceilings scenario achieves a 46% reduction from the energy sector, and a 21% emissions reduction overall (this figure includes non-energy related GHG emissions). Meeting the 51% reduction target in 2030 as set out in the Climate Action Plan does not necessarily mean that 2021-2030 Carbon Budget targets will be met. The reverse is also true. If emissions reductions are early and sustained throughout the cumulation of years, missing the end of period emissions reduction target of 51% by 2030 does not mean that Ireland will not meet its overall Carbon Budget targets.

In addition, emission sectoral ceilings (defined as cumulative emissions limits within each of the GHG emitting sectors) can be missed, and the overall carbon budget can still be met, depending on distribution of emissions across the sectors. In the case of the UCC Sectoral Ceilings for CB1, the transport, residential, industry and electricity sectors overperform, while the agriculture and services sector do not meet their sectoral emissions ceilings, and the overall carbon budget is within the 295 $MtCO_2eq$. limit at 294 $MtCO_2eq$. For the CB1 period, the UCC Sectoral Ceilings Scenario meets the overall carbon budget of 295 $MtCO_2eq$. with cumulative emissions of 294 $MtCO_2eq$. However, for CB2 even with the interventions, the UCC Sectoral Ceiling Scenario does not), with cumulative emissions of 248 $MtCO_2eq$. exceeding the 200 $MtCO_2eq$. budget.

Near term carbon budgets present challenges for both policymakers and energy modellers, especially when part of the carbon budget period is in the past as is the case in the present study. While energy modellers typically calibrate their models to national energy and emission inventories, there is usually a time lag of 1-3 years between when the most reliable data is available and the present. If after a study is published, there is a divergence between modelled years and accepted historic data on emissions, this discrepancy would need to be accounted for in any carbon budget compliance assessment. While simulation tools are helpful for tracking this divergence and providing insights into any future shortfall with existing targets, it requires significant ongoing analysis supported by the timely availability of accurate historical data on emissions.

5.6.2. Interaction Effect of Policy Measures

Deep decarbonisation presents particularly significant challenges regarding the impact of policy measures. While this analysis shows that multiple policy measures are required to meeting deep decarbonisation targets, it also highlights that there are (usually) increasingly diminishing returns from combinations of policy measures. This antagonistic relationship is apparent when considering the relationship between fuel and mode switching in private passenger transport. The emissions savings due to the electrification of electric vehicles competes with an increase in public transportation and active modes. As more public transport, cycling and walking options become available, the role of car use in transport is reduced, thus the typical mileage of a car reduces. This would make the carbon saving benefit of switching the car fuel type lower, relative to a high-car use scenario. By analysing different combination of policy measures this study identifies policy combinations with a synergistic relationship that leads to increased emissions savings relative to their individual implementation. For example, the decarbonisation of electricity generation, coupled with the introduction of heat pumps for residential heating (which increases overall electricity demand), delivers increased emissions reductions when combined, relative to their individual implementation. Similarly, the electrification of public transport, couple with increased modal shift away from private cars to buses, trains etc., delivers increased emissions reduction synergies, relative to the individual implementation of each of the policies.

This increased electrification can create problems, as the increased electricity demand for public transport increases, it becomes harder for the electricity system to decarbonise and can result in a higher generation capacity requirement to achieve a specified percentage of decarbonised or “renewable” electricity. Using the interaction effect and combination scenarios in the LEAP Ireland model, researchers can identify the scale of the relationships between different policy scenarios and the extent of the synergies, antagonisms, and overlaps between them. This policy measures interaction effect methodology helps address several of the challenges, especially the growing energy system complexity and uncertainty in modelling results.

5.6.3. Policy Insights and Recommendations

The Ireland LEAP model demonstrates an ability to simulate existing policy measures and to quantify whether their combined impact will achieve certain targets. This facilitates further analysis on additional policy measures needed to close the gap, or additional policy options in the event of policy measures missing their targets. This analysis shows the contribution of simulation models in the ongoing need to closely align the needs of policy analysis and energy systems models. In particular, the benefits of the modular simulation modelling approach with LEAP allow for recommendations and policy insights both at a sectoral and cross-sectoral level. The following insights should be considered indicative rather than comprehensive, since not every policy measure and combination has been included in this analysis.

Transport

The transport sector within the UCC Sectoral Ceiling scenario consists of a suite of policy measures addressing passenger transport, freight, and cross-cutting measures such as the introduction of increased biofuel blending rates. The passenger transport sub-sector uses the Avoid-Shift-Improve framework and includes demand reduction[7] (Avoid), a shift from private cars to public transport (Shift), and the electrification of private passenger vehicles, public buses, and trains (Improve). While these scenario combinations achieve the sectoral emissions ceilings for the first Carbon Budget (CB1), they are dependent on the rapid introduction of increased biofuel blending rates (E10 and B12 by 2025), increases in public transport and active trips within passenger transport, and the large-scale electrification of private transport vehicles in the short to medium term. The UCC SC scenario does not achieve the transport sectoral ceiling for the second carbon budget (CB2).

Residential

The residential sector within the UCC SC scenario consists of a suite of policy measures addressing the energy efficiency of new and existing dwellings. For new dwellings, strict Nearly Zero Energy Building (NZEB) regulations are introduced from 2023 and there is a ban on the installation of all fossil fuel boilers introduced by 2025. For existing dwellings, the deployment of large-scale deep retrofitting and the introduction of fuel switching in the form of heat pumps is simulated. While these scenario combinations achieve the residential sectoral ceilings for CB1 and CB2, they rely on unprecedented

[7] Demand reduction scenarios include reduced projections for private vehicle passenger-km due to increased use of active modes and increased remote working (2 days per week).

rates of deep retrofitting (Mac Uidhir et al., 2022). These scenarios serve to highlight the need to focus on implementation pathways in place of end year targets, and the need for early adoption to achieve carbon budget targets in the short to medium term.

Industry

There are increases in industry energy demand and emissions for both the reference and UCC SC scenarios. Achieving meaningful reductions in energy demand and emissions in the industry sector will require a more detailed understanding of the end use processes driving energy demand within the sector. These data limitations are reflected in the reduced number of policy scenarios in the industry sector. While the industry scenario combinations achieve the sectoral ceilings in CB1 and CB2, they rely on the introduction of the electrification of 50 – 60% of all heat, and exploratory fuel switching measures such as oil to Hydrogenated Vegetable Oil (HVO) and Natural gas to renewable biogas. The penetration rates for renewable fuels (HVO and Biogas) go well beyond what is likely to be achieved in the short to medium term, highlighting the need for an improved understanding of the sector and additional measures if these emission reductions are to be realised.

Services

Similarly, there is a need to improve the data gathering and suite of policy measures applicable to the services sector, this is in the smaller number of scenarios in the public and commercial services sector within the UCC SC scenario. While the commercial services sector benefits from cross-sectoral measures such as the introduction of renewable fuels (HVO and Biogas), in combination with sectoral specific measures, large-scale deep retrofitting (approximately 55, 000 buildings by 2030), and the wide-scale introduction of electrification of heat, the sector does not stay within the sectoral ceiling emissions limit for CB1 or CB2.

Electricity Supply

The LEAP Ireland model simulates the capacity expansion of the electricity sector as it decarbonises in line with climate action plan targets. These targets include the delivery of onshore wind (8.2GW) and offshore wind (5GW), solar PV (2.5GW), and the closure of coal fired power generation by 2025. The decarbonisation of electricity supply remains critical to the delivery of emissions reductions across all sectors which depend on extensive electrification of heat and transport in the UCC SC scenario. Increasing electricity demand across all sectors impacts the overall decarbonisation of the electricity sector itself. Demand side requirements need to be carefully considered also, for example, the anticipated growth of Data Centres puts the delivery of already challenging decarbonisation targets for electricity supply at risk by requiring additional generation capacity, which may only be met by pre-existing fossil-based generation plants. While the electricity sector achieves the sectoral ceiling in CB1, it does not deliver within CB2, highlighting the need to increase the policy ambition for the electricity sector's decarbonisation between the period of 2026 -2030.

5.6.4. Uncertainty & Limitations of Modelling Approach

All energy models must account for, and acknowledge, the existence of uncertainty with model input assumptions and the model's projections. Detailed bottom-up simulation models, such as LEAP Ireland, depend on disaggregated granular data to represent the implementation of sectoral specific policies, such as the electrification of private passenger vehicles. Cross-sectoral policies depend on sector coupling to adequately understand the impact of an individual policy at national level, such as the introduction of increased biofuel blending rates. At each level, the parameters of the model need to be examined to see whether they can model policy targets. A consistent, multi-sectoral energy system model with the functionality to examine a broad range of scenarios, capture the emissions implications of certain targets, and model the interactions of different targets with one another, is required.

The LEAP Ireland model examines a total of 32 scenarios across all energy sectors, and uses the novel method presented in section 5.5.4 to account for the double counting present in many policy scenarios which inherently interact. This policy interaction analysis provides insight into modelling uncertainty and is currently limited to the private passenger transport sector within this study. At present, the suite of policies which can be analysed (in isolation or in combination) are limited to the energy sectors with aggregate non-energy emissions projections (Environmental Protection Agency, 2021a) in use for the agriculture, F-gases, waste, and Land Use, Land Use Change and Forestry (LULUCF) sectors. Additionally, there are no costs included in the LEAP Ireland model, which precludes its use to evaluate the cost of a particular policy measure or suite of measures. Simulation is exploratory, intended to calculate possible outcomes based on the assumptions listed in the methodology and appendices. Model verification is conducted through calibration with 2019 – 2022 using energy and emissions balances from the Sustainable Energy Authority of Ireland (SEAI) and Environmental Protection Agency (EPA). Model validation is an area for future work to assess whether the model targets were met, and how these targets impacted national emissions, ex-post analyses of these models are critical to policy and social learning as often, learning occurs in the ex-post state rather than the ex-ante analyses (Wilson et al., 2021). The authors encourage past ex-ante simulation models to be analysed as part of a model validation process.

5.6.5. Future Work

Data limitations and uncertainty regarding future policy pathways serve as two drivers for the need for additional research and development of the LEAP Ireland model. Ensemble scenario development is uniquely equipped to answer urgent modelling questions with sufficient parameterisation of supply and demand assumptions on a particular policy intervention or suite of policy interventions.

At present, the residential, transport, and commercial services sectors use bottom-up, detailed data to represent overall energy demand and emissions at national scale. There is scope to improve the data and definition of the public services, industry, and agriculture sectors and provide specific policy insights for these sectors with the LEAP Ireland model. For example, for the agriculture sector, the LEAP Ireland model could adopt the per farm basis approach as introduced by (McGookin et al., 2022) to create a nationally representative livestock model within LEAP. This could be used to investigate GHG emissions budgeting options for the agriculture sector.

The addition of costs to the LEAP Ireland model would enable the use of marginal abatement cost curves for individual policy interventions in the LEAP Ireland model. However, up-to-date costing information and defining the social, infrastructural, operational, and purchase costs are subject to significant uncertainty and unavailability.

5.7. Conclusion

The LEAP Ireland model has proven useful in the simulation of policy pathways in Ireland. The model includes a suite of existing government policies, and several possible new policies. New exploratory scenarios allow for the quantification of emissions associated with increased ambition and provide an evidence base for policy making. The insights from this chapter and the application of the LEAP Ireland model to simulate emissions scenarios can help re-align deep decarbonisation policies that are currently exceeding their carbon budgets. This study presents a methodology for detailed simulation modelling for the planning of deep decarbonisation pathways and carbon budget target setting.

LEAP Ireland presents a useful tool for tracking policy progress, monitoring the delivery of emissions reductions on an annual basis and at a sectoral level. Carbon Budgets and sectoral ceilings are part of the new governance regime in Ireland and the LEAP Ireland model is a valuable tool for that governance regime. It can provide a means of identifying sectors which are under performing with respect to climate mitigation targets.

LEAP Ireland provides insights into the interaction effect between cross-sectorial policies and highlights the need to account for the double counting of emissions savings when policies are combined. It also shows the synergistic effects which can occur through the combination of policies. Modelling transparency and Interdisciplinary research can help to improve our understanding of the broader challenges facing the delivery of real-world deep decarbonisation.

Chapter 6. Conclusions

This thesis improves the robustness of models that inform policy decisions for the transport sector and transport related climate policy. Each chapter of this thesis aims to answer one or more of these research questions by informing climate-related policy and expanding current transportation modelling practices. This concluding chapter summarises the findings of this work within a policy and modelling context and identifies areas of potential future work.

RQ. 1. What was the impact of a past emission-based car tax transport policy at reducing GHG emissions?

Chapter 2 developed an ex-post policy analysis tool, the "Irish Car Stock Model", to look at the impact of an emissions-based car tax policy on Annual Motor Tax and Vehicle Registration Tax. The thesis updates the Irish Car Stock Model and then developed a tax calculation tool to determine the emissions saved and the cost to the exchequer of the car taxation switch. This thesis explored the concepts of ex-post analysis and the tools required to exploit them.

According to the study, Ireland's car tax change in 2008 impacted consumer behaviour, resulting in a slight shift towards more efficient cars. However, despite a cumulative CO_2 savings of 1.2 $MtCO_2eq$. over the ten years, the study indicates that technical and policy efforts to improve internal combustion engine efficiency may not significantly reduce emissions in the long term and in the medium term with looming carbon budget emissions targets. Changes to mobility and fuel type may be necessary, such as car electrification and mode shifting to public transport, walking, and cycling.

The policy was not revenue-neutral; annual motor tax receipts could have been €207 million higher in 2018 without it. The taxation bands were not designed to anticipate consumer purchasing trends towards cars in lower emissions classes, resulting in a disguised tax cut. Furthermore, the high carbon abatement cost of $€_{2018}1,500 - 2,220$ per tonne of CO_2 indicates that alternative policies may reduce emissions more cost-effectively. The car tax policy reduced CO_2 emissions from new cars, but at a higher cost of abatement than anticipated.

The thesis used an established qualitative evaluation method in Chapter 2 by applying the Irish Car Stock Model from 2000 – 2018 to retrospectively examine emissions and cost impacts. In response to the call from Wiese et al. (2018) for enhanced transparency in model development, these analytical tools were made openly available online and in downloadable Excel spreadsheet form.(O'Riordan et al., 2021).

RQ 2. What are the range of transport modes, purposes, and distances travelled for passenger transport demand in Ireland? What are the emissions arising from this?

In Chapter 3, I presented a new methodology and model, the Irish Passenger Transport Emissions and Mobility (IPTEM) model.

This chapter estimates the total number of passenger kilometres travelled throughout Ireland annually. The data reveals that between 2009 and 2019, the total demand for passenger kilometres was between 50 and 65 billion. In 2019, travel for work purposes contributes the greatest to overall passenger transport demand (30% of all passenger kilometres) followed by shopping (19%) and companion journeys (16%). Work travel emits the least per passenger kilometre, while shopping trips double emissions. Solutions like cargo bikes and electrified deliveries can cut shopping emissions. Commuting, with lighter loads and predictable schedules, suits low-emission options. Companion/escort journeys, encompassing supervised trips, point to potential car-sharing benefits and highlight the demand for secure transport. Meeting this demand could involve safer routes, school buses, and accessible public transport, reducing the need for companion/escort journeys.

The IPTEM model is a useful tool that provides trip purpose-based demand reduction calculations, which can inform purpose-based policy incentives. Policymakers can use this data to develop policies such as remote working schemes and school bus programs tailored to reduce transport demand-based emissions.

Understanding the extent of active modes of transport, such as walking and cycling, in Ireland is crucial for providing context to sustainable transport targets set by the Irish Government. However, the data in the IPTEM model indicates that low uptake rates of active modes of transport persist in the Irish context. The IPTEM model calculates the total passenger kilometre demand by trip mode, purpose, and distance. It helps modellers improve their representations of multiple transport modes and purpose-based policy scenarios in energy systems models. Additionally, the IPTEM model serves as a research base for setting policy targets and helping policymakers better understand Ireland's current passenger transport landscape.

As the Irish Government continues with their Climate Action Plan, which includes a multitude of transport-related targets, there is a growing need for a research-informed basis for sustainable transport targets that go beyond private car efficiency and fuel switching and for a systematic way of tracking progress for the model shift to public transport and active modes of travel, which are lower in carbon intensity per passenger kilometre served when compared even to electric vehicles. The IPTEM model provides a basis for this analysis.

RQ 3. How can modal shift and demand reduction interventions contribute to transport climate mitigation targets?

In Chapter 4: "Avoid-Shift-Improve: Bottom-up Simulation Modelling of National Policies for Transport Carbon Budgets", the thesis presents methodological advancements in climate policy modelling for the transport sector. This chapter develops and applies a novel multi-mode and trip-purpose simulation-based model to analyse future transport policy and climate planning. This chapter models and quantifies the impact of avoiding and reducing demand for travel alongside policy measures drawn directly from national and regional low-carbon transition plans. A “business-as-usual” Reference scenario and an “Avoid-Shift-Improve” scenario based on national climate action plans is developed for Ireland using the Irish Passenger Transport Emissions and Mobility (IPTEM) and the LEAP Ireland ASI (Avoid-Shift-Improve) model. Several policy measures based on the Avoid-Shift-Improve Framework (such as reduced vehicle kilometre demand, working from home, more cycling, and increased public transport, increased electrification) highlight the impact of modal shift and demand reduction interventions on a countr''s transport CO_2 emissions profile. The results show how a combination of policies lead to cumulative emissions over Carbon Budget 2 (2026 – 30) of 35 $MtCO_2$eq.; 2 $MtCO_2$eq. lower than the legally required transport carbon budget for that period. The scale of the role of “Avoid”, “Shift”, and “Improve” measures for transport is assessed both individually and collectively. “Avoid” and “Improve” measures account for a greater share of emissions reductions than modal “Shift” measures. Private vehicle electrification and demand reduction targets have the greatest impact. The contribution of passenger transport measures outweighs freight transport measures.

The methodological advancements presented in this study provide a solid foundation for policymakers and planners to design and evaluate effective transport decarbonisation strategies. By understanding the relative impacts of different policy measures, policymakers can chart a more sustainable and ambitious path toward achieving national climate action targets and contribute at a national level to global efforts to manage carbon dioxide emissions.

RQ 4. How can simulation models help us plan for cross-sectoral carbon budgeting?

In Chapter 5: "Policy simulation modelling to inform national carbon-budget Pathways", the thesis presented the LEAP (Low Emissions Analysis Platform) Ireland model, a multi-sectoral model of energy and non-energy demand and emissions for Ireland. The chapter outlined scenarios for the public sector, transport, commercial services, electricity, and residential sectors.

The thesis linked the LEAP Ireland model with carbon budgets to explore the impact of critical national climate mitigation policies in Ireland. The thesis examined the feasibility of these targets using precedent scenarios from the Climate Action Plan 2023, which delivers end-year targets for 2030. The thesis used the LEAP Ireland model to assess whether these targets are sufficient to achieve the carbon budgets.

Energy Systems simulation models are helpful tools to highlight the emerging pathways to a low-carbon future in the passenger transport sector. By engaging with and referring to policy documents, policymakers and academic literature throughout the energy systems modelling development process, the model can and has produced instructive low-carbon pathways and projections for how we could achieve our ambitious emissions reduction targets. In Chapter 5, the thesis discussed how simulation models could highlight deep decarbonisation pathways using policy frameworks from the Intergovernmental Panel on Climate Change (IPCC). The thesis also discusses how these simulation models have informed carbon Irish Climate Policy in the past and matters relating to the synergies and antagonisms that simulation modelling reveals in the case of the deep decarbonisation of passenger transport.

The LEAP Ireland models modular approach offers sectoral and cross-sectoral policy insights. For the transport sector, policies for passenger and freight transport, including demand reduction and vehicle electrification, meet initial emission targets in Carbon Budget 1 (CB1) but require rapid biofuel adoption and public transport use. The second carbon budget (CB2) target is missed. In the residential sector, energy efficiency policies for new and existing homes achieve emission targets for CB1 and CB2, relying on swift retrofitting and early adoption. Electrification and fuel switching help achieve CB1 and CB2 targets, but feasibility concerns arise. The Climate Action Plan's legally binding Carbon Budget across all sectors for CB1 from 2021–- 2025 (inclusive) is 295 $MtCO_2eq$. The UCC Sectoral Ceilings Scenario total carbon budget across all sectors for that time comes in at 294 $MtCO_2eq$. The overall carbon budget for the CB1 period is met, even if the sectoral ceiling emissions limits for the services sector and agriculture sector is not met in the case of the UCC Sectoral Ceilings scenario (Table 27).

Without the policy interventions in the UCC Sectoral Ceiling Scenario, the modelled carbon budget for CB1 exceeds the first carbon budget (CB1) as the reference scenario's total emissions of 319 $MtCO_2eq$. surpasses the 295 $MtCO_2eq$. Carbon Budget target by 24 $MtCO_2eq$. For CB2, the second Carbon Budget period from 2026 – 2030 (inclusive), the UCC Sectoral Ceilings Scenario exceeds the budget of 200 $MtCO_2eq$. by 48 $MtCO_2eq$., at a total of 248 $MtCO_2eq$. Without the policy interventions as modelled in the UCC Sectoral Ceiling Scenario, the carbon budget would have exceeded the budget of 200 $MtCO_2eq$. by 105 $MtCO_2eq$., at a total of 305 $MtCO_2eq$.

The LEAP Ireland model simulates expanding decarbonised electricity with wind, solar, and coal closure, vital for heat and transport. The multi-sectoral simulation model notes growing demand for electricity in the future with increased electrification in the other sectors (chiefly from the residential and transport sectors). It also notes that data centre growth challenge electricity decarbonization, necessitating more ambitious policies and the need for serious consideration of data centres and the deep decarbonisation of the electricity sector as we continue to grow our electricity demands.

6.1. Contribution

This thesis has presented several improvements and outputs beneficial to stakeholders, including model developers, users, and policymakers. This thesis' two key contributions are 1) Modelling Gaps Addressed and 2) Policy Insights.

6.1.1. Modelling Gaps Addressed in this Thesis

This thesis identifies 6 key modelling gaps 1) linking ex-post and ex-ante modelling to facilitate policy learning, 2) the variance of geographical scope and detail, 3) reproducibility of model inputs and outputs, 4) a greater understanding of multi-modal passenger transport, and 5) ensuring energy systems modelling to reflect, keep up with, and engage with, the rapidly changing climate policy landscape and 6) for Ireland specifically, a need to model the deep decarbonisation of the Irish energy system in light of ambitious carbon budget targets. How this this thesis addresses each of these gaps is below.

1) Linking ex-post and ex-ante modelling to facilitate policy learning

In this thesis, the Irish Car Stock Model (Chapter 2) was updated and expanded to include information on tax revenue to facilitate learning on the costs associated with the introduction of a CO2 emissions-based car tax. The bottom-up simulation model which included tax revenue information modelled revenue and emissions for both the actual "reference" scenario and a counterfactual "no-tax change" scenario. This facilitated learning on the cost of the efficiency measure, which at $€_{2018}$1,500 – 2,200 per tCO_2, was high, and could be higher than other transport decarbonisation measures. This insight gives way for focussing on other measures, and measures that go beyond focusing on fossil fuel car efficiency taxation measures.

In Chapter 3, passenger transport demand and emissions by trip purpose and trip distance and mode type was modelled for the first time. The resulting IPTEM model facilitates insights and learning on how and why we travel in Ireland. The ex-post modelling shows that despite setting ambitious targets in 2009 with the "Smarter Travel" policy document to have 10% walking and cycling – only 1% of overall passenger kilometre demand is met by walking and cycling in Ireland. 40% of emissions come from journeys less than 8 kilometres – and this model can inform estimates and calculations on the emission saving potential of targeting certain kinds of journeys – by trip purpose, trip distances, or mode types to gauge the possibilities for emissions reduction from passenger transport.

The model developments of past transport kilometre demand, energy consumptions, and emissions are used to simulate for future scenarios in Chapter 4 and Chapter 5 of this thesis. The Irish Car Stock Model (Chapter 2) establishes a foundation from which decarbonisation scenarios for cars can be developed. The IPTEM model (Chapter 3) establishes a foundation from which modal shift and demand reduction measures can be modelled. These are then linked to assess the role of Avoid-Shift-Improve transport measures in Ireland's decarbonisation pathway up to 2030 (Chapter 4), and the role of the transport sector in carbon budgets alongside all the other sectors that need to decarbonise (the residential, industry, services, agriculture and electricity sectors) in the LEAP Ireland model up to 2030 (Chapter 5).

In Chapter 4,"Avoid-Shift-Improve: Bottom-up Simulation Modelling of National Policies for Transport Carbon Budget", the thesis looked at the impact of passenger transport policies outlined in the Irish Government's Climate Action Plan 2023 through the lens of the Avoid-Shift-Improve framework. This ex-ante analysis allows us to look at how demand reduction through avoiding the need for passenger travel in the first instance through behavioural changes and, park and ride planning, remote working policies. Then it looks at the role of the modal shift from private cars to more resource-efficient modes like public transport and cycling. Lastly, it calculates the impact of technology improvement measures – such as biofuel mixing and electrification. The methodology facilitates the simulation of each policy measure and combines these policies in one scenario to quantify policy interactions. The respective contribution of avoid, shift, and improve measures are also quantified, which guides policymakers on what strategies provide the greatest returns and thus should warrant an appropriate and proportionate level of attention.

The LEAP Ireland model (Chapter 6) demonstrates the capacity to consider specific policy measures from the viewpoint of a carbon budget, shifting away from the current policy design, which tends to focus on end-year targets. Understanding specific policies from a carbon budget perspective highlights the need to understand cumulative carbon emissions in the context of deep decarbonisation strategies for Ireland. This model provides sufficient technical detail to contribute valuable policy insights and implementation pathways, presented on an accessible platform that policymakers and energy modellers can use. The accessible platform and the model's national coverage of all energy and non-energy sectors respond to Lopion's set of three minimum requirements to support governments with decision-making usefully (Lopion et al., 2018).

2) The Variance of Geographical Scope and Detail

Passenger kilometre information is available from other regions and countries – however prior to the development of the Irish Passenger Transport Emissions and Mobility (IPTEM) model, national figures on estimated public transport occupancy were unknown. Also from the updated Irish Car Stock model, the national emissions intensity from cars based on the national car stock was calculated. This ensures accuracy in modelling Irish emission for budgeting and monitoring purposes. Chapter 4's LEAP Ireland Avoid-Shift-Improve calculates the emissions savings from passenger and freight transport based on national and regional policy measures. Chapter 5's LEAP Ireland Model also highlights the unique situation with Ireland's high agricultural emissions, a unique characteristic which will shape Ireland's decarbonisation journey. As measures in the UCC Sectoral Ceiling reduce emissions from the energy sector, the share carbon budget emissions coming of the agriculture sector would increase – provided the agricultural sector continues the EPA's With Additional Measures trajectory.

3) Reproducibility in model inputs and outputs

The Irish Passenger Transport Emissions and Mobility (IPTEM) Model (Chapter 3) is based on a combination of data sources from the National Travel Survey, the Irish Car Stock Model and public transport providers. A detailed description of the IPTEM model data is included in Appendix B – Data in Brief Article, a published Data in Brief article (O'Riordan, V. et al., 2022d) developed as part of this thesis.

The IPTEM model is an input for the LEAP Ireland ASI (Chapter 4) and LEAP Ireland (Chapter 5) models passenger transport sectors. Additionally, IPTEM represents an improvement in the open-source philosophy associated with developing assumptions for passenger transport models in Ireland. It facilitates other model developers to create additional scenarios and use better-informed assumptions about how we travel, how much we travel and the reasons behind it in the future.

The tools developed as part of this thesis provide new functionality previously unavailable. The LEAP Ireland model is provided on an accessible platform (LEAP), meaning users can interrogate model assumptions, data, and results in one coherent platform – without needing advanced modelling skills. The LEAP Ireland is available online, including underlying data and assumptions (O'Riordan, Mac Uidhir, et al., 2023).

4) *A Greater Understanding of Multi-Modal Passenger Transport*

For the first time, in Chapter 3, passenger transport demand by mode, trip purpose, and trip distance is determined for Ireland. It is a method of calculating passenger transport demand and CO_2 emissions by mode type, trip purpose and trip distance. Calculations of occupancy of different modes of transport such as bus and rail, their fuel consumptions and their carbon intensity are calculated over the period of 2009 – 2019.

It combines, in a novel manner, bottom-up technology stock modelling together with public transport reporting and National Travel Surveys. Such data sources can also be found across Europe, the US, New Zealand, Israel, Japan, and Australia and using the methodology in

Chapter 3, insights on the carbon intensities, passenger transport demands, and occupancies for passenger transport modes in those regions could also be determined.

4) *Ensuring Energy Systems Modelling Reflects, Keeps-up, and engages with, the Rapidly Changing Climate Policy Landscape*

The analyses of the 2008 Irish Car Tax (Chapter 2) provided a medium-term ex-post analysis of the measure and provided new information on the cost effectiveness of the policy. The updated Irish Car Stock Model analysis from the chapter featured in a "Good Tax Guide" for Transport and Environment – a European-wide review of the private vehicle taxation policies (Griffin Carpenter & Arnau Oliver Antich, 2022). This analysis responds to the call of Hull et al. (2009) for additional ex-post assessment of energy policies. The ex-post evaluation of the energy efficiency measures identified that the cost of carbon abatement with this policy was quite high for the exchequer. Adopting policies for passenger transport that go beyond cars could deliver improved outcomes by taking a comprehensive approach to passenger transport with the Avoid-Shift-Improve framework rather than focusing on marginal efficiency-based efforts.

The LEAP Ireland ASI (Avoid-Shift-Improve) model in Chapter 4 offers a deep dive into the passenger and freight transport sector scenarios using a sector-specific iteration of the LEAP Ireland model. Here, scenarios related to Ireland's Climate Action Plan 2023 are developed, and the Avoid-Shift-Improve framework is applied to reflect the latest thinking in transport policy planning (OECD, 2022).

The methodology is novel in approach to applying the "Avoid-Shift-Improve" framework to carbon budgets, which account for the cumulative GHG emissions that are responsible for global warming. The model applies this novel approach to evaluate the gaps and possibilities for climate-related transport policy for both the freight and passenger transport sectors. The cumulative decarbonisation impacts of emerging decarbonisation measures such as reduced demand, working from home, the electrification of public transport and increased biofuel mixing in both freight and passenger transport are measured.

The LEAP Ireland model presented in Chapter 5 demonstrates a national model providing evidence-based policy support across multiple sectors of the Irish economy. The model contains a detailed technological representation of transport, residential, commercial services and non-energy agricultural demand and emissions from 2018 to 2030. The publication of the new LEAP Ireland model and underlying data builds on the work of Rogan et al. (2014) by (1) improving the data granularity of subsectors, (2) including new sectors not previously available, e.g. non-energy GHG emissions, (3) significantly improving the transparency of the modelling tool as it has been made available online, (4) supporting the improved institutional capacity to the Department of Climate Change and Environment to operate the tool via workshops, and (5) the development of new key policy insights on how carbon budgets could be achieved.

This new national energy demand and emissions model represents a valuable resource to model developers. It facilitates model transparency and scrutiny in its ongoing use to provide evidence-based policy support in Ireland. It has been coupled with a carbon budget modelling spreadsheet which looks at simulated carbon budgets for Carbon Budget 1 (2021 – 2025) and Carbon Budget 2 (2026 – 2030), which links directly to Irish policy as specified in the Irish Climate Action Plan 2023 (Government of Ireland, 2022) and as legislated for in the Climate Action Bill (Government of Ireland, 2021).

6) Modelling of Irish Deep Decarbonisation Policy

In Chapter 2, the updated Irish Car Stock Model is coupled with up-to-date tax rates to determine the revenue obtained from car tax. It is used to determine the revenue lost through a car tax change that incentivises car owners to choose lower emission cars. It goes beyond looking at just emissions saved from cars to also include revenue costs and provides a valuable insight on the cost effectiveness to the government of a climate policy centred around boosting the efficiency of new cars sold. This advancement keeps in line with the need to monitor past policies in their effectiveness and suggests that the cost of carbon abatement was high.

In Chapter 3, the IPTEM model advances past modelling in Ireland which focused only on emissions from cars (the Irish Car Stock Model), to include all mode types. Now, there is information on passenger transport demand by mode type, trip distance, and trip purpose, enabling insights on the reasons and kinds of journeys behind our passenger transport emissions. Again, this modelling advancement keeps up with the latest thinking in Irish deep decarbonisation policy planning, which advocates for an approach that goes “beyond cars” (OECD, 2022).

In Chapter 4 and 5, The LEAP Ireland, ad LEAP Ireland ASI model couple energy system simulation models with carbon budget analyses for the first time. This methodological advancement addresses the need for energy system models to keep up with the latest deep decarbonisation policy modelling needs in Ireland, as the Climate Action Bill requires Ireland to stay within specified Carbon Budgets. The methods presented in Chapter 4 for the LEAP Ireland ASI model set out an approach to do so for the transport sector and analyse the role of each of the elements in the Avoid-Shift-Improve framework. The modelling methods presenting in Chapter 5 with the LEAP Ireland model provide a multi-sector approach of all GHG emission causing sectors in Ireland, and scenarios for a deep decarbonisation pathway and how that pathway applies to the legally binding carbon budgets, Carbon Budget 1 (2021 – 2025, CB1) and Carbon Budget 2 (2026 – 2030).

6.1.2. Policy Insights

The critical policy insights from this thesis are rooted in the ex-post and ex-ante analyses conducted in this thesis. There is a need for a more robust ex-post analysis of government climate policy (Hull et al., 2009); understanding and evaluating the causes of policy success and failure is critical to producing effective evidence-based policy going forward. The following key policy insights and recommendations from this thesis are summarised as follows:

- Chapter 2, "Impact of an emissions-based car tax policy on CO_2 emissions and tax revenue from private cars in Ireland", advocates that while the car tax policy was effective in reducing new car transport emissions, the cost of abatement was very high over the period of 2008 – 2018. The cost of abatement at €$_{2018}$1,500 – 2,200 per $tCO_2eq.$ could be higher than other transport decarbonisation measures, and an approach going beyond car efficiency could bring greater reductions per euro spent, for example a recent study on the agricultural sector's cost of carbon abatement even indicated that some measures had a net benefit and had negative costs in 2023 real value terms (Teagasc, 2023). All measured outlined had costs less than €500 per tCO_2eq.

- Chapter 3, "How and Why We Travel – Mobility Demand and Emissions from Passenger Transport" highlights the extent of car dependency in Ireland (82% of all passenger kilometres travelled). It also highlights the low rate of walking and cycling in Ireland (1%) compared to a 2020 Smarter Travel target of 10% of walking and cycling by 2020 (Department of Transport, 2009). The study notes that 40% of emissions come from journeys less than 8 kilometres and that these journeys could be candidates for decarbonisation through active modes of travel such as walking and cycling, or public transport. It also highlights that the greatest share of emissions in passenger transport comes from cars (+90%), and so decarbonising public transport through electrification has limited impact, thus reducing car transport demand and electrifying car transport is essential for the deep decarbonisation of transport.
- Chapter 4, "Avoid-Shift-Improve: Bottom-up simulation modelling of national policies for transport carbon budgets" calculates the role of individual policy measures in the achievement of overall carbon budget targets for the transport sector. It also notes that alignment between the regional transport policy plans (for example, the metropolitan area transport strategies for Cork, Galway, Limerick, and Dublin) and national climate policy plans are essential in calculating emissions reductions to avoid double counting of modelled impacts for carbon budgeting. Emissions in the reference scenario for Carbon Budget 1 (2021 – 2025) are projected to be 55 MtCO2eq, above the 54 $MtCO_2eq$. sectoral emission ceiling for transport. In CB2

(2026 – 2030), the reference transport emissions are projected to be 60 $MtCO_2$eq., above the transport sectoral emission ceiling of 37 $MtCO_2$eq ., (Figure 24).

On an individual basis – the most successful measures were as follows – ASI 18 (840,000 EVs by 2030), ASI 22 (10% Biofuels in Petrol, and 20% Biofuels in Diesel by 2030), ASI 2 (20% reduction in all vehicle kilometres by 2030), ASI 3 (20% reduction in car kilometres by 2030), ASI 19 (20,000 commercial EVs by 2030), and ASI 1 (Working from home 2 days per week). The individual "Shift" measures were not as impactful but collectively account for 0.82 $MtCO_2$eq. cumulative emissions reductions in Carbon Budget 1 (9.5% of total emissions avoided in ASI scenario for CB 1) and 1.9 $MtCO_2$eq. cumulative emissions reductions in CB2 (7% of total emissions avoided in the ASI scenario for CB 2). The low impact from "Shift" measures could be related to a relatively low ambition in projects instigating modal shift compared to the "Avoid" and "Improve" measures set by the CAP 2023.

This study also highlights the importance of "Avoid" measures and the need to identify certain combinations of policies that work in synergy with one another (such as the simultaneous uptake and electrification of public transport) to provide additional bonuses in modelled emissions savings.

- Chapter 5 " Policy Simulation Modelling to inform National Carbon Budget Pathways" examines the impacts of transport, residential, industry, services, electricity sector decarbonisation scenarios on overall Irish climate policy. In transport, it is noted that while the measures in the UCC Sectoral Ceilings scenario meet emissions targets for the initial Carbon Budget (CB1), they rely on swift biofuel adoption, increased public transport use, and vehicle electrification. The transport sector misses the target for the second carbon budget (CB2). For the residential sector, policy measures for new and existing homes include strict energy efficiency regulations and retrofitting. While achieving the sector's emissions targets for both CB1 and CB2, these scenarios depend on rapid retrofit rates and early adoption.

In the case of the industry sector, energy demand and emissions increase in scenarios, reflecting data limitations. Achieving meaningful reductions requires deeper understanding of energy use. Achieving emissions targets involves electrifying heat and exploring fuel switching, but such penetration rates might be hard to achieve.

While with the services sector, data limitations affect policy measures for the services sector. Cross-sectoral measures, deep retrofitting, and electrification are considered, yet emissions targets are missed for both CB1 and CB2.

The study also highlights that decarbonizing electricity is crucial for heat and transport sectors. Growing electricity demand affects its decarbonization, and the rise of data centres poses challenges to meeting decarbonization targets.

6.2. Areas for Future Work

This section describes the recommendations identified as part of the development of this thesis. These recommendations are considered concerning (1) data gathering, and (2) energy and emissions modelling.

The methods proposed in this thesis do not represent a silver bullet for a low-carbon future in the transportation sector. However, they are intended to provide the first step towards forming evidence-based transport-focused policies. The energy system is complex and impossible to model to perfect accuracy. However, developing modelling methods and techniques, such as those presented in this thesis, can assist in the initial stages and review stages of policy formation. Further development in this area comes with greater accuracy, strengthening the policy measures identified by energy system models. This section identifies some areas of potential future work that may assist in this area and improve the modelling of the transportation sector.

6.2.1. Decomposing and understanding passenger transport demand and passenger transport decarbonisation enablers

Chapter 3 modelled for the first time, passenger transport emissions by mode type, trip purpose, and trip distance, for Ireland. Future research could focus on a detailed decomposition analysis using the IPTEM model to understand how factors like occupancy rates, modal preferences, trip distances, trip purposes, and fuel types, influence transportation dynamics.

Additionally, integrating urban and rural data could help tailor policies for different population density'. It's important to consider that policies promoting public transportation and modal shifts may work differently in densely populated urban areas compared to sparsely populated rural regions. The Central Statistics Office currently categorizes spatial data as "Dublin" versus "Rest of Country" instead of the more relevant "Urban" versus "rural" breakdown. Expanding this data granularity would improve the precision and relevance of future transportation policy research.

Additional scenario modelling focusing on potential passenger transport decarbonisation enablers such as 15-minute neighbourhoods and car sharing clubs could highlight the potential for these measures to deliver transport emissions savings in the immediate future, possibly at a lower cost than more technology-centric alternatives such as the "Improve" measures that focus on technology switching and biofuel mixing, which can be more costly than travel by other modes of transport, or reducing the need for travel in the first instance with urban planning.

6.2.2. Understanding new technologies such as micro-mobility and EV markets, hydrogen, and load-shifting

Future research needs could include investigating the role of micro-mobility in the context of freight and passenger decarbonisation. As findings from empirical studies inform scenarios for the decarbonisation of transport, more information on technological advancements and progress in the freight transport sector, and in micro-mobility can inform decarbonisation scenario development for these technologies and policies. Modelling over longer periods beyond 2030 could include technologies not yet commercially available or in the policy sphere, as targets are typically not set for technologies that aren't available yet (e.g., hydrogen in the freight sector). A greater understanding of the electric Heavy Goods Vehicle market can also inform whether targets for the electrification of heavy goods in Ireland are feasible and inform scenarios focusing on this issue.

To better understand the role of new technologies and how they contribute to decarbonisation, it is necessary to model these technologies in tandem with "Avoid" and "Shift" interventions. For example, in Chapter 4, demand reduction reduces the emissions reductions impact of electrification of private transport, as in a scenario where there is less driving, the electrification of the driving would have a lower quantity of passenger kilometres to begin with. This can ease the burden for new technologies to deliver all the passenger service demand if there is policy to support reducing the service demand. The sequencing and organisation of transportation energy and emissions models is continually required as urbanisation, active travel, public transport, and remote work policies unfold. The dynamics between increased public transport infrastructure, active travel facilities and reductions in car use was explored in the case of Ireland in Chapter 4, but it is deserving of more interrogation with different combinations of mode-mixes, geographical locations, and demand reduction measures.

6.2.3. Adjusting geographical scope tailored to local transitions

The decarbonisation pathways presented in this thesis in Chapter 4 and Chapter 5 focus on national and city-based plans of cities of a particular size (>40,000 people), however regional based models can and have (Gookin et al., 2022) present tailored solutions and pathways for regions seeking to reduce their emissions. By adjusting the geographical scope of the model to smaller regions, both the transport focused, and multi-sector energy systems decarbonisation models presented in this thesis can be adapted to reflect local advantages, model scenarios for local infrastructure upgrades, and create narratives to guide local area plans on the path to decarbonisation.

On the other hand, broadening the scope of the models, and, more specifically, the "Avoid-Shift-Improve" framework simulation models to focus on other countries, larger regions, or globally, can determine what different infrastructures and transport cultures these regions can harness to decarbonise. For example, motorbike use is widespread in many countries, much unlike Ireland, the region studied in this thesis. Adopting the same methodology, while including scenarios looking at different modes of transport that are available in those regions can again, show more pathways for transport decarbonisation, and the extent to which they can contribute to staying within those region's carbon budgets.

6.2.4. Inclusion of maritime and aviation emissions into national emissions modelling, carbon budget planning and decarbonisation modelling activities

At present, Ireland's emissions modelling and legislative framework do not encompass aviation and maritime transport emission'. It's worth noting that aviation emissions are accounted for in the United Kingdom's emissions balances as of 2023 (United Kingdom HM Government, 2023). To enhance our approach, future carbon budget targets for the transportation sector could be adjusted to incorporate emissions from aviation and maritime activities originating or refuelling in Ireland. Expanding the modelling scope to encompass aviation and maritime transport would facilitate a more comprehensive analysis and regulation of the fuels used in these sectors in relation to Ireland. This expansion would involve integrating aviation and maritime emissions into overall emissions calculations and exploring decarbonization scenarios for these specific sectors.

6.2.5. Data gathering

The effectiveness of an energy model in providing robust evidence-based policy support depends on the quality and granularity of data available. In short, an energy model is only as valuable as the underlying data. This subsection recommends data-gathering improvements to support the ongoing development and improvement of the LEAP Ireland model as more complex and ambitious climate mitigation targets are considered across all sectors. The development process for the LEAP Ireland model highlighted specific areas and subsectors where data collection could be improved.

There needs to be more in gathering industry end-use data in Ireland. The LEAP Ireland Model includes data from the UK Industry end-user survey to provide energy balance consistent *estimates* for energy end-use within Irish industries. Future work to improve the description of the industry and public services subsectors should be prioritised as recent changes in the publication of business energy data have resulted in changes to historical services and industry figures in Ireland's energy balance (Sustainable Energy Authority of Ireland, 2021). Specific information about the energy consumption from the commercial sectors through the new CSRD (Corporate Sustainability Reporting Directive) from the European Union that is to be introduced in the next few years could be a helpful data source for updating the commercial sectors of multi-sector energy systems models such as the LEAP Ireland model. Detailed sub-sectoral data on public services would also be welcome, the LEAP Ireland Model currently features information based on aggregations of schools, offices, hotels, retail outlets and restaurants based on the SEAI (Sustainable Energy Authority of Ireland) heat study (SEAI, 2022), but a closer look at the variance between the energy consumption of certain public ervices – e.g. hospitals, public sector office buildings, libraries, town halls, fire stations, public transport stations, could enable performance benchmarking and an evidence base for modelling the magnitude of the emissions benefit from upgrades.

6.2.6. Modelling Risk and Uncertainty

Future research should focus on modelling risk and uncertainty ranges for each of the scenarios. This entails quantifying and incorporating risk factors into decarbonization scenarios, assigning probabilities to emissions reductions, and providing policymakers with valuable insights into the most promising policy measures. By combining the quantity of emissions savings with their likelihood, we can offer a more comprehensive perspective on policy effectiveness, reducing uncertainties related to achieving carbon budget targets.

6.2.7. Extending LEAP to Include Costs

LEAP should be extended to include costs for all technologies. Basic fuel prices are included in the model-to-model electricity generation profiles successfully. A complete set of costs would allow the LEAP Ireland model to use the LEAP marginal abatement cost curve tool developed within UCC. Hall and Buckley (2016) state that including cost is essential to help define the econometric nature of any energy system model. Including cost would also aid in linking the LEAP Ireland GHG models to other energy system optimisation models which rely heavily on cost figures, e.g., the Irish TIMES model (Ó Gallachóir et al., 2012).

Creating open-source data about the costs consumers face would be helpful for researchers who wish to improve technical representation in modelling. Understanding the situation with cost estimates for construction of active travel, road and rail, bus infrastructure construction, operation and maintenance can help determine the life-cycle costs of projects and estimate the most carbon and cost-reduction effective option from modelling tools.

Further exploration of the embodied carbon costs of the measures outlined in Chapter 2 – 5. For example, Chapter 2, the ex-post analysis does not consider the total life-cycle emissions from new ICE vehicles purchased compared to second hand purchasing. Using a life cycle framing in modelling can further investigate the role of upstream emissions in car manufacturing and distribution processes. The emissions calculations for transport in Chapter 2 – 5 only consider emissions from tank-to-wheel, also considered to be the operational

emissions, from the mode type moving from A-to-B. In Chapter 5, which looks at economy-wide emissions from the residential, service, industry, agriculture, transport, and electricity sector, also does not include the cost of upstream emissions from imports and manufacturing. However, it also means for Ireland's relatively large agri-industry that the greenhouse gas emissions from beef and milk production that is for export. Considerations of imported and exported goods and services that require greenhouse gases to produce and sufficient accounting for embodied emissions can be used to create incentives for manufacturers and service providers to reduce their embodied greenhouse gas emissions, highlight areas and regions that could benefit from additional investment and improvement and provide a solid evidence base and platform for innovative manufacturers that are able to produce goods and services at the lowest carbon cost so people can make more sustainable decisions.
Societal considerations for the monetary cost of different transition options can also be captured through cost-benefit modelling, especially in the case of transport modelling. Capturing the social costs and benefits of policies such as improved walking and cycling infrastructure, bus rapid transit lanes, extensions to light rail, and installations of charging points can illustrate the co-benefits of the different kinds of low or zero carbon transport. Depending on the scope of the cost-benefit model; pricings on air-pollution, increased employment opportunities, time saved, and health outcomes, green space created or lost due to changes in land-use, could be captured.

6.2.8. Reflections on the Limitations of Modelling

This thesis has its origins in a pragmatic approach to developing research questions. The thesis applies the paradigm of using simulation models to define and describe carbon dioxide emissions in numerical terms and develop scenario-based insights and solutions from them. The thesis accepts that using such a methodology deeply rooted in data and numerical analysis can overlook policy interventions that are difficult to define in numerical terms. The origin for adapting demand reduction and modal shift as the primary areas of novel development interest was based on the relative numerical difficulty in representing these policy measures in energy systems models. There was an implicit bias towards car-centric calculations and solutions in our energy systems models due to the need for more available data on demand drivers, alternative mode types and alternative means of reducing passenger transport demand from transport. This thesis aimed to broaden the scope of transport modelling to include demand reduction strategies such as remote working and modal shift strategies such as increased public transport, walking and cycling. The methods developed in this thesis both exacerbate and alleviate some of the consequences of the energy systems modelling paradigm when addressing critical issues in climate action planning. Researchers continue to rely on imperfect simulation techniques but also develop these techniques to include realities and possibilities previously overlooked, further pushing the boundaries of available evidence to support plans and policies for decarbonisation.

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Appendix A: Supplementary Information for Chapter 2

Appendix A.A Data Sources

Metric	Unit	Sources
Fuel efficiency bands	l/100km	(Daly & Ó Gallachóir, 2011) ,(Central Statistics Office, 2020b)
Number of vehicle sales		(Central Statistics Office, 2020b)
Emissions band	gCO_2/km	(Central Statistics Office, 2020b)
On-road factors	%	(Daly & Ó Gallachóir, 2011; Dennehy & Ó Gallachóir, 2018; Tietge et al., 2017)
Engine cc tax rates	€	(Department of Transport, 2019a)
Emission band tax rate	€	(Department of Transport, 2019a)
Vehicle vintage	Year	(Daly & Ó Gallachóir, 2011; Mulholland et al., 2017b)
Distance Travelled	km	(Central Statistics Office, 2019b)

Appendix A.B. On-road factors derived from the Household Budget Surveys

	Petrol	Diesel
2005	0.06	0.14
2006	0.09	0.16
2007	0.12	0.19
2008	0.14	0.22
2009	0.17	0.25
2010	0.2	0.28
2011	0.22	0.32
2012	0.25	0.36
2013	0.28	0.39
2014	0.29	0.41
2015	0.3	0.43
2016	0.3	0.43
2017	0.3	0.43
2018	0.3	0.43

Appendix A.C. Private Households in Permanent Housing Units 2011 to 2016 (Number) by County and City, Motor Car Availability and Census Year Census 2016 (Central Statistics Office, 2017b)

Number of households	Number of cars	Total cars in household
696684	1	696,684
567414	2	1,134,828
95238	3	285,714
30413	4.3	130,776
All households		**2,248,002**

Appendix A.D. Taxation rates based on the engine cc.

Engine CC	Annual Payment
Not over 1,000	€199
1,001-1,100	€299
1,101-1,200	€330
1,201-1,300	€358
1,301-1,400	€385
1,401-1,500	€413
1,501-1,600	€514
1,601-1,700	€544
1,701-1,800	€636
1,801-1,900	€673
1,901-2,000	€710
2,001-2,100	€906
2,101-2,200	€951
2,201-2,300	€994
2,301-2,400	€1034
2,401-2,500	€1080
2,501-2,600	€1294
2,601-2,700	€1345
2,701-2,800	€1391
2,801-2,900	€1443
2,901-3,000	€1494
3,001 or more	€1809

Appendix A.E. Engine cc-based taxation rates (Source: DTTAS, 2019)

Band	CO_2 emissions-grams per km	Annual Payment
A0	0	€120
A1	1-80g	€170
A2	More than 80g/km up to and including 100g/km	€180
A3	More than 100g/km up to and including 110g/km	€190
A4	More than 110g/km up to and including 120g/km	€200
B1	More than 120g/km up to and including 130g/km	€270
B2	More than 130g/km up to and including 140g/km	€280
C	More than 140g/km up to and including 155g/km	€390
D	More than 155g/km up to and including 170g/km	€570
E	More than 170g/km up to and including 190g/km	€750
F	More than 190g/km up to and including 225g/km	€1200
G	More than 225g/km	€2350

Appendix A.F. Biofuel mixing rates by energy content (2001 – 2018)

	Bioethanol	Biodiesel
2001	0%	0%
2002	0%	0%
2003	0%	0%
2004	0%	0%
2005	0%	0%
2006	0%	0%
2007	0%	0%
2008	0%	0%
2009	0%	0%
2010	1.8%	2.7%
2011	3.4%	3.8%
2012	3.6%	3.0%
2013	3.9%	3.8%
2014	3.9%	4.4%
2015	4.6%	4.4%
2016	5.3%	3.6%
2017	5.4%	5.4%
2018	5.5%	5.0%

Appendix B: Data in Brief Article - Passenger Transport Demand, Fuel Consumption, and Emissions Data for the Irish Passenger Transport Emissions and Mobility (IPTEM) Model

Abstract

These data and analyses support Chapter 3 "How and Why We Travel – Mobility Demand and Emissions from Passenger Transport (O'Riordan, Rogan, Ó Gallachóir, Mac Uidhir, et al., 2022a). This appendix refers to a spreadsheet model, the Irish Passenger Transport Emissions and Mobility Model (IPTEM V2.9). The spreadsheet model is available for download from Zenodo (O'Riordan, Rogan, Ó Gallachóir, & Daly, 2022d). The model and the underlying data, details the passenger transport demand by trip purpose (work, shopping, education etc.,), mode type (car, rail, bus, cycling, walking) and trip distance for Ireland over the period –f 2009 - 2019. Passenger occupancy rates for public transport modes in Ireland, CO_2 emissions intensities and annual CO_2 emissions are also included in the Data in Brief. Assumptions and equations used to develop the IPTEM V2.9 are available in the Experimental design, materials, and methods section.

Specifications table

Subject	Engineering
Specific subject area	Passenger transport demand and CO_2 emissions in Ireland

Type of data	Table Chart Figure
How the data were acquired	• National transport survey data gathered from Central statistics office (CSO) (Central Statistics Office, 2020c) • Information from the Irish Car Stock Model V 2.4 on an online repository (O'Riordan, Mulholland, et al., 2021) • Calculations as mentioned in the Data in Brief's reference chapter and outlined in further detail in Experimental design, materials, and methods equations: Equation 14 – Equation 23
Data format	Raw Analysed
Description of data collection	• Irish Car Stock Model, retrieved from an online repository (O'Riordan, Mulholland, et al., 2021), referred to in a Data in Brief (Mulholland et al., 2017b) that provides technological stock data of car characteristics such as stock, mileage, and energy consumption per kilometre.

	• Population data made available from Eurostat (Eurostat, n.d.-a) • National Travel Survey Data is available from the Central Statistics Office (Central Statistics Office, n.d.-a)
Data source location	Raw data sources used: National Travel Survey 2009, 2012, 2013, 2014, 2016 and 2019, available online at: https://www.cso.ie/en/statistics/ Sustainable Energy Authority of Ireland conversion rates, available online at: https://www.seai.ie/data-and-insights/seai-statistics/conversion-factors/ Irish Car Stock Model V2.4, available online at: https://zenodo.org/record/4651477#.YjD5fXrMKUk
Data accessibility	• Data is provided with this appendix in the following formats: Irish Passenger Transport Emissions and Mobility Model (IPTEM V2.9) is available on open-source repository Zenodo. Repository name: Zenodo Data identification number: 10.5281/zenodo.6359991 Direct URL to the data: https://doi.org/10.5281/zenodo.6359991

Related Chapter	V. O’Riordan, F. Rogan, B. Ó Gallachóir, T. Mac Uidhir, H. Daly, How and why we travel – Mobility demand and emissions from passenger transport, Transp. Res. Part D Transp. Environ. 104 (2022b). https://doi.org/10.1016/j.trd.2022.103195.

Value of the data

- This data provides clarity behind the modelling assumptions and methods used to model passenger transport demand and emissions in Ireland.

- While the data is Ireland specific, it serves as a guideline for the scientific community to ways to replicate similar modelling methods designed for other regions at a local, national, or international level.

- It provides valuable insights into the sources available at a national level which most European member states have freely available, and which can be used to replicate the modelling methods provided in Chapter 2. This data can be used to gain insights into the link between modal shift to low carbon dioxide passenger transport.

- Energy analysts can benefit from the detailed passenger transport demand information, serving to aid in replication of transport emissions and demand analyses. Policymakers also benefit from the information on occupancy rates, CO_2 emissions intensity and passenger transport demand listed.

Data description

The dataset referred to in this appendix exists as an Excel spreadsheet available on Zenodo (O'Riordan, Rogan, et al., 2022d). The spreadsheet model has a series of sheets contained within the Excel file 'IPTEM V2.9'. The dataset within this appendix provides secondary data from the Irish National Travel Survey conducted by the Central Statistics Office (Central Statistics Office, 2020), data from the Irish Car Stock Model (H. Daly & Ó Gallachóir, 2011; O'Riordan, Mulholland, et al., 2021), energy and emissions conversion factors from the Sustainable Energy Authority of Ireland (Sustainable Energy Authority of Ireland, 2020). Occupancy, annual energy consumption figures, and passenger numbers from public transport providers: Dublin Bus (city bus transportation system) (Dublin Bus, 2021), Irish Rail (national rail network in Ireland) (Irish Rail, 2021), Bus Éireann (national bus network in Ireland) (Bus Éireann, 2021), and Luas (light rail system in Dublin, Ireland) (National Transport Authority, 2021), are also included. Assumptions underpinning the IPTEM V2.9 model are also shared in the sheet "Pkm (Passenger Kilometre) Calculation Assumptions". Calculations for passenger kilometre demand in Ireland by trip purpose, trip distance and mode type are found in "Pkm distance by distance and mode", "Pkm by distance and journey type" sheets. Excel formulae and references to previous sheets are embedded in the calculation sheets. Calculations for CO_2 emissions by trip distance, mode type and trip purpose are found in Excel sheet "CO_2 Emissions Intensity" and "CO_2 Emissions by mode, purpose and distance". An index and content description of the sheets in the IPTEM V2.9 model is listed in Table 29. This Data in Brief contains sample rows and entry values to describe the tables in the repository. The sample table entries are included in the data in brief to assist navigation of the accompanying Excel spreadsheet repository.

Table 29: Index of IPTEM V2.9 Excel spreadsheets

Sheet label	**Content Description**
Readme	Provides information on the contact details of the author, and the latest revision date.
CSO Tables	Contains secondary data from the Central Statistics Office's National Travel Surveys in 2009, 2012, 2013, 2014, 2016 and 2019. Data is referred to in Table 31 - *Table 54*.
Irish Car Stock Model V 2.4	Contains references to the Irish Car Stock Model, which was developed by Daly and Ó Gallachóir (H. Daly & Ó Gallachóir, 2011), (O'Riordan, Mulholland, et al., 2021). Data is referred to in *Table 55* - Table 62
Occup., Energy Cons., Emission	Shorthand for "Occupancy, Energy Consumption and

	Emissions". This contains information on occupancy rates, passenger kilometre estimates for public transport. Data is referred to in Table 63 - Table 86.
Pkm (passenger kilometres) calculation Assumptions	Contains calculations for assumptions underpinning the Irish Passenger Transport Emissions and Mobility (IPTEM) model. Data and calculation tables are referred to in Table 87 - Table 95.
Pkm by distance and mode	Shorthand for passenger kilometre by distance and mode. It is a calculation of total passenger kilometres by year, trip distance and mode type. Method to calculate the Total Passenger Kilometres is listed in Equation 16.
Pkm by distance and purpose	Shorthand for passenger kilometre by distance and trip purpose. A sample row with descriptions of

	each of the entry fields is noted in Table 97. Methods to calculate Total Passenger Kilometres is listed in Equation 16.
Passenger Kilometre Tables	Contains tables derived from pivot tables from Table 96. For years unsurveyed by the National Travel Survey, the values for passenger kilometres are interpolated. The passenger kilometres by mode type, trip distance and trip purpose over the period –f 2009 - 2019 are listed in Table 99, Table 100 and Table 101.
CO_2 Emissions Intensity	Data is listed in Table 76 - Table 84. Method to calculate the CO_2 emissions intensity is listed in Equation 22.
CO_2 Emission by mode, purpose, dist.	Shorthand for “CO_2 Emissions by mode, purpose and distance.” Data is listed in Table 102. Methods to calculate the emissions are listed in Equation 22 and Equation 23.

Emissions tables	Contains calculations that are interpolations of Passenger Kilometres by trip distance, mode type and trip purpose derived from pivot tables from Table 102. Outputs are listed in *Table* 103, Table 104, Table 105.

CSO Tables

The CSO tables are based on the National Travel Survey conducted by the Central Statistics Office (CSO). The survey was conducted for Ireland and is based on travel diaries by respondents in 2009, 2012, 2013, 2014, 2016 and 2019. Data for the intervening years is interpolated. A description of the mode types available in the survey is listed in

Table 30: Overview of transport modes referred to in the IPTEM model (O'Riordan, Rogan, Ó Gallachóir, Mac Uidhir, et al., 2022d).

Table 30: Overview of transport modes referred to in the IPTEM model (O'Riordan, Rogan, Ó Gallachóir, Mac Uidhir, et al., 2022d)

Mode	Description
Private Car – Driver	People travelling in a car as the main driver
Private Car – Passenger	People travelling in a car driven by another person
Walk	People walking, also known as “active travel”
Bus	People taking the bus, there are two main bus transit providers in Ireland, Dublin Bus, which operates urban driving style city routes in Dublin, Ireland, and Bus Éireann, providing a mix of urban and intercity driving. Private bus transport is assumed to be negligible.
Cycle	Includes the use of both mechanical bikes and e-bikes for cycling and is also categorized as an “active mode” of transport
Rail/DART/Luas	This mode choice refers to the three rail providers in Ireland; Iri–h Rail - which operates long distance rail in Ireland, DART- the Dublin Area Rapid Transit, a commuter rail operating in the Greater Dublin area and Luas - a city light rail which operates in Dublin
Taxi/hackney	People travelling in a car operated by a registered taxi driver
Lorry/Motorcycle/Other	This mode includes lorries, motorcycles and any other mode choice not included in the preceding categories

Passenger kilometres, occupancy figures, energy, and CO_2 emissions intensity per passenger kilometre serviced are determined for the following public transit authorities in Ireland

5. Bus Éireann – The intercity and nation-wide bus service in Ireland
6. Dublin Bus – The urban bus service operating in Ireland's largest city, Dublin.
7. Irish Rail/DART – The heavy rail cross country and commuter rail service operating in Ireland
8. Luas – The light rail service

Passenger kilometres by trip purpose was also calculated. The following trip purposes are covered in this study

- Work
- Education
- Shopping
- To eat or drink
- Other
- Entertainment/Leisure/Sports
- Personal Business
- Companion/Escort Journey
- Visit family/friends

Trip distance categories from the National Travel Survey were as follows:

- < 2 kilometres
- 2–4 kilometres
- 4–6 kilometres
- 6-8 kilometres
- >8 kilometres

The average of each of the categories are used in calculating overall Passenger Kilometre demand. The figure for passenger kilometres for the >8-kilometre category was calculated through calibration with the Irish Car Stock Model.

Table 31: Percentage distribution of journey distance for all region–, 2009 - 2019 Source: CSO, National Travel Survey (Central Statistics Office, 2020c)

	2009	2012	2013	2014	2016	2019
	%	%	%	%	%	%
<2 kilometres	22	22.3	21.1	18.8	25.5	28.6

Table 32: Percentage distribution of journeys by mode of travel and distance < 2km, 2009 - 2019, Source: CSO, National Travel Survey (Central Statistics Office, 2020c)

	2009	2012	2013	2014	2016	2019
	%	%	%	%	%	%
Priv–te car - Driver	40	51.9	46.3	49.1	50.3	51.4

Table 33: Percentage distribution of journeys by mode of travel and distance 2 - 4 km, 2009 - 2019, Source: CSO, National Travel Survey (Central Statistics Office, 2020c)

	2009	2012	2013	2014	2016	2019
	%	%	%	%	%	%
Priv–te car - Driver	63.4	69.5	67.4	65.6	66.1	66.1

Table 34: Percentage distribution of journeys by mode of travel and distance 4 - 6 km, 2009 - 2019, Source: CSO, National Travel Survey (Central Statistics Office, 2020c)

	2009	2012	2013	2014	2016	2019
	%	%	%	%	%	%
Priv–te car - Driver	71.7	72.6	73.1	70.6	71.9	70.6

Table 35: Percentage distribution of journeys by mode of travel and distance 6 - 8 km, 2009 – 2019, Source: CSO, National Travel Survey (Central Statistics Office, 2020c)

	2009	2012	2013	2014	2016	2019
	%	%	%	%	%	%
Priv–te car - Driver	71.7	73.1	73.9	75.4	75.6	70.6

Table 36: Percentage distribution of journeys by mode of travel and distance >8 km, 2009 - 2019, Source: CSO, National Travel Survey (Central Statistics Office, 2020c)

	2009	2012	2013	2014	2016	2019
	%	%	%	%	%	%
Priv–te car - Driver	74.0	79.7	79.3	78.3	80.2	71.9

Table 37: Population , 2009 - 2019 , Source: Eurostat (Eurostat, 2023)

2009	2012	2013	2014	2016	2019
population					
4,521,000	4,589,000	4,610,000	4,638,000	4,726,000	4,904,000

Table 38: Number of respondents, National Travel Survey, 2009 - 2019, Source: CSO, National Travel Survey (Central Statistics Office, 2020c)

2009	2012	2013	2014	2016	2019
Number of respondents					
7,221	14,759	14,759	10,382	11,027	8,400

Table 39: Total journeys per person per day, National Travel Survey, 2009 - 2019, Source: CSO, National Travel Survey (Central Statistics Office, 2020c)

	2009	2012	2013	2014	2016	2019
Number of journeys per day	2.43	1.88	1.88	1.74	1.78	3

Table 40: Total journeys per year total, National Travel Survey, 2009 - 2019, Source: CSO: National Travel Survey (Central Statistics Office, 2020c)

	2009	2012	2013	2014	2016	2019
Number of journeys	4,007,543,571	3,165,688,023	3,171,485,717	2,940,102,001	3,079,198,792	5,369,880,000

Table 41: Private vehicle activity (vehicle kilometres, vkm), based on the Irish Car Stock Model, 2001 – 2018

2009	2012	2013	2014	2016	2019
Vkm					
32,873,713,915	29,535,056,173	31,821,299,194	32,323,075,433	36,171,159,701	36,195,324,272

Table 42: Average journey distance by mode (vehicle kilometres), Source: CSO, National Travel Survey (Central Statistics Office, 2020c)

	2009	2012	2013	2014	2016	2019
	Vkm					
Priv–te car - driver	14	14.3	15.4	15.6	16.3	13.6

Table 43: Weighting factor for distance based on mode, 2009 – 2019, calculation

	2009	2012	2013	2014	2016	2019
Priv–te car - driver	1.00	1.00	1.00	1.00	1.00	1.00

Table 44: Percentage distribution of journeys by reason of travel and distance <2km, 2009 – 2019, Source: CSO, National Travel Survey (Central Statistics Office, 2020c)

	2009	2012	2013	2014	2016	2019
	%	%	%	%	%	%
Work	13	13.6	16.4	15.2	17.4	14.2

Table 45: Percentage distribution of journeys by reason of travel and dist–nce, 2 - 4km, 2009 – 2019, Source: CSO, National Travel Survey (Central Statistics Office, 2020c)

	2009	2012	2013	2014	2016	2019
	%	%	%	%	%	%
Work	17.0	16.8	19.1	20.3	24.4	17.4

Table 46: Percentage distribution of journeys by reason of travel and dis–ance 4 - 6 km, 2009 – 2019, Source: CSO, National Travel Survey (Central Statistics Office, 2020c)

	2009	2012	2013	2014	2016	2019
	%	%	%	%	%	%
Work	23.0	18.9	22.5	21.8	27.3	22.1

Table 47: Percentage distribution of journeys by reason of travel and dis–ance 6 - 8 k–, 2009 - 2019, Source: CSO, National Travel Survey (Central Statistics Office, 2020c)

	2009	2012	2013	2014	2016	2019
	%	%	%	%	%	%
Work	24.0	24.5	23.4	22.6	33.3	22.3

Table 48: Percentage distribution of journeys by reason of travel and distance >8km, 2009 – 2019, Source: CSO, National Travel Survey (Central Statistics Office,2020c)

	2009	2012	2013	2014	2016	2019
	%	%	%	%	%	%
Work	37	32	21.8	33.4	38.1	31.4

Table 49: Average journey distance by purpose of travel, 2009 – 2019 (kilometres), Source: CSO, National Travel Survey (Central Statistics Office, 2020c)

	2009
	km
Work	18

Table 50: Reason for car journeys by percentage, based on average values from Dublin and rest of county as specified in Equation 15.

	2009	2012	2013	2014	2016	2019
	%	%	%	%	%	%
Work	24.4	24.4	24.4	25.2	28.8	21.3

Table 51: Reason for public transport journeys by percentage, based on average values from Dublin and rest of county as specified in Equation 15.

Reason for public transport journeys by percentage	2009	2012	2013	2014	2016	2019
	%	%	%	%	%	%
Work	28.8	28.8	28.8	25.3	32.2	35.4

Table 52: Reason for walking/cycling journeys by percentage, based on average values from Dublin and rest of county as specified in Equation 15.

	2009	2012	2013	2014	2016	2019
	%	%	%	%	%	%
Work	17.7	17.7	17.7	15.6	18.5	21.0

Table 53: Reason for Lorry/motorcycle/other journeys by percentage, based on average values from Dublin and rest of county as specified in Equation 15.

	2009	2012	2013	2014	2016	2019
	%	%	%	%	%	%
Work	52.1	52.1	52.1	50.9	57.8	48.3

Table 54: Reason for journey (percentage), Source: Irish Car Stock Model (Central Statistics Office, 2020)

Reason for journey by percentage %	2009	2012	2013	2014	2016	2019
	%	%	%	%	%	%
Work	25	23.0	24.8	25.0	29.3	23.6

Irish Car Stock Model V 2.4

The tables listed in the sheet "Irish Car Stock Model V2.4" are extracted from an open source model (O'Riordan, Mulholland, et al., 2021). A Data in Brief appendix corresponding to elements of an earlier version of the Irish Car Stock Model is available (Mulholland et al., 2017b). The methodology behind the calculation of vehicle kilometres and fuel consumption of private vehicles in Ireland is based on a study on technology stock modelling of private cars in Ireland (Daly & Ó Gallachóir, 2011).

Table 55: Energy consumption of hybrid vehicles (Source: Irish Car Stock Model, (O'Riordan, Mulholland, et al., 2021; Pye et al., 2021)*)*

Energy Consumption of Hybrid Vehicles	Year	2001
Engine size: < 1300cc	MJ/100km	1.45
Engine size:–1300cc - 1700cc	MJ/100km	1.45
Engine size: > 1700cc	MJ/100km	2.73
Diesel energy consumption	MJ/100km	1.87
Diesel Energy consumption	MJ/km	0.02
Share of Petrol based energy consumption	%	0.60
Share of Electricity based energy consumption	%	0.40
Electrical Energy consumption of a Hybrid	MJ/km	0.02
Total Energy consumption of a Hybrid	**MJ/km**	**0.04**

Table 56: Energy Consumption of Plug in Hybrid (MJ/100km), Source: (Mulholland et al., 2017b)

Energy Consumption Plug in Hybrid	MJ/100km	
Share of Diesel based energy consumption	%	40%
Share of Electricity based energy consumption	%	60%
Average Diesel Plug in Hybrid	(MJ/100km)	1.06
Diesel Plug in Hybrid	(MJ/km)	0.01
Electric	(MJ/km)	0.03
Total		0.04

Table 57: Energy Consumption of Electric cars (MJ/km), Source: Irish Car Stock Model, (O'Riordan, Mulholland, et al., 2021; Yue et al., 2020)

Energy Consumption of Electric ca–s	2001 - 2018
	MJ/km
	0.04222222

Table 58: Energy Consumption of Hybrid vehicles (MJ/km), Source: (O'Riordan, Mulholland, et al., 2021)

	2001
	MJ/km
Diesel Hybrid	0.0140
Electric Hybrid	0.0169
All	**0.0309**

Table 59: Energy Consumption of electric cars (kWh/km), Source: Irish Car Stock Model, (Daly & Ó Gallachóir, 2011; O'Riordan, Mulholland, et al., 2021)

Energy Consumption of Electric ca–s	2001 - 2018
	kWh/km
Electricity	0.152

Table 60: Energy Consumption of Plug-in Hybrids (kWh/km), Source: Irish Car Stock Model, (Daly & Ó Gallachóir, 2011; O'Riordan, Mulholland, et al., 2021)

Energy Consumption of Plug in Hybri–s	2001 - 2018
	kWh/km
Diesel	0.0382364
Electricity	0.0912
Total	**0.1294364**

Table 61: Energy consumption of Hybrid cars (kWh/km)

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
kWh/km																		
Diesel	0.050	0.050	0.050	0.048	0.054	0.059	0.062	0.063	0.069	0.068	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067

Table 62: On-road factors for diesel cars (factors), Source: Irish Car Stock Model, (H. Daly & Ó Gallachóir, 2011; O'Riordan, Mulholland, et al., 2021)

2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
On-road factor																	
0.13	0.13	0.13	0.13	0.13	0.12	0.14	0.16	0.17	0.2	0.25	0.27	0.33	0.39	0.41	0.42	0.42	0.42

Occupancy, Energy Consumption and Emissions

Table 63: Occupancy Public Transport, based on passenger kilometres (Table 34) and Vehicle kilometres (Table 67)

	2010	2011	2012	2013	2014	2015	2016	2017	2018
	Number of people								
Dublin Bus (Urban Bus)	27	21	21	27	31	31	20	20	34

Table 64: Passenger kilometres from Public Transport, based on passenger kilometres by mode (Table 99)

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
	Pkm										
Dublin Bus (Urban Bus)		1,657,005,44	1,249,888,23	1,214,931,14	1,536,441,90	1,765,668,62	1,777,305,98	1,160,134,74	1,195,332,29	1,962,684,82	

Table 65: Multiplication of number of passengers serviced (Table 66) by public transport vehicle kilometres (Table 67)

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
	non-unit factor										
Dublin Bus (Urban Bus)		7.23369E+15	6.91291E+15	6.49912E+15	6.29944E+15	6.62682E+15	6.82974E+15	7.18256E+15	7.95758E+15	7.99628E+15	

Table 66: Number of passengers serviced by each public transport type

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
	Number of passengers										
Dublin Bus (Urban Bus)		117,050,000	115,050,000	113,280,000	112,490,000	116,260,000	119,820,000	125,350,000	136,260,000	140,040,000	

Table 67: Vehicle kilometres by public transport provider

Vehicle kilometres	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
	Vkm										
Dublin Bus (Urban Bus)		61,800,000	60,086,140	57,372,160	56,000,000	57,000,000	57,000,000	57,300,000	58,400,000	57,100,000	

Table 68: Diesel consumption per year Public Transport (kWh)

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
	kWh										
Dublin Bus (Urban Bus)		318,229,000	305,663,000	284,767,000	278,385,000	279,911,000	280,847,000	278,405,000	280,716,000	267,592,000	

Table 69: Electricity consumption per year Public Transport (kWh)

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
	kWh										
Dublin Bus (Urban Bus)		6,500,000	6,422,000	5,786,000	5,430,000	5,240,000	5,223,000	4,614,000	4,517,000	4,457,000	

Table 70: Natural Gas consumption per year Public Transport (kWh)

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
	kWh										
Dublin Bus (Urban Bus)		11,850,000	8,791,000	8,900,000	9,229,000	8,563,000	10,508,000	11,489,000	9,997,000	11,111,000	

Table 71: CO_2 Emissions Intensity by fuel type (gCO_2/kWh) based on conversion factors from the Sustainable Energy Authority of Ireland (Sustainable Energy Authority of Ireland, 2020)

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
	gCO_2/kWh									
Diesel	263.9	263.9	263.9	263.9	263.9	263.9	263.9	263.9	263.9	263.9

Table 72: Energy Intensity per passenger kilometre by Fuel Type - Dublin Bus (kWh/km) calculated from fuel consumption (Table 68, Table 69, Table 70) And per passenger kilometres (Table 64)

	2010	2011	2012	2013	2014	2015	2016	2017	2018
	kWh/km								
Diesel	0.1921	0.2446	0.2344	0.1812	0.1585	0.1580	0.2400	0.2348	0.1363

Table 73: Energy Intensity by Fuel Type - Bus Éireann(kWh/km) calculated from fuel consumption (Table 68, Table 69, Table 70) and passenger kilometres (Table 64)

	2010	2011	2012	2013	2014	2015	2016	2017	2018
	kWh/km								
Diesel	0.2585	0.3262	0.3161	0.2422	0.2215	0.2234	0.3301	0.3182	0.1724

Table 74: Energy Intensity by Fuel Type – Irish Rail (kWh/km) calculated from fuel consumption (Table 68, Table 69, Table 70) and passenger kilometres (Table 64)

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
	kWh/km									
Diesel		0.191	0.201	0.197	0.194	0.180	0.178	0.183	0.191	0.197

Table 75: Energy Intensity by Fuel Type – Luas (kWh/km) calculated from fuel consumption (Table 68, Table 69, Table 70) and passenger kilometres (Table 64

	2010	2011	2012	2013	2014	2015	2016	2017	2018
	kWh/km								
Electricity	0.0639	0.0485	0.0496	0.0481	0.0434	0.0457	0.0515	0.0454	0.0424

Table 76: CO_2 Emissions Intensity by Dublin Bus (gCO_2/km) based on calculation of energy intensity per passenger kilometre (Table 72) and CO_2 Emissions intensity by fuel type (Table 71)

	2010	2011	2012	2013	2014	2015	2016	2017	2018
	gCO_2/km								
Diesel	50.68	64.54	61.86	47.82	41.84	41.70	63.33	61.98	35.98

Table 77: CO_2 Emissions Intensity of Bus Éireann (gCO_2/km) based on calculation of energy intensity per passenger kilometre (Table 73) and CO_2 emissions intensity by fuel type (Table 84)

	2010	2011	2012	2013	2014	2015	2016	2017	2018
	gCO_2/km								
Diesel	68.22	86.09	83.42	63.92	58.45	58.95	87.10	83.98	45.49

Table 78: CO_2 Emissions Intensity of Irish Rail (gCO_2/km) based on calculation of energy intensity per passenger kilometre (Table 74) and CO_2 Emissions Intensity by fuel type (Table 71)

	2010	2011	2012	2013	2014	2015	2016	2017	2018
	gCO_2/km								

Diesel	50.47	52.92	51.99	51.14	47.61	47.09	48.23	50.41	52.02

Table 79: CO_2 Emissions Intensity of the Luas (gCO_2/km) based on calculation of energy intensity per passenger kilometre (Table 75) and CO_2 Emissions intensity by fuel type (Table 72)

	2010	2011	2012	2013	2014	2015	2016	2017	2018
	gCO_2/km								
Electricity	40.63	25.71	24.24	25.49	20.30	20.78	23.92	21.81	18.51

Table 80: CO_2 Emissions Intensity of private vehicles by fuel type (gCO_2/km), source: Irish Car Stock Model, (Daly & Ó Gallachóir, 2011; O'Riordan, Mulholland, et al., 2021)

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
	gCO_2/km																	
Diesel	179.35	180.07	182.36	182.81	181.61	185.70	186.53	184.62	182.36	179.44	177.20	175.76	175.53	174.56	174.49	173.71	172.36	173.48

Table 81: CO_2 Emissions Intensity of Electric vehicles by fuel type (gCO_2/km) calculated from CO_2 Emissions intensity of electricity (Table 71) and the energy intensity of electric vehicles (Table 59)

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
	gCO_2/km									
Electricity	96.58	96.58	80.53	74.33	80.56	71.01	69.14	70.66	73.02	66.36

Electric vehicles by fuel type (gCO_2/km)

Table 82: CO_2 Emissions Intensity of Plug in Hybrids by fuel type (gCO_2/km) calculated from CO_2 Emissions intensity of fuels (Table 71) and the energy intensity of Plug-in hybrid vehicles (Table 60)

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
	gCO_2/km									
Electricity	57.95	57.95	48.32	44.60	48.34	42.61	41.49	42.40	43.81	39.82

Table 83: CO_2 Emissions Intensity of Hybrids by fuel type (gCO_2/km) calculated from the CO_2 Emissions intensity of fuels and the energy intensity of hybrid vehicles (Table 58)

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
	gCO_2/km									
Electricity	38.63	38.63	32.21	29.73	32.22	28.41	27.66	28.27	29.21	26.55

Table 84: CO_2 Emissions Intensity of private vehicles by fuel type per passenger kilometre (gCO_2/Pkm) based on CO_2 Emissions intensity per vehicle kilometre (Table 80 - Table 83), and occupancy of private vehicles (Table 89).

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018

	gCO_2/Pkm									
Diesel	120.4	120.9	122.4	122.7	121.9	124.6	125.2	123.9	122.4	120.4

Table 85: Energy intensity of private vehicles by fuel type (kWh/Pkm)

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
	kWh/Pkm									
Diesel	0.456	0.458	0.464	0.465	0.462	0.472	0.474	0.470	0.464	0.456

Table 86: Synthesized CO_2 Emissions intensity by mode type (gCO_2/pkm) based on the CO_2 Emissions intensity of cars (Table 84) and public transport (Table 76 -Table 79)

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
	gCO_2/Pkm										
Private car – Driver	121.7	122.2	123.2	123.3	122.8	124.1	124.1	122.5	121.2	119.5	119.5

Passenger Kilometre Calculation Assumptions

Table 87: Average Distance by kilometre grouping for mode types

	2009	2012	2013	2014	2016	2019
	km	km	km	km	km	km
<2 kilometres	1	1	1	1	1	1

Table 88: Private vehicle kilometres from the Car Stock Model

2009	2012	2013	2014	2016	2019
Vkm	Vkm	Vkm	Vkm	Vkm	Vkm
32,873,713,915	29,535,056,173	31,821,299,194	32,323,075,433	36,171,159,701	36,195,324,272

Table 89: Private Vehicle Occupancy rates

Private Vehicle Occupancy	2009 – 2019
	people
Private Vehicle	1.49

Table 90:Private vehicle passenger kilometres from the Irish Car Stock Model (H. Daly & Ó Gallachóir, 2011; O'Riordan, Mulholland, et al., 2021)

	2009
	Pkm
Passenger Kilometres	48,981,833,733

Table 91: Average distance by kilometre grouping for trip purpose

	2009	2012	2013	2014	2016	2019
	km	km	km	km	km	km
<2 kilometres	1	1	1	1	1	1

Table 92: Adjustment factor for distance based on trip purpose

	2009	2012	2013	2014	2016	2019
Work	1	1	1	1	1	1
Education	0.888888889	0.888888889	0.888888889	0.888888889	0.888888889	0.888888889

Table 93: Vehicle Kilometres by fuel type of private cars (km)

Fuel Type	2001
PETROL	20,379,511,457
DIESEL	4,721,440,677
HYBRID	-
PLUGIN	-
ELECTRIC	-
Private Vehicle	25,100,952,134

Table 94: Number of journeys by trip purpose, calculated by Table 50, reason of journeys by percentage and total journeys per year (Table 40)

	2009	2012	2013	2014	2016	2019
	Number of journeys					
Work	1,001,885,893	728,108,245	786,528,458	735,025,500	902,205,246	1,267,291,680

Table 95: Average distance of journeys by trip purpose, calculated by dividing Table 94: Number of journeys by trip purpose by Table 100: Interpolation of Passenger Kilometres by trip purpose

Average distance of journeys by trip purpose	2009	2012	2013	2014	2016	2019
	%	%	%	%	%	%
Work	21.3	21.7	15.5	25.3	25.9	15.4

Passenger Kilometres by Distance and Mode

Table 96: Sample row entry from Passenger kilometres by trip distance and mode type with additional reference row for Table references within the Data in Brief

Title	Value description	Unit	Value	Data in Brief reference
Passenger kilometres by trip distance and mode type	**Year**		2009	
	Trip distance	km	<2 kilometres	
	Mode Type		Priv–te car - Driver	
	Decimal distribution of journey distance for all region–, 2009 - 2019	%	22	Table 31
	Distribution of journeys by mode of travel and distance < 2k–, 2009 - 2019	%	40	Table 32
	Distribution of journeys by mode of travel and dis–ance 2 - 4 k–, 2009 - 2019	%	0	Table 33
	Distribution of journeys by mode of travel and dis–ance 4 - 6 k–, 2009 - 2019	%	0	Table 34
	Distribution of journeys by mode of travel and dis–ance 6 - 8 k–, 2009 - 2019	%	0	Table 35
	Distribution of journeys by mode of travel and distance >8 k–, 2009 - 2019	%	0	Table 36
	Average Journey Length	km	1.00	Table 42
	Mode distance adjustment factor		1.000	Table 43
	Number of journeys		4,007,543,571	Table 40
	Total Passenger Kilometres for the journey grouping	Pkm	352,663,834	Calculation based on Equation 17.
	Total Vehicle Kilometres (for that year)	Vkm	32,873,713,915	Table 41

Passenger Kilometres by Distance and Purpose

Table 97: Sample entry row passenger kilometres by trip distance and purpose with additional reference row for Table references within the Data in Brief

Title	Value description	Unit	Value	Data in Brief reference
Passenger kilometres by distance and trip purpose	Year		2009	
	Trip distance	km	<2 kilometres	
	Trip purpose		Work	
	Distribution of journey distance for all region–, 2009 - 2019	%	22	Table 31
	Distribution of journeys by mode of travel and distance < 2k–,2009 - 2019	%	13	Table 44
	Distribution of journeys by purpose of travel and dis–ance 2 - 4 k–, 2009 - 2019	%	0	Table 45
	Distribution of journeys by purpose of travel and dis–ance 4 - 6 k–, 2009 - 2019	%	0	Table 46
	Distribution of journeys by purpose of travel and dis–ance 6 - 8 k–, 2009 - 2019	%	0	Table 47
	Distribution of journeys by purpose of travel and distance >8 k–, 2009 - 2019	%	0	Table 48
	Average Journey Length		1.00	Table 49
	Trip purpose distance adjustment factor		1.000	Table 92
	Number of journeys		4,007,543,571	Table 40
	Total Passenger Kilometres		114,615,746	Calculation based on Equation 16
	Total Vehicle Kilometres		32,873,713,915	Table 41

Emissions by Trip mode, Purpose, and Distance

Table 98: Sample entry row of emissions by trip mode, purpose, and distance with additional reference row for Table references within the Data in Brief

Value description		Unit	Value	Ref
Passenger kilometres by mode type, trip purpose and distance	**Year**	2009		
	Mode Type	Private car - Driver		
	Purpose	Work		
	Trip Distance	<2 kilometres	Km	
	Passenger Kilometres for that mode type across all purpose	41,186,265,415	Pkm	Table 100
	Percentage of journeys by trip purpose	24	%	Table 50
	Passenger Kilometres by purpose and mode type	10,028,855,628	Pkm	Equation 16
	Average distance based on mode type	1	km	Table 87
	Average distance based on trip purpose type	1	km	Table 91
	Average distance based on trip purpose and mode type	1	km	Equation 18
	Distance weighting	0.02108148		Equation 14
	Calibration factor	1		
	Passenger Kilometres by distance category, mode type and trip purpose	211423118.6	Pkm	
	% Pkm for that year by distance, mode type and trip purpose category	0.003464316	%	Equation 19
	CO_2 Emissions intensity by mode type	121.68	gCO_2/Pkm	Table 86
	Emissions from category	25726686424	gCO_2	Equation 23
	Emissions from category	0.025726686	$MtCO_2$	

Passenger Kilometre Tables

Table 99: Interpolation of Passenger Kilometres by mode type (2009 – 2019)

	2009
Bus	2,807,733,663
Cycle	223,983,168
Lorry/Motorcycle/Other	5,875,413,924
Priv–te car - Driver	41,186,265,415
Priv–te car - Passenger	7,789,254,560
Rail/Dart/Luas	2,755,466,733
Taxi/hackney	-
Walk	157,552,740
Total	**60,795,670,202**

Table 100: Interpolation of Passenger Kilometres by trip purpose

Trip Purpose	**2009**
Companion / escort journey	4,912,442,902
Education	2,294,831,660
Entertainment / leisure / sports	3,875,062,196
Other	5,507,218,474
Personal business	4,968,776,942
Shopping	10,147,549,168
To eat or drink	736,414,184
Visit family / friends	7,027,564,286
Work	21,336,198,042
Total	**60,806,057,855**

Table 101: Interpolation of Passenger Kilometres by trip distance

Year	2009
<2 kilometres	1,281,662,701
2-4 kilometres	3,844,988,102
4-6 kilometres	6,408,313,503
6-8 kilometres	8,971,638,904
8+ kilometres	40,289,066,993
	60,795,670,202

Emissions Intensity

Table 102: Sample row from Emissions Intensity Table, with Table references for each entry

Title	Value description	Unit	Value	Data in Brief reference
Emissions intensity	Year		2010	
	Mass transit or vehicle		Mass transport	
	Mode		Irish Rail (Heavy Rail)	
	Fuel Type		Diesel	
	Vehicle Kilometres	Vkm	15,950,000	Table 88, Table 67
	Occupancy	Vkm/Pkm	152.8	Table 63, Table 89
	Passenger Kilometres	km	2,436,460,870	
	CO_2 Emissions Intensity	gCO_2/Pkm	50.47378412	Table 64, Table 76 - Table 81
	Total CO_2 Emissions	gCO_2	122,977,400,000	Calculation based on Equation 23
	Total CO_2 Emissions	$MtCO_2$	0.12	
	Energy Intensity	kWh/100Pkm	19.13	Table 73, Table 74, Table 75, Table 85, Equation 22
	Energy Consumption	kWh	466,000,000	Table 55: Energy consumption of hybrid vehicles (Source: Irish Car Stock Model, Calculation based on Equation 21
	Energy Consumption (MWH)	MWh	466,000	

Emissions Tables

Table 103: Total Emissions by trip purpose ($MtCO_2$)

	2009
Companion/Escort Journey	1.08
Education	0.21
Entertainment/leisure/sports	0.47
Other	0.21
Personal Business	0.40
Shopping	1.39
To eat or drink	0.08
Visit family/friends	0.67
Work	1.45
Grand Total	5.96

Table 104: Emissions by trip distance category ($MtCO_2$)

2009	
<2 kilometres	0.125635
2-4 kilometres	0.376906
4-6 kilometres	0.628176
6-8 kilometres	0.879447
8+ kilometres	3.949344

Table 105: Emissions by mode type ($MtCO_2$)

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Bus	0.00	0.05	0.11	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16

Experimental Design, Materials, and Methods

This section will discuss the methods used to acquire the secondary data and calculate the primary data used in the IPTEM V2.9 spreadsheet.

Acquisition of Secondary Data

This section outlines the steps required to acquire, process, and analyse the data referenced in this appendix.

The National Travel Survey conducted by the CSO (Central Statistics Office, 2020c) forms a key source of secondary data for the "CSO Tables" sheet in IPTEM V2.9. The data was extracted from the interactive data tool available from the Central Statistics Office (Central Statistics Office, n.d.-a).

The open-source Irish Car Stock Model formed the basis of on the secondary data included in the "Irish Car Stock Model V2.4" spreadsheet (O'Riordan, Mulholland, et al., 2021). The Irish Car Stock Model as described in Daly and Ó Gallachóir develops a picture of private car energy demand in Ireland (H. Daly & Ó Gallachóir, 2011). The study documents the method and data needed to create a bottom-up private vehicle technology stock for Ireland. A Data in Brief corresponding to the Irish Car Stock Model is available (Mulholland et al., 2017b).

Figures for the energy consumption, vehicle kilometres and passenger numbers for public transport operators in Ireland were extracted manually from Annual Reports by Luas (National Transport Authority, 2021), Bus Éireann (Bus Éireann, 2021), Irish Rail (Irish Rail, 2021), and Dublin Bus (Dublin Bus, 2021). These figures were referred to in "Occupancy, Energy Consumption and Emissions" sheet.

Equations for primary data

In this section, equations for the calculation of the primary data listed in the IPTEM V2.9 model are defined. The equations are previously referenced in the Data Description section as the method used to calculate values in table entries.

The CSO distance categorization does not account for mode types that typically service distances on the shorter end of the distance grouping. Distance weighting factors based on mode are calculated by comparing average distance travelled by that mode with the "Private car – driver" mode as shown in Equation 14.

$$Distance\ Weighting_{mode,year} = \frac{Average\ distance\ of\ all\ journeys_{mode,year}}{Average\ distance\ for\ private\ car - driver_{year}} \quad (14)$$

The distribution of journeys by distance is recorded by the National Travel Survey over the period of 2009 – 2019.

Average values for reasons of journeys by mode type are based on aggregate values from Dublin and the rest of the country. As approximately 1 in 4 people in Ireland are Dublin based, a weighting of 0.25 is given to the Dublin statistics, and a weighting of 0.75 is given to the rest-of-country figures. Equation 15 for this is outlined below:

$$Average\ reason\ of\ journey\ by\ mode\ type = 0.25(\%\ Reason\ for\ journey\ by\ mode\ type_{Dublin}) + 0.75(\%\ Reason\ for\ journey\ by\ mode\ type_{Rest\ of\ Country}) \quad (15)$$

Total Passenger Kilometres for a given distance and mode category is calculated as a function of the share of journeys by distance and the share of journeys that are of that mode type, then applying the average distance by the kilometre grouping and applying weighting factors based on the mode type as calculated in Equation 16.

$$Total\ Pkm\ by\ distance\ and\ mode\ category = \%\ distribution\ of\ journey\ distance \times Percentage\ of\ journeys_{mode} \times average\ distance\ by\ distance\ grouping_{mode} \times weighting\ factor_{mode} \times number\ of\ journeys \quad (16)$$

Passenger kilometres for the intermittent years that were not surveyed (2010, 2011, 2015, 2017, 2018) are interpolated.

To calculate total passenger kilometres by distance and trip purpose, the method used in Distance weighting factors based on trip mode are applied to adjust the average distance calculated to reflect the average journey lengths given for a given trip mode. Weighting factors based on trip purpose are also applied and calculated by comparing the average distance of journeys by trip purpose.

Passenger kilometres by trip purpose was calculated as shown in Equation 17

$$\begin{aligned} &Passenger\ kilometres\ by\ trip\ purpose \\ &\quad = percentage\ distribution\ of\ journey\ distance \\ &\quad \times percentage\ distribution\ of\ joruneys\ by\ trip\ purpose\ and\ distance \\ &\quad \times average\ distance\ by\ kilomtre\ grouping\ for\ trip\ purpose \\ &\quad \times adjustment\ factor\ based\ on\ trip\ purpose\ \times total\ number\ of\ journeys \quad (17) \end{aligned}$$

Weighting factors based on trip purpose are also applied to adjust the average distance calculated to capture the varying average journey lengths for certain trip purposes. Only figures from 2009 are available as average distances based on trip purpose are given from the 2009 National Travel Survey.

Average distance based on trip purpose and mode type is based on the average distance based on trip purpose type (Table 49) and average distance based on mode type (Table 87). As the average distance based on trip purpose is only calculated from the 2009 National Travel Survey, these figures are used for all journeys up to 2019. The average distance is shown in Equation 18.

$$\begin{aligned} &Average\ distance\ based\ on\ trip\ purpose\ and\ mode\ type \\ &\quad = \frac{Average\ distance_{trip\ purpose} + Average\ distance_{mode\ type}}{2} \quad (18) \end{aligned}$$

The share of passenger kilometres for that year by distance, mode type and trip purpose, as listed in Table 97. The share is based on comparing the passenger kilometres from the listed mode type, trip purpose and distance entry to the entire passenger kilometres calculated for that year in Equation 19.

$$\%\ Pkm\ for\ that\ year\ by\ distance, mode\ and\ trip\ purpose = \frac{Passenger\ kilometres\ by\ distance, mode, trip\ purpose}{Total\ Passenger\ Kilometres} \quad (19)$$

The energy intensity of each mode type per passenger kilometre (Pkm) was calculated as follows in Equation 20.

$$Energy\ Intensity\left(\frac{kWh}{pkm}\right) = \frac{Energy\ intensity\ per\ kWh_{f,t} \times Energy\ consumption\ per\ year_{f,t}}{Pkm_t} \quad (20)$$

Where:

- f is the fuel type
- t represents the transit provider.

Energy consumption of a given journey type by mode, trip purpose or trip distance is calculated as a function of the mode type's energy intensity and the passenger kilometres serviced by the journey's passenger kilometres for the specified trip purpose, distance, and mode. Equation 21 shows the calculation for the energy consumption of a given journey purpose, distance, and mode.

$$Energy\ Consumption_{purpose,distance,mode} = Energy\ Intensity_{mode}\left(\frac{kWh}{Pkm}\right) \times Passenger\ Kilometres_{purpose,distance,mode}\ (Pkm) \quad (21)$$

The CO_2 emissions intensity of each mode type per passenger kilometre (Pkm) was then calculated as shown in Equation 22

$$CO2\ Emissions\ Intensity\ \left(\frac{gCO2}{pkm}\right) = \frac{C0\ \ emissions\ intensity\ per\ kW\ \ _{f,t} \times Energy\ consumption\ per\ year_{f,t}}{Pkm_t} \quad (22)$$

Where:

- *f* is the fuel type
- *t* represents the transit provider.

CO_2 emissions intensity per kWh were based on the Sustainable Energy Authority of Ireland conversion rates (Sustainable Energy Authority of Ireland, 2020).

Annual energy consumption values for private vehicles were derived from the Irish Car Stock Model (O'Riordan, Mulholland, et al., 2021), annual energy consumption values for bus, heavy rail and light rail were derived from national public transport annual reports (Bus Éireann, 2021; Dublin Bus, 2021; Irish Rail, 2021; National Transport Authority, 2021).

Total CO_2 emissions (Table 103)is calculated as a function of the passenger kilometres by the given mode type, trip purpose and trip distance and the CO_2 emissions intensity of the given mode type, trip purpose and passenger kilometre category (Table 76,Table 77,Table 78,Table 79, Table 84).

The equation for total CO_2 emissions is outlined in Equation 23.

$$Total\ CO2\ Emissions\ (gC02) = Emissions\ Intensity\ \left(\frac{gCO2}{pkm}\right) \times Passenger\ Kilometres(pkm) \quad (23)$$

Appendix C: Supplementary Information for Chapter 4

Appendix C.A: Assumption for ASI 1: Working from home 2 days per week

ASI 1: Working from home 2 days per week
The work-from-home rate is based on a study which measured the percentage of duties which could be completed remotely by the NACE category. NACE categories are defined as employment types (CSO, 2022c). They are divided based on the specification from the Central Statistics Office and each industry sector's Gross Domestic Product contributions. Information from the Central Statistics Office is then used to determine how many people are employed in each category. Combining the percentage of work duties that can be completed from home with the number of people employed by the NACE category makes it possible to determine what percentage of work overall could be completed from home, assuming Wi-Fi and remote work technology are provided to employees. The calculation is summarized in this equation: $$\boldsymbol{Remote\ working\ potential = \frac{Remote\ working\ factor_{NACE\ category} \times Number\ in\ workforce_{NACE\ category}}{Total\ workforce}}$$ **Following this, a 2-day work-from-home scenario is developed based on the assumption that there is a 2-way commuting route and a 5 out of 7 days of the working week pattern. This pattern can vary from worker to worker; however, based on a combination of labour laws which only permit a maximum of 40 hours of work per week and a consensus that, on average, people work five days per week, this is the value used in the calculation. The employment figures are based on Full-Time**

Equivalents (FTEs); therefore, part-time workers are combined in the figures. The 2-day work-from-home passenger kilometre reduction is calculated as per equations: $$\textit{Passenger Kilometre Reduction}\ (\%) = \frac{\textit{number of days of working from home}}{5\ \textit{days}} \times \textit{Remote working potential}$$			
Passenger kilometres (2019)	**65,666,270,295**		IPTEM V2
What share of working employees can be WFH	55	%	
Mode – share - car (work)	71.9	%	IPTEM V2
Mode– share - bus (work)	8.1	%	IPTEM V2
Mode– share - rail (work)	8.7	%	IPTEM V2
Mode– share - walk (work)	0.4	%	IPTEM V2
Mode– share - taxi (work)	0.7	%	IPTEM V2
Mode– share - lorry/motorcycle/other (work)	10	%	IPTEM V2
Mode– share - cycle (work)	0.3	%	IPTEM V2
Average journey distance (work)	15.4	km	
Number of days working from home	2		
% Share employees that can work from home (FTE equivalent)	22	%	

Taxi passenger kilometre reduction	Walk passenger kilometre reduction	Rail passenger kilometre reduction	Bus passenger kilometre reduction	Car passenger kilometre reduction	% Share of Pkm (passenger kilometres) that's work related	Work passenger kilometres	Total passenger kilometres	
28,948,821	17,282,878	377,198,812	348,249,991	3,101,844,527	30	19,465,135,173	65,687,960,410	**2019**
					30	n/a	44,857,325,231	**2020**
					30	n/a	50,386,031,244	**2021**
30,794,895	18,385,012	401,252,881	370,457,986	3,299,649,981	30	20,706,432,047	69,876,899,205	**2022**
31,209,805	18,632,719	406,659,102	375,449,297	3,344,107,327	30	20,985,417,096	70,818,375,269	**2023**
31,624,716	18,880,427	412,065,324	380,440,608	3,388,564,673	30	21,264,402,144	71,759,851,333	**2024**
32,039,626	19,128,135	417,471,545	385,431,919	3,433,022,019	30	21,543,387,193	72,701,327,396	**2025**
32,461,935	19,380,260	422,974,172	390,512,237	3,478,272,143	30	21,827,347,196	73,659,592,174	**2026**
32,884,245	19,632,385	428,476,799	395,592,554	3,523,522,267	30	22,111,307,199	74,617,856,951	**2027**
33,306,554	19,884,510	433,979,426	400,672,872	3,568,772,391	30	22,395,267,202	75,576,121,728	**2028**
33,728,863	20,136,635	439,482,053	405,753,189	3,614,022,515	30	22,679,227,204	76,534,386,506	**2029**
34,151,172	20,388,760	444,984,679	410,833,507	3,659,272,639	30	22,963,187,207	77,492,651,283	**2030**

Lorry/motorcycle/other passenger kilometre reduction	Cycling passenger kilometre reduction
13,394,230	434,232,309
14,248,384	461,923,420
14,440,358	468,147,077
14,632,331	474,370,734
14,824,305	480,594,390
15,019,701	486,929,030
15,215,098	493,263,669
15,410,495	499,598,308
15,605,892	505,932,947
15,801,289	512,267,586

Appendix C.B: Assumption for ASI 2: 20% Reduction in total vehicle kilometres by 2030

ASI 2: 20% Reduction in total vehicle kilometres by 2030											
Method	It is assumed there is no change in the occupancy of cars, and that a decrease in vehicle kilometres applies to both freight and passenger transport. In the case of passenger transport, the reduction of vehicle kilometres would correspond with an equal reduction in passenger kilometres. Linear interpolation to increase reduction in passenger and vehicle kilometres to 20 by 2030										
Car Passenger kilometres reduction	20%										
Light Duty vehicle kilometres reduction	20%										
Heavy Duty Vehicle kilometre reduction	20%										
Year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Reduction in passenger kilometres	0.00	0.00	0.00	2.50	5.00	7.50	10.00	12.50	15.00	17.50	20.00

Appendix C.C: Assumption for ASI 3: 20% reduction in car kilometres by 2030

ASI 3: 20% reduction in car kilometres by 2030	
Method	It is assumed there is a linear reduction in car vehicle kilometres and there no change in occupancy for cars, there is a corresponding 20% reduction in passenger kilometres. The reduction in car passenger kilometres increases linearly to 20% by 2030.
20% in total vehicle kilometres	Car Pkm * share of reduction to Pkm (%)

Year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Reduction in passenger kilometres	0.00	0.00	0.00	2.50	5.00	7.50	10.00	12.50	15.00	17.50	20.00

Appendix C.D: Assumption for ASI 4: 20% reduction in total car commuting kilometres by 2030

ASI 4: 20% reduction in total car commuting kilometres by 2030			
Method	It is assumed there is a linear reduction in car commuting kilometres and there no change in occupancy for cars, there is a corresponding 20% reduction in commuting passenger kilometres. The reduction in car commuting passenger kilometres increases linearly to 20% by 2030. It is based on a reduction of the share of passenger kilometres for work purposes based on the IPTEM model.		
Share of travel that is commuting (from IPTEM)	0.3		
Reduction of 20%	0.2		
20% Reduction of car passenger passenger kilometres	Car Pkm		
		*	0.94

Year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Reduction in passenger kilometres	0	0	0	0.00750	0.01500	0.02250	0.03000	0.03750	0.04500	0.05250	0.06000

Appendix C.E: Assumption for ASI 5: Remote working hubs

ASI 5: Remote working hubs	
Method	55% of people could work from Remote Working Hubs (based on remote working potential and employment numbers by job type) and 40% of Pkm is for commuting (O'Riordan et al., 2022b) a survey from November 2021 found that 18% of people working from home would use a Remote Working Hub. It is assumed there is a linear decrease of passenger kilometres from car use based on share of travel that is commuting factored by the share of people who can work from home, the total share of people that would work from remote working hubs,

	employment rates and the average commuting distance saved of 60 kilometres per round trip journey (Caulfield and Charly, 2022).										
Share of travel that is commuting (from IPTEM)	0.3										
WFH share	0.55										
Share of WFH people who would like to work from remote working hub	0.18										
Total share of population employment that would use remote working hubs	0.0297										
Employment	76329										
Average commuting distance saved (km)	60										
Pkm saved (2030)	4,579,740										
Share Pkm saved (%)	0.0065										
	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Reduction in Pkm	0	0	0	572468	1144935	1717403	2289870	2862338	3434805	4007273	4579740

Appendix C.F: Assumption for ASI 6: Additional Park and Ride Provisions for Cork and Dublin

ASI 6: Additional Park and Ride Provisions for Cork and Dublin		
Method	It is assumed that the increase in 1,200 spaces in Dublin, (National Transport Authority, 2022), and 500 in Cork (Creegan et al., 2020). It is assumed that this would lead to a modal shift for the final part of the journey of 3 kilometres from car transport to bus transport. It is assumed that each car parking space has an occupancy of 1.3 people per space.	
	Current number	2030
Dublin	2650	1200
Cork	950	500
Occupancy rate per year (number of cars in each day)	474.5	
Kilometres avoided by car	2419950	
Kilometres added by bus	474.5	
Passenger kilometres (Pkm) 2030	62,826,665,237	
Pkm change by 2030 (car)	0.0038%	
Pkm change by 2030 (bus)	0.57%	

ASI 7: 125,000 sustainable journeys per day										
Method	The number of journeys by bus, rail, cycling, and walking increases in proportion to their 2019 shares until their numbers have increased by 125,000 per day in 2030 compared to 2019 rates. The average distance for these journeys is assumed to be the same as 2019 values.									
Pkm change	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Private car - Driver	-102993478	-205986957	-308980435	-411973913	-514967391	-772451087	-1029934783	-1287418478	-1544902174	-2574836957
Private car - Passenger	-21050512	-42101023	-63151535	-84202046	-105252558	-157878836	-210505115	-263131394	-315757673	-526262788
Walk	15470058	30940116	46410174	61880233	77350291	114478430	151606570	188734709	225862849	371281395
Bus	33206512	66413023	99619535	132826047	166032558	245728186	325423814	405119442	484815070	796956279
Cycle	3628779	7257558	10886337	14515116	18143895	26852965	35562035	44271105	52980174	87090698
Rail/ Dart/Luas	23304826	46609651	69914477	93219302	116524128	172455709	228387291	284318872	340250453	559315814
Taxi/ hackney	-980179	-1960358	-2940537	-3920716	-4900895	-7498370	-10095844	-12693318	-15290793	-25974744

Lorry/Motor cycle/Other	-5115601	-10231202	-15346803	-20462404	-25578005	-39134348	-52690691	-66247033	-79803376	-135563427
Total Private Car	-124043990	-248087980	-372131969	-496175959	-620219949	-930329923	-1240439898	-1550549872	-1860659847	-3101099744

Average journey distance by mode (kilometres), National Travel Survey 2009 - 2019	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Private car - driver	13.6	13.6	13.6	13.6	13.6	13.6	13.6	13.6	13.6	13.6	13.6
Private car - passenger	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
Walk	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
Bus	16.3	16.3	16.3	16.3	16.3	16.3	16.3	16.3	16.3	16.3	16.3
Cycle	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7
Rail/DART/Luas	32.3	32.3	32.3	32.3	32.3	32.3	32.3	32.3	32.3	32.3	32.3
Taxi/hackney	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5
Lorry/motorcycle/other	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7

Lorry/Motor cycle/Other	Taxi/ha ckney	Rail/Dart/ Luas	Cycle	Bus	Walk	Private car - Passenger	Private car - Driver	**Total number of journeys per year by mode type**
130,403,389	32,600,847	61,579,378	54,334,745	173,871,185	489,012,707	318,763,839	2,350,883,312	**2020**
130,029,987	32,507,497	62,300,890	54,971,373	175,908,394	494,742,359	317,736,985	2,343,310,262	**2021**
129,656,586	32,414,146	63,022,401	55,608,001	177,945,603	500,472,010	316,710,130	2,335,737,212	**2022**
129,283,184	32,320,796	63,743,913	56,244,629	179,982,813	506,201,661	315,683,276	2,328,164,162	**2023**
128,909,782	32,227,446	64,465,424	56,881,257	182,020,022	511,931,312	314,656,422	2,320,591,112	**2024**
128,536,380	32,134,095	65,186,936	57,517,884	184,057,231	517,660,963	313,629,568	2,313,018,062	**2025**
127,546,867	31,886,717	66,918,564	59,045,792	188,946,534	531,412,126	311,062,432	2,294,085,438	**2026**
126,557,353	31,639,338	68,650,192	60,573,699	193,835,836	545,163,289	308,495,297	2,275,152,813	**2027**
125,567,839	31,391,960	70,381,820	62,101,606	198,725,138	558,914,452	305,928,161	2,256,220,188	**2028**
124,578,325	31,144,581	72,113,448	63,629,513	203,614,441	572,665,614	303,361,026	2,237,287,564	**2029**
120,508,248	30,127,062	78,895,657	69,613,815	222,764,208	626,524,335	293,092,483	2,161,557,065	**2030**

Passenger kilometre change	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Priv–te car - Driver	-0.20	-0.29	-0.44	-0.57	-0.71	-1.05	-1.38	-1.70	-2.02	-3.32
Priv–te car - Passenger	-0.04	-0.06	-0.09	-0.12	-0.14	-0.21	-0.28	-0.35	-0.41	-0.68
Walk	0.03	0.04	0.07	0.09	0.11	0.16	0.20	0.25	0.30	0.48
Bus	0.07	0.10	0.14	0.19	0.23	0.33	0.44	0.54	0.63	1.03
Cycle	0.01	0.01	0.02	0.02	0.02	0.04	0.05	0.06	0.07	0.11
Rail/Dart/Luas	0.05	0.07	0.10	0.13	0.16	0.23	0.31	0.38	0.44	0.72
Taxi/hackney	0.00	0.00	0.00	-0.01	-0.01	-0.01	-0.01	-0.02	-0.02	-0.03
Lorry/Motorcycle/Other	-0.01	-0.01	-0.02	-0.03	-0.04	-0.05	-0.07	-0.09	-0.10	-0.17
Total private car	0	0	-1	-1	-1	-1	-2	-2	-2	-4

Appendix C.H: Assumption for ASI 8: Additional 300 buses

ASI 8: Additional 300 buses				
Method	The share increase in the number of buses compared to the current number of buses is calculated (+25%, with an additional 300 buses). It is assumed that the same increase of bus passenger kilometres would follow, and this modal shift occurs from car to bus.			
Mode	**2020**	**2025**	**Reference 2020**	**2025**
Car	85.35	84.29	0	-0.01252
Rail	0.38	0.37	0	
Bus	4.22	5.28	0	0.25
Walk	0.68	0.67	0	
Cycle	0.38	0.37	0	
Lorry/Motorcycle/ Other	3.17	3.13	0	
	94.18	94.12	0	
+300 bus factor	25			
Number of buses	1,200			

Appendix C.I: Assumption for ASI 9: E-bikes

ASI 9: E-bikes				
Method	It is assumed that 5% of people in Ireland would start using e-bikes. The average e-bike distance per day would be 11.2 kilometres and the increase in biking passenger kilometres would be increased to 4.41% of all passenger kilometres.			
Units	% Mode share	% Mode share	Multiplicative factor change to mode share	Multiplicative factor change to mode share
Year	2020	2030	Reference 2020	E-bike factor
Car	68.27	67.32	0	-1.38292
Rail	17.08	16.84	0	-1.38292
Bus	0.68	0.66	0	-1.38292
Walk	4.22	4.16	0	-1.38292
Cycle	.38	16.7	0	340.58500
Lorry/Motorcycle/ Other	3.17	3.12	0	-1.38290
Share of population e-biking	5%			
Republic of Ireland population	5,000,000 people			
Total e-biking population	225000 people			
Average e-biking distance per day	11.2 km			
Pkm per year in population	919,800,000 km			
Biking Pkm (2020)	170,148,850 km			
Increase in biking (%) as total mode share across all modes	4.41 %			

Appendix C.J: Assumption for ASI 10: Increased cycling infrastructure

ASI 10: Increased cycling infrastructure						
Method	The current length of cycling infrastructure in Ireland is approx. 500 kilometres in distance. The Transport Infrastructure Ireland proposals plan for an increase in cycling infrastructure by 3,000 kilometres to a total length of network of 3,500 kilometres (Transport Infrastructure Ireland, 2022b). It is assumed this is introduced by 2030. It is assumed this would result in a seven-fold increase in cycling infrastructure. The decrease from other modes of transport is proportional to their 2019 shares in the modal mix.					
Mode Type	**2020 (Pkm)**	**2030 (Pkm)**	**2020 Mode share (decimal)**	**2030 mode share (decimal)**	**2020 adjustment to road share (decimal)**	**2030 (adjustment to road share (decimal)**

Private car - Driver	46,499,035,268	49,903,460,340	0.657	0.649	0	-0.011
Private car - Passenger	11,635,387,163	12,248,334,735	0.164	0.159	0	-0.023
Walk	327,106,539	338,035,868	0.0046	0.0044	0	-0.0477
Bus	3,927,249,067	4,089,189,673	0.055	0.053	0	-0.0405
Cycle	251,284,869	1,758,994,084	0.0035	0.0229	0	5.4504
Rail/Dart/Luas	4,256,360,544	4,434,493,767	0.0601	0.0577	0	-0.03994
Taxi/hackney	325,631,029.86	336,509,860.80	0.004598115	0.004378711	0	-0.04772
Lorry/Motorcycle/Other	3,596,320,790	3,742,335,0378	0.050782311	0.04869576	0	-0.04109

Total Private Car	58,134,422,431	62,151,795,075	0.820894608	0.808727398	0	-0.01482

Appendix C.K: Assumption for ASI 11: Bus Connects – 5 cities in Ireland: Cork, Galway, Waterford, Limerick, Dublin.

ASI 11: Bus Connects – 5 cities in Ireland: Cork, Galway, Waterford, Limerick, Dublin.					
Method	This scenario divides passenger kilometres out to the cities based on their respective populations, then the scenario assumes a moderately successful bus connects system where 25% of car transport is switched to bus transport passenger kilometres. The year of implementation is 2030. The increase in passenger kilometres is proportional to the population of the city the bus connects systems is implemented (Central Statistics Office, 2017b)				
	Commuting share %				
Commuting share	Cork City and suburbs	Dublin City and suburbs	Galway City and suburbs	Limerick City and suburbs	Waterford City and suburbs
Bicycle	3	8	6	3	2
Bus, minibus, or coach	9	16	10	8	4
Motor car: Driver	43	33	40	42	44
Motor car: Passenger	21	12	18	20	27
Motorcycle or scooter	0	1	0	0	0
On foot	20	21	23	23	20
Other, incl. lorry	0	0	0	0	0
Train, DART, or LUAS	0	7	0	0	0
Van	3	2	2	2	3
Population of Cork City	190384				
Population of Galway City	75549				
Population of Limerick City	90054				
Population of Waterford City	53504				
Dublin Pkm share	Population factor	Distance factor	Travel positive factor		
	0.28	0.76	1.05		
Cork Pkm share	Population factor	Distance factor	Travel positive factor		
	0.0387	1	1		

Galway Pkm share	Population factor	Distance factor	Travel positive factor		
	0.015350808	1	1		
Limerick Pkm	Population factor	Distance factor	Travel positive factor		
	0.01829808	1	1		
Waterford Pkm	Population factor	Distance factor	Travel positive factor		
	0.010871482	1	1		

25% car to bus switch with BRT – Cork			**0.00**	**0.62**		
25% car to bus switch with BRT – Galway			0.00	0.22		
25% car to bus switch with BRT - Limerick			0.00	0.29		
25% car to bus switch with BRT - Waterford			0.00	0.19		
25% car to bus switch with BRT - Cork, Galway, Limerick, Waterford			0.00	1.32		
70% car to bus switch with Dublin BRT			0.00	7.64		
Total increase in share of bus switch from car				8.96		
Mode	**Pkm without BRT 2030**	**Pkm with BRT 2030**	**Share 2020**	**Share BRT 2030**	**2020**	**2030**
Car	63,613,299,626	60,965,788,901	0.85	0.79	0	-0.07

Bus	4,297,372,558	6,944,883,282	0.042	0.09	0	1.12

Appendix C.L: Assumption for ASI 12: Metrolink in Dublin

ASI 12: Metrolink in Dublin		
Method	It is assumed that the Metrolink in Dublin would cause an increase of rail passenger kilometres of 400 million passenger kilometres, as the average length of the rail is planned to increase by 19 kilometres, the average journey to be 8 kilometres and the number of passengers per year at 50 million (Transport Infrastructure Ireland, 2022c). It is assumed year of completion 2030. The modal shift from car to metro accounts for 50%, bus 45%, and bike 5%.	
Average journey	8	km
Length of rail	20	km
Source	50	Million passengers
Total Pkm	400	Million Pkm

Mode Type	2020 Pkm	2030 without Metrolink Pkm	2030 with Metrolink Pkm	2020 (adjustment to mode share %)	2030 (adjustment to mode share %)
Private car - Driver	30,622,603,400	50,881,335,689	50,681,335,689	-	-0.00393
Private car - Passenger	7,662,650,300	12,731,963,937	12731963937	0	0
Walk	303,409,409	357,934,686	357934686	0	0
Bus	1,894,225,188	4,297,372,558	4,117,372,558	-	-0.04189
Cycle	170,148,850	274,967,205.38	254,967,205	-	-0.07274
Rail/Dart/Luas	1,421,283,545	4,657,501,137	5,057,501,137	-	0.085883
Taxi/hackney	214,448,963	356,320,118	356320118	0	0
Lorry/Motorcycle/Other	2,568,555,578	3,935,255,953	3935255953	0	0
Total Private Car	38,285,253,699	63,413,299,626	63,413,299,626		0

Total	44,857,325,231	77,492,651,283	77,492,651,283		0
Modal shift shares					
Car to metro modal shift	0.5				
Bus to metro modal shift	0.45				
Bike to metro modal shift	0.05				

Appendix C.M: Assumption for ASI 13: DART+ West (commuter rail) expansion

ASI 13: DART+ West (commuter rail) expansion				
Method	The DART+ West project would correspond with an increase of rail infrastructure from approximately 2,000 kilometres of rail to 2,100 kilometres of rail, and the increase of passenger transport rail transport is assumed to be in proportion to the increase in rail length (DART, 2022). The decrease in other modes of transport is in proportion to their 2019 mode shares. It is assumed the project would be completed in 2030.			
Mode Type	**Share 2020**	**Share 2030**	**2020**	**2030**
Private car - Driver	68.27	68.15	0	-0.112
Private car - Passenger	17.08	17.05	0	-0.028
Walk	.68	.68	0	-0.001
Bus	4.22	4.22	0	-0.007
Cycle	.38	.38	0	-0.001
Rail/Dart/Luas	3.17	3.33	0	0.158
Taxi/hackney	.48	.48	0	-0.001
Lorry/Motorcycle/Other	5.73	5.72	0	-0.009
Private car	85.35	85.21	0	-0.140

Appendix C.N: Assumption for ASI 14: Sustainable school transport schemes

ASI 14: Sustainable school transport schemes		
Method	Passenger kilometres for school transport are calculated based on travel distances for school as recorded by the Central Statistics Office (CSO, 2017a) and the number of children going to school. The passenger kilometres for school transport by mode were determined based on average distance journeys by mode from the Irish Passenger Transport Emissions and Mobility (IPTEM) model.	
Number of primary school children	(CSO, 2017a)	571964
Number of secondary school children	(CSO, 2017a)	392276

Average distance to school - primary	(CSO, 2017a)	1.5 km	
Average distance to school	(CSO, 2017a)	3.8 km	
School Pkm primary	314,008,236		Pkm
School Pkm secondary	545,577,461		Pkm
School days per year	183		
Companion journeys - with parent or guardian	0.8		
School pkm with companion - primary	565,214,825		Pkm
School pkm with companion - secondary	982,039,429		Pkm
Population of Ireland	4,900,000		
per–capita - primary	115.35		Pkm/yr
per capita -secondary	200.42		Pkm/yr
School bus rate (2016) primary	10		%
Walk/cycle rate (2016) primary	25		%
School bus rate (2030) primary	20		% (1996 rate)
Walk/cycle rate (2030) primary	50		%
School bus rate (2016) secondary	28		%
Walk/cycle rate (2016) secondary	22		%
School bus rate (2030) secondary	40		% (1996 rate)
Walk/cycle rate (2030) secondary	45		% (1986 rate)
Reference walk/cycle primary Pkm	141,303,706	Pkm	
Reference walk/cycle secondary Pkm	216,048,674	Pkm	
Reference bus primary Pkm	56,521,482	Pkm	
Reference bus secondary Pkm	274,971,040	Pkm	
Scenario walk/cycle primary Pkm	282,607,412	Pkm	
Scenario walk/cycle secondary Pkm	441,917,743	Pkm	
Scenario bus primary Pkm	113,042,965	Pkm	
Scenario bus secondary Pkm	392,815,772	Pkm	
School walk/cycle addition Pkm	367,172,775	Pkm	

School bus addition Pkm	174,366,214	Pkm
Change in walking and cycling	**2016** (% share additions)	**2030** (% share additions)
Walk/cycling Pkm addition	0	0.5590
Bus Pkm addition	0	0.2654
Walking Pkm addition (50%)	0	0.28
Cycling Pkm addition (50%)	0	0.28
Car reduction	0	(0.8244)

Appendix C.O: Assumption for ASI 15: Bike share schemes

ASI 15: Bike share schemes		
Method	The number of bike shares currently in operation is determined from the Bike Share Ireland scheme website (Bikeshare.ie, 2023). The number of bikes is increase and the respective passenger kilometres arising from these additional bikes is added on to the current share of bicycle passenger kilometres. The modal shift from other modes of transport to cycling is in proportion to the current modal shares of each of the modes.	
	Number of bikes	**Number of stations**
Waterford	220	14
Limerick	195	23
Cork	215	23
Galway	390	36
Dublin		
	2019	**2030**
Number of bikes	1020	20000
Frequency of use (times per year)	104	104
Typical length of journey	2	2
Passenger kilometres added per year	212160	4160000
Additional Pkm	**2020**	**2030**
Modal shift		278915045
Bike share (overall) - Reference	.35%	.3548%
Bike Pkm (2020) - Reference	233080616	274967205

Mode Type	**2020 Pkm**	**2030 without additional bike share**	**2030 Pkm with additional bike share**	**2020 % change**	**2030 % change**
Private car - Driver	30622603400	50881335689		0	-.00006539

Private car - Passenger	7662650299	12731963937		0	-.00006539
Walk	303409408	357934686	357726686	0	-0.00058
Bus	1894225188	4297372558	4297372558	0	0
Cycle	170148849	274967205	274967205	0	
Rail/Dart/Luas	1421283545	4657501137	4657501137	0	0
Taxi/hackney	214448963	356320118	356320118	0	0
Lorry/Motorcycle/Other	2568555578	3935255953	3935255953	0	0
Total Private Car	38285253699	63613299626	4160000	0	-.00006539
Total	44857325231	77492651283			

Appendix C.P: Assumption for ASI 16: Rural bus transport scheme – Carlow, Mullingar, Portlaoise, and Leitrim

ASI 16: Rural bus transport scheme – Carlow, Mullingar, Portlaoise, and Leitrim				
Method:	The modal shift towards the bus from car transport is determined based on the population of these towns, the average passenger kilometres per person and a 10% modal shift from car passenger transport to bus transport.			
Population				
Carlow Town	24272			
Mullingar	20928			
Portlaoise	22050			
Leitrim	32000			
Total population represented	99250			
Total population	5,000,000			
Pkm midlands town	1,303,906,014			
Pkm car (midlands) 2019	992,272,477			
Pkm bus (midlands) 2019	28,685,932			
Pkm reduction car	893,045,229			
Pkm increase bus	99,227,248			
	Pkm by mode		Mode Share change	
Mode Type	2019	2030	2020	2030
Walk	303409409	303409409	0	0.00
Bus	3642740747	3,741,967,995	0	2.72
Cycle	233080616	233080616	0	0.00
Rail/Dart/Luas	3948009846	3948009846	0	0.00
Taxi/hackney	302040792	302040792	0	0.00
Lorry/Motorcycle/Other	3335786464	3335786464	0	0.00

Total Private Car	53922892534	53,029,847,305	0	-1.66
Total	65687960410	65687960410	0	0.00

Appendix C.Q: Assumption for ASI 17: Luas (light rail) extension in Cork, Galway, Limerick

ASI 17: Luas (light rail) extension in Cork, Galway, Limerick				
Method	Assumes a modal shift to light rail transport in proportion to the populations of the cities where the light rail is being implemented and the current share of light rail transport in Dublin, where the Luas is currently in operation. The travel positive factor accounts for the higher frequency of use which people choose to travel in Dublin and the distance factor accounts for the changes in journey lengths depending on the region.			
Mode Type	**2019**	**2030 with additional light rail**	**2020 % change**	**2030 % change**
Walk	303,409,409	303,409,409	0	0.00
Bus	3,642,740,747	3,616,129,021	0	-0.73
Cycle	233,080,616	226,427,685	0	-2.85
Rail/Dart/Luas	3,948,009,846	4,014,539,162	0	1.69
Taxi/hackney	302,040,793	302,040,793	0	0.00
Lorry/Motorcycle/Other	3,335,786,464	3,335,786,464	0	0.00
Total Private Car	53,922,892,534	53,889,627,877	0	-0.06

Census 2016: Profile 6 - Commuting in Ireland– E6013 - Population Usually Resident and Present in the State 2016					
	Cork City and suburbs	**Dublin City and suburbs**	**Galway City and suburbs**	**Limerick City and suburbs**	**Waterford City and suburbs**
Bicycle	3275	54061	2879	1561	529
Bus, minibus, or coach	11837	111819	4941	4091	1353
Motor car: Driver	54200	236574	19128	22367	13238
Motor car: Passenger	25902	86814	8638	10753	7976
Motorcycle or scooter	444	4125	127	124	90
On foot	25506	151447	11032	12375	5944
Other, incl. lorry	271	866	76	72	42
Train, DART, or LUAS	475	51231	99	95	76
Van	3489	15310	1056	1237	829
	Cork City and suburbs	**Dublin City and suburbs**	**Galway City and suburbs**	**Limerick City and suburbs**	**Waterford City and suburbs**
Bicycle	3	8	6	3	2
Bus, minibus, or coach	9	16	10	8	4
Motor car: Driver	43	33	40	42	44

Motor car: Passenger	21	12	18	20	27
Motorcycle or scooter	0	1	0	0	0
On foot	20	21	23	23	20
Other, incl. lorry	0	0	0	0	0
Train, DART, or LUAS	0	7	0	0	0
Van	3	2	2	2	3
Total	100	100	100	100	100
Population of Cork City	190384				
Population of Galway City	75549				
Population of Limerick City	90054				
Population of Waterford City	53504				
Dublin Pkm	Population factor	Distance factor	Travel positive factor		
23	0.283572082	0.76374389	1.053719008		
Cork Pkm	Population factor				
3.9	0.0387				
Galway Pkm	Population factor				
1.5	0.015350808				
Limerick Pkm	Population factor				
1.8	0.01829808				
Waterford Pkm	Population factor				
1.1	0.010871482				
Dublin Pkm	23				
Dublin Luas Pkm	209,900,000				
PKM for light rail	0.3195				
	2020	2030			
Cork Pkm	0	35,580,280			
Galway Pkm	0	14,119,120			
Limerick Pkm	0	16,829,915			
Cork & Galway Limerick light rail Pkm	0	66,529,315			

Appendix C.R: Assumption for ASI 18: 840,000 EVs by 2030

ASI 18: 840,000 EVs by 2030													
Share of total private car mileage (%)	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Petrol <1300	13	14	15	15	16	16	16	16	16	15	14	14	13
Petrol 1300 - 1900	19	14	12	11	10	9	9	8	8	8	7	7	6
Petrol >1900	2	1	1	1	1	1	1	1	1	1	1	1	1

Diesel <1300	2	2	1	1	1	1	1	1	1	1	0	0	0
Diesel 1300 - 1900	40	44	45	45	44	43	41	38	35	31	28	24	20
Diesel >1900	23	23	23	23	22	21	20	19	18	16	14	12	10
Hybrid <1300	0	0	0	1	1	2	2	3	3	3	3	3	3
Hybrid 1300 - 1900	0	0	0	0	0	0	0	0	0	0	0	0	0
Hybrid >1900	0	1	1	1	1	1	1	1	1	1	1	1	1
Plug in Hybrid <1300	0	0	0	0	0	0	0	0	0	0	0	0	0
Plug in Hybrid 1300 - 1900	0	0	0	0	0	0	0	1	1	1	2	2	3
Plug in Hybrid >1900	0	0	0	1	1	1	2	3	3	5	7	9	12
Electric	0	0	1	1	2	3	6	9	13	17	22	26	30
Electric	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
	0	0	1	1	2	3	6	9	13	17	22	26	30

Appendix C.S: Assumption for ASI 19: 20,000 commercial Electric Vehicles by 2030

ASI 19: 20,000 commercial Electric Vehicles by 2030											
Methodology	The number of commercial electric vehicles is increased from the current number of 700 in 2022 to 20,000 by 2030. The increase in commercial electric vehicles is linear. The number of commercial vehicles in Ireland is approx. 25,600 and it is assumed that the share of commercial EVs by 2030 is 78 of the entire commercial vehicle fleet. The increase in vehicle kilometres for electric commercial vehicles is proportional to the increase in the number of electric commercial vehicles.										
Number of commercial vehicles	25,589										
Number of electric commercial vehicles (2022)	691										
Share of commercial EVs by 2030	78%										
	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Share of activity	3	3	3	12	22	31	40	50	59	69	78

Million km Electric	130.66	132.61	140.38	662.42	1,242.57	1,870.68	2,551.94	3,306.15	4,100.92	4,926.06	5,772.86
Million km Diesel	4,708.44	4,778.93	5,058.96	4,797.55	4,519.51	4,164.36	3,760.17	3,324.50	2,815.33	2,241.60	1,613.23

Appendix C.T: Assumption for ASI 20: Electrification of Rail

ASI 20: Electrification of Rail													
Method	The share of electric rail is linearly interpolated to increase to 100 by 2030.												
Year	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
% Share of rail that is electrified	12	12	12	12	12	23	34	45	56	67	78	89	100

Appendix C.U: ASI 21: Electrification of 1,500 EV buses

ASI 21: Electrification of 1,500 EV buses											
Method	The projected number of electric buses is increased linearly to 1,500 EV buses in 2030. This accounts for 87% of all buses.										
Year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Projection of the number of electric buses				166.6667	333.3333	500	666.6667	833.3333	1000	1166.667	1500
Number of buses	1715	1715	1715	1715	1715	1715	1715	1715	1715	1715	1715
Share of buses that are electric (%)	0.00	0.00	0.00	9.72	19.44	29.15	38.87	48.59	58.31	68.03	87.46
Bus Eireann	588				(National Transport Authority, 2019)						
Dublin Bus	1127				(National Transport Authority, 2019)						

Appendix C.V: ASI 22: Biofuel mixing: 10%, E10; 22% B12 (2025), 10% E10; 20% B20 (2030)

ASI 22: Biofuel mixing: E10 B12 (2025), E10 B20 (2030)	
Method	This scenario projects a linear increase in the share of ethanol in gasoline mixes to 10% of all ethanol used by 2030, and a projected increase in biodiesel mixing in diesel for 12% in 2025 to 20% by 2030

		2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Ethanol - MJ	**ASI 22**	**1.20**	**1.44**	**1.09**	**1.32**	**1.82**	**1.92**	**2.02**	**2.12**	**2.06**	**2.01**	**1.96**	**1.92**	**1.88**
	Reference	**1.20**	**0.96**	**0.70**	**0.85**	**1.19**	**1.23**	**1.26**	**1.26**	**1.18**	**1.09**	**1.00**	**0.91**	**0.81**
Biodiesel - MJ	**ASI 22**	**6.54**	**7.35**	**6.19**	**8.37**	**11.34**	**12.76**	**14.53**	**16.41**	**18.96**	**21.60**	**24.34**	**27.17**	**30.12**
	Reference	**5.79**	**7.64**	**5.47**	**6.42**	**7.70**	**7.76**	**8.01**	**8.27**	**8.43**	**8.59**	**8.75**	**8.93**	**9.10**

Appendix C.W: ASI 23: Reducing speed limits for fuel efficiency

ASI 23: Reducing speed limits for fuel efficiency		
Method	This scenario linearly reduces the fuel consumption of passenger and rail transport by 7% in 2030 on the basis of improved fuel efficiency and lower emissions from introducing lower speed limits on national and regional roads (Transport Infrastructure Ireland, 2022d)	
Year	2020	2030
Reduction in fuel consumption for diesel and ethanol (%)	0	7

Appendix D: Supplementary Information for Chapter 5

Appendix D.A: Assessment Grid for the LEAP Ireland model

		Complexity				Uncertainty					Interdisciplinary			Utilization				Scientific standards				
		Sector coupling	resolution	input data	result processing	epistemic	aleatory	linguistic	decision	planning	human dimension	energy-water-food	common understanding	usability	applicability	re-usability	result communication	transparency	repeatability	reproducibility	scrutiny	scientific progress
Open-source philosophy	open source											Partially available										
	documentation	Available												Available	Available	Available	Available	Available	Available	Available	Available	Available
	version control	Partially available										Partially available						Available	Partially available	Available		Partially available
	openness of data			Partially available								Partially available		Partially available	Partially available			Partially available	Partially available	Partially available		Partially available
	code review																					
Collaborative development	consistency of terminology							Available				Available		Available			Available	Available	Available	Available	Available	Available
	developer perspective spectrum																					
	interdisciplinary										Available	Available	Available	Available	Available	Available	Available	Available	Available	Available	Available	Available
	testing procedures																					
Structural properties	modular	Available	Partially available	Available	Available						Partially available	Available		Available	Available	Available	Available	Available	Available	Available	Available	Available
	object-oriented	Available		Available										Partially available			Partially available					
	generic concept	Available		Available	Partially available																	
	data model				Partially available																	

Key	
(white)	Not available/ not appliable
(yellow)	Partially available
(green)	Available

Appendix D.B: Summary of spreadsheet inputs and details for the LEAP Ireland model

Spreadsheet name	Details
LEAP_IE_TRA_FRT_LGV	Contains sectoral level information on light good vehicle (LGV) freight (FRT) transport (TRA) for the LEAP Ireland model
Commercial Building Archetypes	Contains the survey data based on the survey commissioned by the Sustainable Energy Authority of Ireland and conducted by Element Energy and the commercial building sectoral divisions for the commercial sector
LEAP_IE_TRA_FRT_HGV	Contains input data on heavy good vehicle (HGV) freight (FRT) transport (TRA) for the LEAP Ireland model
IPTEM_V2.9	The spreadsheet model which contains Version 2.9 of the Irish Passenger Transport Emissions and Mobility (IPTEM) model. The model is soft linked to the LEAP_IE_TRA spreadsheet as it calculates passenger kilometre demand by mode as an input for the LEAP Ireland model.
Irish Car Stock Model Version 2.5	The spreadsheet model for the Irish Car Stock Model Version 2.5, which is described in Chapter 2.
LEAP_IE_NON_ENERGY_AGRI	Contains non-energy agriculture information, which refers to the sources of methane and other greenhouse gases that are emitted from the agricultural sector.
LEAP_IE_TRA_AVIATION	Contains aviation data for the transport (TRA) sector in LEAP Ireland
LEAP_IE_RES	Contains residential (RES) sector data
LEAP_IE_IND	Contains industry (IND) sector data
LEAP_IE_TRA	Contains transport (TRA) sector data
LEAP_IE_TRA_FRT_LGV_ELEC	Contains data for scenarios on the electrification (ELEC) of light good vehicle (LGV) freight (FRT) transport (TRA).
LEAP_IE_MACRO	Contains macroeconomic (MACRO) data on gross domestic product (GDP), fuel prices and population data for the LEAP Ireland model.
LEAP_IE_NONENERGY_OTHER	Contains non-energy sources of greenhouse gas emissions that do not include agriculture (these are included in LEAP_IE_NON_ENERGY_AGRI). Non energy, non-agricultural greenhouse gas emissions such as F gases
LEAP_IE_SRV	Contains services (SRV) energy consumption and emissions data for the LEAP Ireland model

Appendix D.C: Other models and data sources for inputs into the LEAP Ireland model

Data Source	**Description**
UN Population projections	The medium range of population projections for Ireland up to 2030 are used as inputs in the LEAP Ireland model (United Nations, 2019)
I3E Model (Bruin et al., 2020)	The I3E (Ireland Environment, Energy, and Economy) model is a single-country, intertemporal computable general equilibrium (CGE) model focusing on environmental policies in Ireland. It provides GDP projections in the LEAP Ireland model.
Commercial building services data	Commercial building services data is based on a commercial energy Heat Study by the Sustainable Energy Authority of Ireland. This gives energy consumption data for buildings of different building types and purposes (Sustainable Energy Authority of Ireland, 2021)
Low Carbon Pathways for Light Good Vehicles (Mulholland, O'Shea, Murphy and Ó Gallachóir, 2016)	Information on LGVs (Light Good Vehicles) in Ireland is based on research initially conducted by Mulholland et al. (2016) which connected the energy consumption of light commercial vehicles with energy systems models.
Central Statistics Office	The Central Statistics Office provide aviation, heavy good vehicle, and industry output data (Central Statistics Office, 2022; Central Statistics Office, 2018).
Construction Energy Consumption (Whyte, Hannah E. Daly and Ó Gallachóir, 2013)	Energy consumption of heavy good vehicles is based on a study of the construction sector
SEAI Energy Balance	The Sustainable Energy Authority of Ireland's Annual Energy Balances provides information on data centres, the services and industry sectors of the LEAP Ireland model (SEAI, 2021)
UK Industry Data	Services energy consumption data from the United Kingdom Government's Department of Energy is used to support assumptions on the energy consumption of industry processes (Office of National Statistics, 2022). These energy consumption figures are linked to the economic output of the processes by industry type.
PLEXOS Ireland	The PLEXOS Ireland Electricity sector model provides information on the electricity generation plants (Geffert and Strunk, 2021)
AGRI-Times Model (Chiodi et al., 2016)	The inputs for the number of livestock by animal type and the total areas dedicated to tillage farming is derived from outputs from the AGRI-TIMES Model

Appendix D.D: General Assumptions in LEAP Ireland model for GDP, population, and conversion rates

	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
GDP (Billion Euro)	331	341	348	356	365	374	385	395	406	417	428	440	452
Population (Thousand People)	4,857	4,922	4,977	5,017	5,057	5,098	5,139	5,180	5,221	5,263	5,305	5,347	5,390

Appendix D.E: Key assumptions for passenger transport by mode type for the reference scenario

Key Assumptions for passenger transport demand														
Key Assumptions	Unit	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Total passenger kilometres	Billion Pkm	64.7	65.7	46.0	48.3	69.9	70.8	71.8	72.7	73.7	74.6	75.6	76.5	77.5
Road Private Cars	% share of Pkm	82.1	81.4	86.6	86.1	81.4	81.4	81.4	81.4	81.4	81.4	81.4	81.4	81.4
Passenger Rail	% share of Pkm	6.0	5.9	2.4	2.6	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9
Buses	% Share of Pkm	4.8	5.3	1.6	1.8	5.3	5.3	5.3	5.3	5.3	5.3	5.3	5.3	5.3
Active Modes (Cycling and walking)	% share of Pkm	0.8	1.9	1.6	1.6	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9
Taxis	% share of Pkm	0.5	0.5	0.3	0.3	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Lorry, Motorcycle, Other	% share of Pkm	5.8	5.0	7.4	7.6	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0

Appendix D.F: Categories for Heavy Good Vehicle Transportation as defined by the European Union

Category	Million Tonne-kilometres (MTkms)	Definition
NST 1	% share of Tkm	Agriculture, forestry, and fishing
NST 2	% share of Tkm	Coal and Natural Gas
NST 3	% share of Tkm	Quarry Products
NST 4	% share of Tkm	Foodstuffs
NST 5	% share of Tkm	Textiles
NST 6	% share of Tkm	Wood and Paper

NST 7	% share of Tkm	Refined Coke
NST 8	% share of Tkm	Chemicals and Plastics
NST 9	% share of Tkm	Non-Metallic Minerals
NST 10	% share of Tkm	Metal Products
NST 11 & 12	% share of Tkm	Machinery, Transport equipment
NST 13	% share of Tkm	Furniture
NST 15 - 20	% share of Tkm	Mail, Parcels, Baggage, Unknown and Other Goods

Appendix D.G: Domestic and International aviation fuel consumption for 2018 – 2030 – reference scenario

	2018	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Units	ktoe												
Domestic	6.0	6.0	1.5	1.5	6.1	6.3	6.4	6.6	6.7	6.8	6.9	6.9	7.0
International	1,097.0	1,110.0	277.5	111.0	1,136.9	1,163.8	1,190.7	1,217.6	1,234.0	1,250.3	1,266.7	1,283.0	1,299.4

Appendix D.H: Diesel energy consumption for Navigation

Sector	**Subsecto**	**Unit**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Transport	Navigation	ktoe	87	89	92	93	95	97	98	99	100	101	102	103	104

Appendix D.I: Energy consumption by fuel type relating to cross border fuel tourism

Branch	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
	ktoe												

Diesel	162.5	168.3	162.5	162.5	162.5	162.5	162.5	162.5	162.5	162.5	162.5	162.5	162.5
Gasoline	-	-	-	-	-	-	-	-	-	-	-	-	-
Biofuel	7.5	7.8	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5

Appendix D.J: NACE categories as defined by the European Union

NACE category number	Definition
NACE 5–9	Non-Energy Mining;
NACE 10–11	Food;
NACE 13–14	Textiles;
NACE 16–18	Wood Products and Printing;
NACE 20–21	Chemical;
NACE 22–23	Rubber and Non-Metallic;
NACE 24–25	Basic Metals;
NACE 26–27	Electrical and Optical;
NACE 28	Machinery and Equipment;
NACE 29–30	Transport Equipment;
NACE 31–33	Other Activity

Appendix D.K: Building condition types as per commercial building survey

Type	Description
Type 1	windows are of good quality; walls are of good quality
Type 2	windows are of good quality; walls are of bad quality
Type 3	windows are of bad quality, walls are of good quality
Type 4	windows are of bad quality, walls are of bad quality

Appendix D.L: Data Centre electricity demand for the reference scenario (2018 - 2030)

Demand (TWH)	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Electricity	2.5	4.0	4.4	5.2	6.1	6.9	7.8	8.6	9.4	10.3	11.1	12.0	12.8

Appendix D.M: Heat rates of electricity generation plants (GJ/MWH)

Heat Rate (GJ/MWH)	2018	2030
	GJ/MWH	GJ/MWH
Condensing steam cycle Money point	9.92	10.696
Steam turbine lignite	9.57	8.249
Combined Cycle Gas Turbine	6.18	5.945
Combined Cycle Gas Turbine	7.12	6.166
Natural Gas turbines	6.5	5.013
Open cycle	11.23	9.191
Wind onshore	3.6	3.6
Wind offshore	3.6	3.6
Hydro	3.6	3.6
Solar	3.6	3.6
Biomass	3.6	3.6
Natural Gas Carbon Capture and storage	3.6	3.6

Appendix D.N: Cost for Generation Plants

Unit	€ '000 per MWH capacity		
Condensing steam cycle Money point	0.2	40	1.4
Steam turbine lignite	0.2	40	1.42
Combined Cycle Gas Turbine	0.2	10	0.7
Combined Cycle Gas Turbine	0.2	10	0.8
Natural Gas turbines	0.2	10	0.8
Open cycle	0.2	22.5	0.44
Wind onshore	0.2	25	1.3
Wind offshore	0.2	25	1.5
Hydro	0.2	10	1
Solar	0.2	25	0
Biomass	0.2	25	0
Natural Gas Carbon Capture and storage	0.2	25	0

Appendix D.O: Availability of electricity generation plants

Electricity-generation process	Maximum Availability
	%
Condensing steam cycle Money point	90.9
Steam turbine lignite	92
Combined Cycle Gas Turbine	93
Combined Cycle Gas Turbine	93
Natural Gas turbines	93
Open cycle	97.6

Wind onshore	LEAP defined Wind Generation Profile
Wind offshore	LEAP defined Wind Generation Profile
Hydro	50
Solar	LEAP defined Solar Availability Profile
Biomass	92
Natural Gas Carbon Capture and Storage	93

Appendix D.P: Exogenous capacity of generation plants

Power Generation site/type	Exogenous Capacity												
	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
	MW												
	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Condensing steam cycle Money point	855	855	855	855	855	855	0	0	0	0	0	0	0
Steam turbine lignite	350.6	350.6	0	0	0	0	0	0	0	0	0	0	0
Combined Cycle Gas Turbine	1580	1580	1580	1580	1580	1580	1580	1580	1580	1580	1580	1580	1580
Combined Cycle Gas Turbine	468	468	468	468	468	468	468	468	468	468	468	468	468
Natural Gas turbines	1746	1746	1746	1746	1746	1746	1746	1746	1746	1746	1746	1746	1746
Open cycle	208	208	208	208	208	208	208	208	208	208	208	208	208
Wind onshore	3572	3572	3572	4500	4700	4900	5100	5300	5420	5540	5660	5780	5900
Wind offshore	25	25	25	25	25	25	25	25	395	1445	2475	3354	3500
Hydro	234	234											
Solar	10	10	10	261	384	507	630	692	753	815	877	938	1000
Biomass	54	54	54	54	54	54	54	54	54	54	54	54	54

Natural Gas Carbon Capture and Storage	0	0											0
Small Scale Hydro	26	26	26	26	26	26	26	26	26	26	26	26	26

Appendix D.Q: Electricity demand of Data Centres (TWH) – Reference Scenario

Year	Electricity Demand (TWH)
2019	4
2020	4.4
2021	11.36

Appendix D.R: Summary of the scenarios, underlying methods, and assumptions

Code	Scenario description	Method
TR_PAS7	Extension of Luas line to Finglas	The increase in passenger kilometres for Luas rail extensions is assumed to be in proportion to the current number of passenger kilometres served per kilometre of light rail. The passenger kilometres for light rail are derived from the Irish Passenger Transport Emissions and Mobility (IPTEM) model (O'Riordan et al. 2022b, 2022c). Luas passenger mode share is increased accordingly and a decrease in other modes of transport in Dublin is in proportion to their current mode shares.
TR_PAS8	CAP93 Electrification of Maynooth, Kildare and Drogheda	This scenario is based on Climate Action Plan 2021's Action #93 to electrify heavy rail in the Greater Dublin Area. The increase in electricity share for rail is in proportion to the kilometres of rail covered by the Maynooth, Kildare and Drogheda lines with respect to the entire country starting in 2023 and completed by 2027 (Government of Ireland, 2021b)
TR_PAS14	CAP 93 Electrification of all lines by 2030	This scenario electrifies all heavy rail by 2030, with the electricity fuel share of rail increasing to 100% by 2030.
TR_PAS32	Bus Connects BRT (Bus Rapid Transit) Dublin – high success	BRT Transit for–Dublin - assuming 20% of car ridership in Dublin switches from car to bus, based on studies from past success of mode switching with BRT from studies mentioned below, which indicate mode share potential of be–ween 5 - 25%. This is based on a review of BRT case studies around the world which reported between 10 – 70+% switches from car to bus travel (Levinson et al., 2003). It is also based on other studies from the Nantes Bus Rapid Transit service (BHLS, Buses with High Level of

		Service) in France was 29% from private cars (CERTU, 2010). 18% of BRT riders in Los Angeles were shifted from private cars (Callaghan and Vincent, 2007). In China, on the Beijing BRT Line 1, only 12.4% of riders previously were private car users (Zhao et al., 2014).
TR_PAS33	E-bike uptake, full coverage	E-bike uptake following base diffusion model and Netherlands e-bike modal shift study that looked at effects of e-bike ownership on modal shift from other modes. Diffusion model sets number of e-bikes at 480,000 by 2030. This shift increases the modal share of e-bikes to 20% of all passenger kilometres by 2030. A study on medium sized cities in China noted that E-bike riders in general travel 32% farther than bicycle riders (5.8km/trip versus 4.4km/trip on average on a mechanical bike) (Weinert et al., 2007) It is also important to note that bicycle route choice modelling findings being developed at Portland State show that environments more conducive to cycling lengthen the distance a cyclist would be willing to travel. For example, cyclists are willing to travel 22% further to travel on a bicycle boulevard than on a route with a standard bike lane (McNeil, 2011) E-bike trips are 60% longer than trips by regular bicycles. A non-electric bicycle's average trip distance is approximately 3.6 km. An e-bike's average trip distance is 5.9 km (Harms and Kensen, 2011).
TR_PAS34	Program for Government WFH (Work from home) for 20% of Civil Service	Assumes 20% of civil service will work from home from 2021, following COVID, as outlined in the Program for Government (Government Information Service, 2021)
TR_PAS35	WFH (Work from home) 2 day per week	Based on remote working potential recorded by (Crowley and Dornan, 2020) for each economic sector and applying 2019 work numbers by economic sector, a potential of 55% full time equivalent (FTE) was calculated. An uptake of 2 days working from home is assumed.
TR_PAS37	Cycling Infrastructure	Adding cycling infrastructure bonus effect based on a case study which found that cyclists are willing to travel 22% further on a bicycle boulevard than on a route with a standard bike lane alongside the road (MacNeil, 2011)

TR_PAS38	School Sustainable Transport	Increased modal share of walking and cycling passenger kilometres for primary and secondary school students. Walking and cycling rates are increased to 1996 levels based on CSO school travel surveys for both primary schools. Walking and cycling rates are increased to 1986 levels for secondary school levels, as these have the highest figures for walking available. The total passenger kilometres are based on estimate from the total number of school children's numbers and on the average distance travelled for children going to school.
TR_PAS39	BRT (Bus Rapid Transit) Cork, Limerick, Galway	Based on a medium success of car to bus switchover for passenger kilometres. 25% of car passenger kilometres in Cork, Galway, Limerick, and Waterford cities would switch to bus passenger kilometres. The passenger kilometres in Cork, Galway, Limerick, and Waterford are proportional to the population as data specific to passenger kilometres in those cities are not yet available
TR_PAS40	Light Rail – Cork, Limerick, Galway	Introduction of light rail to Cork Limerick and Galway by 2027. Uptake of light rail mode share % is assumed to be the same as Dublin, and passenger kilometres in these cities is proportional to the population of each of the cities. Assumes 50% mode shift from car to light rail, 25% from bus to light rail and 25% from bike to light rail
TR_PAS41	100% Electric buses by 2030	Assumes that all buses in Ireland will be electric by 2030. This includes private charter buses.
TR_PAS45	Additional 500,000 public transport and active trips	Based on CAP 2021 ambition of additional 500,000 trips by walking, cycling and public transport. This is calculated based on adding 500,000 trips to the current number of public transports, walking. and cycling trips taken in Ireland, derived from the IPTEM model. The increase in passenger kilometres for each of these trips is in proportion to the current shares of each of the mode types, and the average distances that each of these modes serve. This increased mode share that is given to public transport, walking and cycling is then deducted from car and taxi transport modes.
TR_PAS46	CarSET with ICSM V2.5 845K EV and PHEV	Based on CarSet diffusion model with Irish Car Stock Model V 2.5 in leaptransport_inputs.xlsx. Assumes 660k BEV and 180k PHEV by 2030 following bass diffusion model. (Bass, 1969, 1963)

TR_PAS47	1,500 Electric buses by 2030	Based on CAP target to have 1500 EV Buses by 2030, split 2/3 Dublin bus (as 2/3 of buses in public fleet are Dublin bus). This means 87% of the fleet will be electric by 2030.
TR_FR1	Climate Action Plan Freight Electrification 95k LGV (Light Good Vehicles) by 2030	CAP 2019 Section 10.2 Transport targets, LGV Electrification target to deliver 95,000 ELE LGV Vehicles by 2030 (DCCAE, 2019)
TR_FR3	Eco driving for Heavy Goods Vehicles (HGV) – 10% fuel consumption improvement	An average 10% fuel saving can be achieved when drivers are given the training and tools to change their driving style. Such a programme is in development and is assumed to be rolled out starting in 2023 (Gallachóir and McDonagh, 2021)
TR_FR4	Climate Action Plan (CAP) Freight HGV (Heavy Good Vehicles) electrification 3,500	Scenario explores deployment of Battery Electric HGV's (BEHGV) by 2030. This is based on the Climate Action Plan 2021. The uptake of BEHGV's are as follows: 2021: 0 BEHGV 2025: 700 BEHGV 2030: 3500 BEHGV With linear diffusion between 2021 – 2025 period up to 700, a–d 2025 - 2030 up to 3500 respectively, with an even replacement across all weight classes and economic activity (NST) categories.
TR_BLN5	Biofuel Blending: E10 (Ethanol mix for petrol 10%) and Biodiesel B20 (Diesel mix for diesel 20%)	See CAP 2021 table 15.5, table describes increasing biofuel blending (E10 & B20) Based on the Climate Action Plan 2021, where increased biofuel blending is described for both ethanol (of up to 10% for petrol) and biodiesel (up to 20%).
RES2.3	District Heating with Deep Retrofitting	District heating (DH) scenario exploring the combination of DH with deep retrofitting in line with CAP21 i.e., 500,000 deep retrofits and 400,000 heat pumps to determine the level of DH introduced when combined with Deep Retrofitting.
RES8	Ban on Fossil Fuel Boiler	CAP60: No Oil boilers installed from 2022 & No Gas boilers installed from 2025

		Key assumptio“ under "Resi–ential -”General" allows for control of ban year for new dwellings.
RES10	Residential Net Zero Energy Buildings (NZEBs)	Scenario to explore CA19P action 56, the implementation of Nearly Zero Energy Buildings (NZEB) Building Regulations (BR) in private residential sector. For Residential Dwellings, NZEB 25% improvement defined as 25% reduction in Maximum Permitted Energy Performance Coefficient (MPEPC) from 0.4 to 0.3 and improvement within Maximum Permitted Carbon Performance Coefficient (MPCPC) from 0.46 to 0.35. see attached building regs 2011 (inc. 2017 amendments) for definition and further detail. New Building regulation standards lag their introduction by 2 years, commencing in 2023. New Key Assumption "Key\Residential\General\Year for introduction of private NZEB BR" allows for the year of introduction to be altered within LEAP. Current setting = 2023.
SRV_COM2	Commercial Sector Deep Retrofit	Commercial Services Deep retrofit scenario. Based on SEAI/ Element Energy survey of commercial buildings. Assumption: Linear implementation over period 2021 - 2030
SRV_COM3	Commercial Sector Electrification of Heat	Scenario explores the complete electrification of heat in all commercial subsectors. Action aligned with CAP 2022 – section 13.3.3. Assumption: Linear implementation over period 2022 – 2030. Details: Includes fuel switching from Natural Gas and Oil to Electricity.
SRV_PUB1	Public Sector 50% Climate Action Plan Target	From page 69 of CAP2021 Emission reduction targets will be based on an absolute tonnage of GHG emissions. The total tonnage target will be a 51% reduction of direct energy-related emissions (thermal and transport consumption), plus projected supply side reductions in indirect energy-related emissions (i.e., electricity – because of the achievement of the up to 80% renewable electricity target). The baseline for the methodology is the period 2016-18, with a scaling factor applied to ensure the individual targets equal the total ambition.

SRV_DTC1	Data Centre Low Scenario from EirGrid Generation Capacity Statement (GCS) 2021	Explores impact of lower data centre projections in line with EirGrid GCS 2021 'Low Demand' scenario (EirGrid Group and SONI Ltd., 2021)
IND_ELC2	Industry Electrification of Heat	alternative electrification of heat scenario base on McKinsey projections and 50-60% share of ELE in heat demand
BLD_BLN1	HVO in 20% of heating fuels	Increased ambition scenario exploring the impact on residential energy demand/ emissions due to increased share of HVO within oil heating. Assumption: Start Year = 2023. Data derived from chart in source (Page 17): Year 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 HVO 0% 1.0% 2.0% 2.5% 5.0% 7.0% 10.0% 15.0% 17.0% 18.5% 20.0% (Swedish Energy Agency, 2020)
BLD_BLN2	Biogas 20% heating fuels	Increased ambition scenario exploring the impact on Increased Biogas penetration in line with ERVIA projections, 20% by 2030. Assumption: Start Year = 2023. Data derived from KPMG report (Page 18) & Interp function: Year 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 Biogas 0% 0% 0% 2% 4% 6% 8% 10% 12% 14% 16% 18% 20.0% (KPMG, 2018)
ELC5	Residential Capacity CAP 2021 (Electricity generation scenario that aligns with CAP2021 capacity numbers)	Electricity generation scenario that aligns with CAP2021 capacity numbers Onshore wind = 8.2GW Offshore wind = 5GW Solar PV = 2.5GW Dispatch rule: Running Costs
ELC8	Renewable Electricity Scheme Max Carbon	Electricity generation scenario that aligns with Climate Action Plans 2021 capacity numbers for onshore wind

	Capture and Storage	Onshore wind = 8.2GW Offshore data aligns with maximum TIMES Ireland Model scenario for offshore wind Offshore wind = 8GW EA Report for Solar & Gas CCS Solar PV = 3.3GW Gas CCS = 420MW Dispatch rule = priority dispatch for RES-E
NEE2	80% reduction in F gases CAP 2021	F-gases target to reduce by 80% compared to 2014 values. This is modelled as a 74% reduction compared to 2018 values (Environmental Protection Agency, 2021b)

Appendix D.S: Summary of annual emissions impact of individual policy measures and the combination CAP2021 scenario ($MtCO_2eq.$)

Scenario	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
							$MtCO_2eq.$						
REF1	65.7	65.1	62.2	62.7	65.2	68.4	67.9	65.6	64.7	65.1	65.6	66.2	67.2
TR_PAS7	65.7	65.1	62.2	62.7	65.2	68.4	67.9	65.6	64.7	65.1	65.6	66.2	67.2
TR_PAS14	65.7	65.1	62.4	62.6	65.0	68.4	67.9	65.6	64.7	65.0	65.4	66.0	67.0
TR_PAS32	65.7	65.1	62.2	62.7	65.2	68.4	67.9	65.6	64.7	65.1	65.6	66.2	67.2
TR_PAS33	65.7	65.1	62.2	62.4	64.9	68.1	67.6	65.3	64.4	64.7	65.2	65.8	66.8
TR_PAS34	65.7	65.1	62.2	62.7	65.2	68.4	67.9	65.6	64.7	65.1	65.6	66.2	67.2
TR_PAS35	65.7	65.0	62.0	62.3	64.7	67.9	67.4	65.2	64.3	64.6	65.1	65.7	66.8
TR_PAS37	65.7	65.1	62.2	62.7	65.2	68.4	67.9	65.6	64.7	65.1	65.6	66.2	67.2
TR_PAS38	65.7	65.1	62.2	62.7	65.2	68.3	67.9	65.6	64.7	65.1	65.5	66.1	67.2
TR_PAS39	65.7	65.1	62.2	62.7	65.2	68.3	67.9	65.6	64.7	65.1	65.5	66.2	67.2
TR_PAS40	65.7	65.1	62.2	62.7	65.2	68.4	67.9	65.6	64.7	65.1	65.6	66.2	67.2
TR_PAS41	65.7	65.1	62.2	62.7	65.2	68.4	67.9	65.6	64.7	65.1	65.5	66.1	67.1
TR_PAS45	65.7	65.1	62.2	62.6	65.2	68.3	67.8	65.5	64.6	64.9	65.4	66.0	67.0

TR_PAS46	65.7	64.9	62.2	62.5	65.0	68.0	67.4	64.8	63.6	63.7	63.7	63.9	64.4
TR_FR1	65.7	65.1	62.2	62.7	65.2	68.3	67.9	65.6	64.6	65.0	65.4	66.0	67.0
TR_FR3	65.7	65.1	62.2	62.7	65.2	68.4	67.9	65.6	64.7	65.1	65.5	66.1	67.1
TR_FR4	65.7	65.1	62.2	62.7	65.2	68.3	67.9	65.6	64.6	65.0	65.4	66.0	67.0
TR_BLN5	65.7	65.1	62.2	62.7	65.2	68.3	67.9	65.6	64.7	65.0	65.5	66.1	67.1
RES2.3	65.7	65.1	62.1	62.4	64.8	67.8	67.1	64.7	63.6	63.8	64.1	64.6	65.4
RES8	65.7	65.1	62.2	62.7	65.2	68.3	67.9	65.6	64.7	65.0	65.5	66.1	67.1
RES10	65.7	65.1	62.2	62.7	65.2	68.3	67.9	65.6	64.7	65.1	65.5	66.1	67.2
SRV_COM2	65.7	65.0	62.2	61.3	63.9	66.9	66.3	64.3	63.3	63.8	64.1	64.7	65.6
SRV_COM3	65.7	65.1	62.2	62.7	65.0	67.9	67.2	64.9	63.8	64.1	64.4	64.9	65.8
SRV_PUB1	65.7	65.0	62.1	62.5	64.9	68.0	67.5	65.2	64.2	64.6	65.0	65.6	66.6
IND_ELC2	65.7	65.1	62.2	62.7	65.2	68.4	67.9	65.5	64.5	64.8	65.2	65.7	66.5
BLD_BLN1	65.7	65.1	62.2	62.5	65.0	68.2	67.5	65.1	64.0	64.2	64.4	64.9	65.7
ELC5	65.7	65.2	62.3	62.6	65.1	68.2	67.6	65.4	64.4	64.7	64.7	65.2	66.3
NEE2	65.7	65.1	62.2	62.7	65.1	68.3	67.7	65.4	64.5	64.8	65.2	65.8	66.8

Appendix D.T: Per annum emissions change by sector for Carbon Budget 1 & 2

Sector	Per annum emissions change ($MtCO_2eq.$ p/a) (2021 – 2025, Carbon Budget 1)	Per annum emissions change ($MtCO_2eq.$ p/a) (2026 – 2030, Carbon Budget 2)
Transport	-2.06	-3.21
Services	-2.02	-1.46
Residential	-1.78	-2.23
Electricity	-0.39	-0.71
Industry	-0.15	-0.72
F-Gases	-0.24	-0.23

Appendix E: Passenger Transport Demand, Mode Share, and CO_2 Emissions following COVID-19 Travel Restrictions: A Case Study of Ireland

Abstract

The COVID-19 pandemic resulted in wide-ranging travel restrictions and 'work-f'om-home' orders in many countries, including Ireland. I observe trends in traffic volume data for car, motorbike and caravan transport, passenger numbers for bus and rail, and bicycle counter data. Trends are compared with mobility patterns from 2019 traffic counter and passenger intake numbers. Passenger transport demand and mode shares and associated CO_2 emissions are calculated from March 2020 to May 2022. Public transport passenger numbers and car traffic have returned to pre-pandemic levels and continue to grow in the post-pandemic era. Emissions reductions of 4.2 $MtCO_2$ occurred during the COVID-19 travel restriction period relative to a simulated counterfactual "No COVID-19" scenario. The analysis suggests that the reIuction in passenger transport demand was short-lived, and demand for car, bus, and rail transport has recovered and is growing. Car dependency has increased (from 82% of passenger kilometres in 2019 to 85% in 2022) and the mode share of bus and rail transport has decreased. I discuss the emissions reductions over the COVID-19 era in the context of national climate action commitments and the policy implications of these emission reductions and modal shifts.

Introduction

The World Health Organization declared the COVID-19 outbreak a pandemic on the 11th of March 2020. The following week, the Irish Government began to introduce restrictions on venues and by the 27th of March there was a national ‘stay at home’ order issued for the country.

Country, county, and radius-based travel restrictions and restrictions on dining, large events, and mask wearing on public transport were in place from March 2020 until March 2022. Significant restrictions for the COVID-19 pandemic are not anticipated to return. An overview of historical travel restrictions over the period of March 2020 to March 2022 is shown in Figure 31 (below).

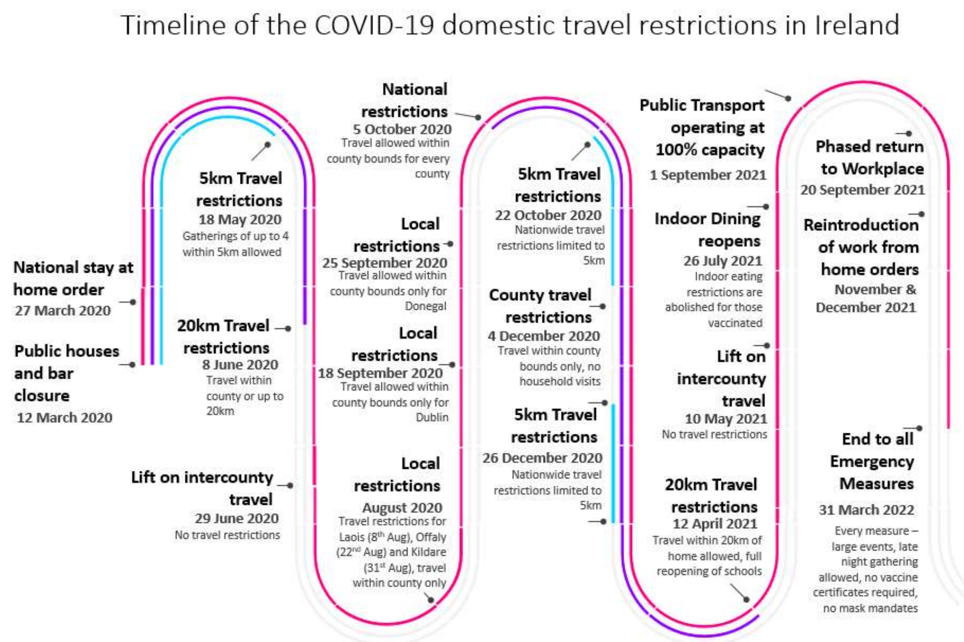

Figure 31: Overview of travel restrictions introduced by the Irish Government

Measuring the impact of the restrictions quickly became a prevalent topic amongst the transport research community, with short-term studies looking at the impact severe travel restrictions had during the first wave of the COVID-19 pandemic. The COVID-19 pandemic led to a shift in transport patterns and a reduction of mobility for millions of people (Abu-Rayash & Dincer, 2020). These studies used quantitative data sources such as counters, flight, and mobility trackers to document changes in travel. A summary of the regions, time periods, characteristics measured, and their associated net changes during the onset of the COVID-19 travel restrictions are included below (Table 106).

Table 106: Overview of mobility and traffic counter studies during the COVID-19 pandemic by transport section

Reference	Transport sector	Region	Time period	Net change in mobility/ traffic counter data
(Abu-Rayash & Dincer, 2020) (Nižetić, 2020)	Aviation Aviation	Canada EU	March 2020 – July 2020	-71% -89%
(Gualtieri et al., 2020) (Saladié et al., 2020) (Goenaga et al., 2021) (Chen et al., 2020)	Urban Road traffic Motorway traffic Ex-urban network Road traffic Road traffic Road traffic Road traffic	Italy Tarragona, Spain Santander, Spain North Carolina and Virginia Global Munich, Cape Town, Oslo, Norway, San Francisco Bay Area, California	March – May 2020 –arch 16 - April 26, 2020 March 15 – April 20, 2020 March 8 – September 2020 Month of February, March, April March – December 2020	-48 - -60% -55 – -75% -64.5 – -80.1% -62.9% -76% -27% ~-10%, ~-25%, ~-45% -7 - -22%
(Aloi et al., 2020)	Public transport users	Santander, Spain	March 15 – April 20 2020	-93%
(Millefiori et al., 2020)	Container ships	Global	March – June 2020	-5.62 – -13.77%
(Arellana et al., 2020)	Freight trips Flights Public Transport	Colombia (various cities)	March – mid-June 2020	-38% ~-40 – -60% ~ -80 – -90%

Public transportation has always been the major sector to be affected in case of similar epidemic out breaks even in the past (Kelly et al., 2015; Lau, Yang, Tsui & Kim, 2003). Studies on public transport remarked on the initial “chilling” effects of the COVID-19 pandemic in 2020, and looked at frequency and occupancy rates on public transport (Tiikkaja & Viri, 2021), but that this effect lessened with subsequent lockdowns (Wang, 2014). Links between mobility data and the incidence of COVID-19 by tracking passenger numbers, pedestrian and cyclist data was also explored (Manzira et al., 2022).According to a study from Germany, public transport lost popularity during the pandemic, while car dependency increased (Eisenmann et al., 2021). Reduced public transport usage and increased car dependency was also noted in a case study of Budapest during the COVID-19 related travel restrictions (Bucsky, 2020). The study confirms an observation made at the beginning of the pandemic that the need for social distancing would mean that fewer people would travel by public transport (De Vos, 2020). A study from Gdansk warned of an almost impossible effort to return to the pre-pandemic popularity of public transport following the first wave. It also noted that more research is required to observe what happens in subsequent “waves” of the virus’ spread (Przybylowski et al., 2021). This study aims to address this gap.

Narratives around changes in transport behaviour inspired by policies emerging during the pandemic related travel restrictions was the subject of Zhang and Zhang (2021), where scenarios looking at bus service reduction, online shopping, working from home, and bike friendly design were explored. In this case a computable general equilibrium energy systems model was used to draw observations on possibilities based on emerging trends and topics arising from the pandemic.

Extreme reductions in traffic during health emergencies are not exclusive to the COVID-19 pandemic. Analysis of the 2003 Severe Acute Respiratory Syndrome (SARS) crisis found that passenger air transport demand was reduced by about 35% at the height of the crisis

(IATA, 2020). The demand remained below the typical pre-pandemic traffic volumes for six months after the initial onset of the epidemic. Other health epidemics following SARS include the Avian Flu outbreaks of 2005 and 2013, as well as the Middle Eastern Respiratory Syndrome in 2015. Although these two viruses caused disruption in the transportation sector, air travel recovered fairly quickly (Abu-Rayash & Dincer, 2020). The study found that the reductions in transport activity were most acute in the 6-month period after the start of the crisis. It also highlighted that the severity of the transport reductions is sometimes different. The Avian flu in 2005 and 2013 did not impact the South-East Asian airlines significantly, but the SARS pandemic of 2003 had severe effects on Asian Pacific airlines.

Hensher highlights the importance of updating traffic models with intermediary data such as traffic counter and passenger transport data. Hensher then explores the example of the severe impacts of the COVID-19 pandemic to make the case for continual monitoring and adjustment to models (Hensher et al., 2021). This study contributes to this cause of continual monitoring of transport trends and model adjustments in the face of disruptions such as the COVID-19 pandemic.

Previous studies have linked traffic volumes with CO_2 emissions (Xiang et al., 2016; Xu et al., 2018). Gensheimer et al. examined the inconsistencies with applying traffic counter data and satellite-based tracking devices to national and regional emissions and overall mobility models. Based on the studies of several cities, there was a moderate range of error depending on the data source used, noting errors of up to 60% when using these data sets, and recommended a cautious approach when using these data sets. For the short term however, they can be helpful indicators of the general direction of traffic patterns and driving behaviour, but subsequent updates to the “pandemic restrictions” scenario will be required to update a clearer representation based on fuel consumption and car odometer data from the period being studied (Gensheimer et al., 2021). A study for Macao linked a light-duty passenger transport fuel consumption model with traffic volume data to generate a high-resolution inventory of fuel use (S. Zhang et al., 2016). Traffic counter information was also combined with meteorology monitoring, carbon emissions, and driving characterizations to provide micro to macroscopic carbon emissions from arterial traffic on urban road systems in Jian et al., (Jian et al., 2017). Average daily traffic values have been used previously to estimate transport emissions for a national road network (Fu et al., 2017).

A study of the Canadian transport sector provides a forecast of greenhouse gas (GHG) emissions of the Canadian transport sector for 2020 of 93 $MtCO_2$ (Abu-Rayash & Dincer, 2020). Results showed energy savings and GHG reductions associated with the pandemic for 2020.

Ireland also observed dramatic changes in energy trends due to the COVID-19 pandemic initially. Glynn et al. (2020) estimated that Irish energy system CO_2 emissions reduced by 3 $MtCO_2$ over the period of March to May 2020, or 2 $MtCO_2$ excluding aviation, a 5.3% drop relative to the previous year.

It is important to note that overtime, in the context of a broader time of more than 50 years globally, the direct climate effect of the pandemic-driven response will be negligible, as the modelled long-term human behaviour up to 2100 will eclipse the temporary aberration in GHG emissions caused by the COVID-19 pandemic (Forster et al., 2020). However, the potential longer term effects of the COVID-19 pandemic on systems, behaviours, and technology uptakes could have a lasting impact – provided there are these long term impacts. Usman et al.(2021) noted that no prior global shock had been scrutinized as a prelude to the threat of climate breakdown as the COVID-19 pandemic has. Enormous restrictions on mobility and closures of industry have reduced emissions and has had positive impacts on climate change in the immediate term, whether it has positive effects in the *aftermath* of travel restrictions on modal share and passenger demand is a question addressed in this study. This study also discusses changes in travel trends related to the COVID-19 pandemic in the context of Ireland's passenger transport emissions targets. CO_2 emissions modelling for passenger transport is important as, prior to the pandemic, transport was the fastest growing source of Ireland's energy-related CO_2 emissions, and was responsible for 40% of all energy-related CO_2 emissions in 2019, prior to the COVID-19 pandemic (SEAI, 2021). To meet GHG reduction commitments under the 2021 Climate Act, the Government plans to reduce transport emissions from 2018 levels by between 42 – 50% by the year 2030, and stay within legally-binding carbon budgets over the period 2021-30 (Government of Ireland, 2021b). Ireland has failed to achieve GHG emissions reductions targets in the past. For example, Ireland's Effort Sharing Decision targets for emissions were not in compliance for 2016, 2017, or 2018, and exceeded annual limits by 0.30, 2.94, and 5.57 $MtCO_2$, respectively (Environmental Protection Agency, 2022a). Across all sectors Ireland's 2021 greenhouse gas emissions were 69.3 $MtCO_2$, 11.13 $MtCO_2$ more than the annual recommended limit to stay within the carbon budget for 2021, if you assume the total carbon budget over the 5 year period of 2021 – 2025 of 295 $MtCO_2$ is split evenly over each of the years (Environmental Protection Agency, 2022a).Therefore, it is necessary to monitor developments in passenger transport emissions closely to assist transport and climate policy planning.

Creutzig et al. (2022) focused on the policy responses that could be beneficial to passenger transport GHG emissions reduction and beneficial in response to COVID-19. Making pedestrian and cyclist centric interventions permanent provides an opportunity in the long-term for a modal shift away from car transport towards more sustainable modes in cities. Creutzig et al. also noted a slump in public transport in several cities. A study on Polish cities found that those on higher incomes were more likely to shift to car use during the COVID-19 pandemic and that high quality transport systems were more resilient to fluctuations in transport demand during health crises (Krysiński & Uss-Lik, 2022), and a study from the Netherlands found that ample and free parking encouraged car use during the COVID-19 pandemic (Taale et al., 2022). A case study from India found that habitual users of public transport were more likely to continue using public transport with the onset of the pandemic (Bandyopadhyaya & Bandyopadhyaya, 2022).

The extent of which public transport has been affected during the lockdown period and in the aftermath is explored in this study in the context of Ireland.

This study determines a) the change in traffic volumes from car, caravan, and motorbikes from on-road traffic counters in Ireland, b) the change in passenger transport numbers for bus and rail services in Ireland, c) the change in bicycle counts from bicycle counters based in Dublin city, Ireland. These data points are applied to passenger kilometre demand models to calculate the passenger kilometre demand over the period of January 2020 – July 2022 and the shift in modal share, i.e., cycling, rail. Mode share and passenger kilometre demands inform a "COVID-19 Passenger Transport" adjusted scenario in the energy systems LEAP Ireland model (Mac Uidhir et al., 2020c). The overall reduction of passenger transport CO_2 emissions over the period January 2020 – July 2022 is measured. The changes in CO_2 emissions are discussed with respect to Ireland's Climate Action Plan targets, which set out its pathway to achieve its emissions reductions targets that are in line with Ireland's Climate Action Plan 2021 and the subsequent Climate Action Plan 2023 that stemmed from the Paris Agreement. The structure of the study is as follows: Section 1 gives an overview of the literature and background to the study, Section 2 covers the methodology – including the data collection process and the models used in the study, Section 3 shares the results, Section 4 discusses the results, the uncertainty involved in the calculations and models, and the policy implications arising from the results. The study concludes in Section 5.

Therefore, the specific aims of the study are to:

- Develop a methodology to calculate passenger transport emissions based on intermediary passenger number data for bus and rail transport, and traffic counter data for car, caravan, and motorcycle data

- Analyse the impact of pandemic-related restrictions on passenger transport demand over the period of March 2020 – July 2022
- Assess CO_2 emission reductions due to travel restrictions and the responsive change in behaviour and mobility
- Discuss the implications of changes to passenger transport demands in the context of medium-term climate action commitments.

Materials and Methods

The process by which traffic counter, passenger number and bicycle counter data were collected, and used to generate inputs for the energy systems simulation model, LEAP Ireland, and model passenger transport emissions for 2020, 2021 and 2022 is explained in this section. Figure 32 presents an overview of the methodology developed in this study. Moving from left to right, passenger kilometre demand by mode from the IPTEM model, bus, and rail passenger numbers, road traffic volumes and bicycle counter data are used to calculate the change in monthly passenger kilometre demand and pre-COVID mode shares of passenger transport. These figures are input in the transport branch of the LEAP Ireland model, as there is an inventory and inbuilt accountancy facility within the platform. This is used to calculate the passenger transport emissions from January 2019 to May 2022. These figures are then compared with the Environmental Protection Agency's (EPA) Emissions Accounts and the Sustainable Energy Authority of Ireland's (SEAI) Energy Balances (Environmental Protection Agency, 2022a; SEAI, 2021)

The passenger kilometre demands up to 2019 are based on outputs from the Irish Passenger Transport Emissions and Mobility (IPTEM) model, which I discuss in section 2.1.

Irish Passenger Transport Emissions and Mobility (IPTEM) model

The Irish Passenger Transport Emissions and Mobility (IPTEM) model factors in trip-purpose and modal shift in quantifying passenger transport demand and GHG emissions

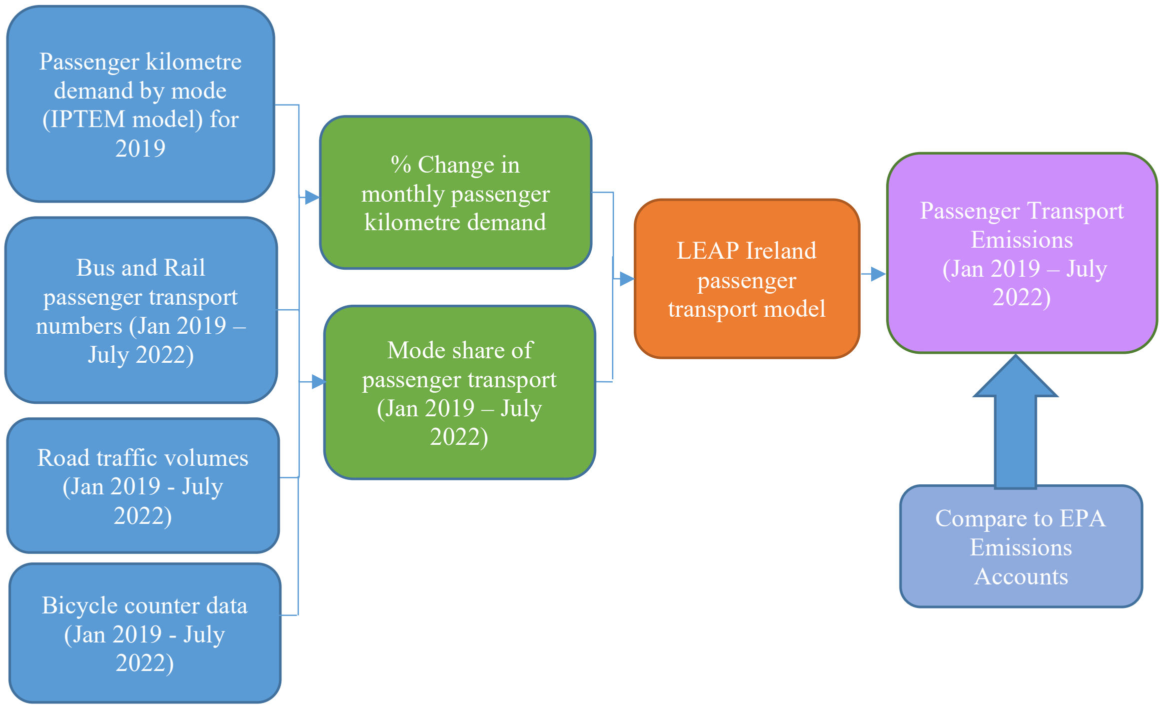

Figure 32: Overview of the methodology from data collection to model output

(O'Riordan, Rogan, Ó Gallachóir, Mac Uidhir, et al., 2022b; O'Riordan, Rogan, Uidhir, et al., 2022c) . The IPTEM model is open-source and provides information on the overall passenger kilometre demand by mode share, trip purpose, and trip distance over the 2009-2019 period (O'Riordan, Rogan, Ó Gallachóir, & Daly, 2022b). The IPTEM model is based on the Irish National Travel Survey (Central Statistics Office, 2020), the Irish Car Stock Model (Daly & Ó Gallachóir, 2011; O'Riordan, Mulholland, et al., 2021), and on information from public transport providers, Bus Éireann and Irish Rail (O'Riordan, Rogan, Uidhir, et al., 2022c). It also provides energy consumption and GHG emissions per passenger kilometre by passenger transport mode, trip purpose, and trip length. These outputs are used to inform the adjustments to passenger kilometres and the associated emissions reductions in passenger transport in 2020 and 2021 due to the COVID-19 travel restrictions to quantify the impact of pandemic restrictions on overall passenger transport GHG emissions. Key passenger kilometre demand data for 2019 is listed in Table 107 (below).

Table 107: Passenger Kilometre demand by mode for 2019 (source: O'Riordan et al., 2022c)

Mode Type	2019 (million Pkm)
Pri–ate car - Driver	43,130
Pri–ate car - Passenger	10,792
Walk	303
Bus	3,642
Cycle	233
Rail/Dart/Luas	3,948
Taxi/hackney	302
Lorry/Motorcycle/Other	3,335
Total	65,687

LEAP Ireland Model

This study uses a bottom-up GHG emissions energy systems simulation model for Ireland using LEAP (Heaps, 2022). The aim of the study is to provide a detailed bottom-up simulation model of all economic sectors to provide an evidence base for emissions fluctuations in the transportation system.

In this study, I use a bottom-up simulation modelling approach, which accounts for, and projects the energy and associated emissions flows of an energy system based on technology stock data on technology types and passenger activity (H. Daly & Ó Gallachóir, 2011; O'Riordan, Mulholland, et al., 2021). This study is confined to the passenger transport system, which is simulated for both a reference scenario, which reflects the "factual" case (what actually happened) – in this case, passenger transport demand dynamics which took place over the COVID-19 period, and an alternative reference scenario – a counterfactual scenario, in this case the "No COVID-19" scenario, which is designed to understand the impact of the COVID-19 travel-related projections. Typically, simulation is used to project emissions for future years, based on changes in demand side requirements, or supply side fuel types. In this study, I apply an energy systems simulation model retrospectively to understand the impact of a trend "ex post". This approach was used in an ex-post study on a car tax policy in O'Riordan et al. (2022a).

The LEAP Ireland simulation model is used in this study to calculate GHG emissions. The LEAP Ireland model captures GHG emissions associated with industry, transport, residential, services, agriculture, and electricity generation (Mac Uidhir et al., 2020c). In the past, sector specific research questions have been explored with the LEAP Ireland model. For example, previous versions of the LEAP Ireland model have been used to examine the impact of energy efficiency measures on Ireland's energy system and as a soft-link to electricity systems cost-optimisation models (Rogan, Cahill, Daly, Dineen, Deane, Heaps, Welsch, Howells, et al., 2014). In this study I focus on the passenger transport section of the LEAP Ireland model. The LEAP Ireland model links passenger transport demand and technology data with fuel intensities from the Technology and Environmental Database (Heaps, 2022) and calculates greenhouse gas emissions for both the COVID-19 scenario and the 'no-COVID' counterfactual scenario. Passenger transport in the LEAP Ireland model includes car stocks and passenger kilometre demand by mode and fuel type. This information is based on the Irish Car Stock Model (H. Daly & Ó Gallachóir, 2011; O'Riordan, Mulholland, et al., 2021) and the Irish Passenger Transport Emissions and Mobility (IPTEM) model (O'Riordan, Rogan, Ó Gallachóir, & Daly, 2022b; O'Riordan, Rogan, Ó Gallachóir, Mac Uidhir, et al., 2022c). The models and databases calculate carbon dioxide emissions by mode and fuel type up to 2022 for the "No COVID-19" scenario for 2020, 2021, 2022.

An overview of the data sources used to inform Ihe LEAP IrelInd Model iI provided in Table 108 (below).

Table 108: Overview of data sources

Description	**Source**
Passenger Transport Demand	(O'Riordan et al., 2022c)
Bicycle Counter numbers	Dublin City Council (Appendix F.C
Car traffic volumes	(Transport Infrastructure Ireland, 2022a)
Caravan traffic volumes	(Transport Infrastructure Ireland, 2022a)
Bus Passenger Numbers	Transport Infrastructure Ireland (Appendix F.B
Heavy rail Passenger Numbers	Transport Infrastructure Ireland (Appendix F.B
Light rail (Luas) Passenger Numbers	Transport Infrastructure Ireland
Fuel carbon intensity data	(Heaps, 2022)
Car technology and stock data	(O'Riordan, Mulholland, et al., 2021)

COVID-19 Passenger Transport Scenario

This scenario calculates actual passenger transport demand and associated GHG emissions over the period January 2020- May 2022 based on monthly indexes comparing traffic volumes, bicycle counter data and passenger transport numbers to 2019 figures. Traffic volumes for car, motorbike and caravan traffic volumes are from traffic counter data from sites in Ireland. Traffic counter information is available from Transport Infrastructure Ireland, a publicly available data source of 300+ camera sites, which provides information on aggregated monthly, daily, and hourly traffic flows (Transport Infrastructure Ireland, 2022a). Monthly rail and bus passenger numbers over the period of 2019 up to July 2022 are provided from Transport Infrastructure Ireland, and the National Transport Authority. These figures are included in the supplementary information (Appendix F.A, Appendix F.B). Bicycle counter data from Dublin City Council shows monthly traffic volumes of bicycles passing 6 sites in the Dublin City area, these figures are included in the supplementary information (Appendix F.C).

The modelled passenger kilometre demand for the "private car" and "motorbike/caravan/other" transport mode categories were calculated as follows (Equation 24):

$$PKM\ demand_{year,mode} = traffic\ volume\ index_{year\ to\ 2019,mode} \times PKM_{2019,mode} \quad (24)$$

The passenger kilometre demand for a 2020, 2021, and 2022 is adjusted based on the rate of change of traffic volumes for each mode from the traffic counter data over those years. The traffic volume index is the % change in transport mode traffic volumes relative to 2019. This is then multiplied by the total passenger kilometres for each mode in 2019. As this equation indicates, it is assumed that passenger kilometre demand follows vehicle activity data in each category (i.e., that vehicle occupancy stays the same).

The same approach is taken for public transport: Bus and rail passenger transport passenger kilometre demand are reduced in proportion to the passenger numbers of bus and rail transport services in Ireland, retrieved from Transport Infrastructure Ireland and public transport operators.

The modelled passenger kilometre demand from "Rail/DART/Luas" (which includes intercity and urban rail and tram services) and "Bus" transport mode categories for 2020, 2021, and 2022 was calculated as follows (Equation 25)

$$PKM\ demand_{year,mode} = passenger\ number\ index_{year\ to\ 2019,mode} \times PKM_{2019} \quad (25)$$

Cycling passenger transport demand and passenger kilometres is based on changes in bicycle count numbers from the Dublin City Council bike counters.

The modelled passenger kilometre demand from "cycling" transport mode categories for 2020, 2021, and 2022 were calculated as follows (Equation 26)

$$PKM\ demand_{year,mode} = bicycle\ count\ index_{year\ to\ 2019,mode,} \times PKM_{2019} \quad (26)$$

The passenger kilometre demands are then input into the LEAP Ireland model. The passenger transport CO_2 emissions calculations from the LEAP Ireland COVID-19 Passenger Transport scenario for 2019, 2020 and 2021 are then compared against annually reported emissions figures from the Sustainable Energy Authority of Ireland's (SEAI) energy balances and the Environmental Protection Agency's (EPA) emissions accounts (Environmental Protection Agency, 2022a; SEAI, 2021). Sources of uncertainty are investigated later in Section 0 in the Discussion Section.

"No COVID-19" Scenario

Recorded passenger kilometre demand from 2009 – 2019 are based on passenger kilometre demands and emission factors from the previously described IPTEM model. For the purposes of simulating passenger transport demand under "Business as Usual" conditions, where the COVID-19 pandemic and associated travel restrictions did not occur, passenger transport demand with the IPTEM model are projected up to 2022 for the "No COVID-19" scenario using the Gompertz function which is an econometric model of future car stock based on 1) income per adult based on GDP growth and 2) population as drivers.

I quantified the car stock and the associated demand stemming from this car ownership using income per adult and cars per adult as the drivers. The growth rate of income per adult is based on economic growth models developed by the ESRI (Bruin et al., 2020). This income per adult is further used to project the number of cars per adult, using a Gompertz function as shown below in Equation 27 (Lian et al., 2018).

$$y = \alpha e^{-\beta e^{-\gamma}} \quad (27)$$

Where α is the saturation level (maximum number of cars per 1000 persons); β and γ are estimated based on historical regressions of car ownership in Ireland. Vehicle kilometres per car based on odometer readings from 2000 – 2018 from the National Car Test centre and car per adult are then used to calculated total vehicle kilometres. Car passenger kilometres are calculated by combining the vehicle kilometres with the average occupancy per car. The average occupancy per car in this study is 1.49, based on a range of estimates from Eurostat, and occupancy rates from other EU countries (Eurostat, 2021b). For the reference scenario, it is assumed that growth in car passenger kilometres corresponds with an equivalent growth in passenger kilometres of other transport modes.

Results

Road Traffic Volumes, Bicycle Counter Activity, and Passenger Numbers

For January and February 2020, traffic counter data showed a net increase in traffic volumes in 2020 compared to 2019, with volumes 14.8% and 6.8% higher than January and February 2019, respectively. With the introduction of the COVID-19 travel restrictio[ns] on the 12th of March 2020 in Ireland, monthly traffic volumes for March 2020 fell 18.8% below 2019 traffic volumes. De–pite March - May 2020, and January – April 2021 having the same severity of travel restrictions, the traffic reducing impact during the second wave for road traffic was not as severe. By March 2022, overall traffic volumes had returned to pre-pandemic levels. Changes in road traffic volumes for all types of road vehicles over the period of January 2019 – May 2022 is shown in Figure 33.

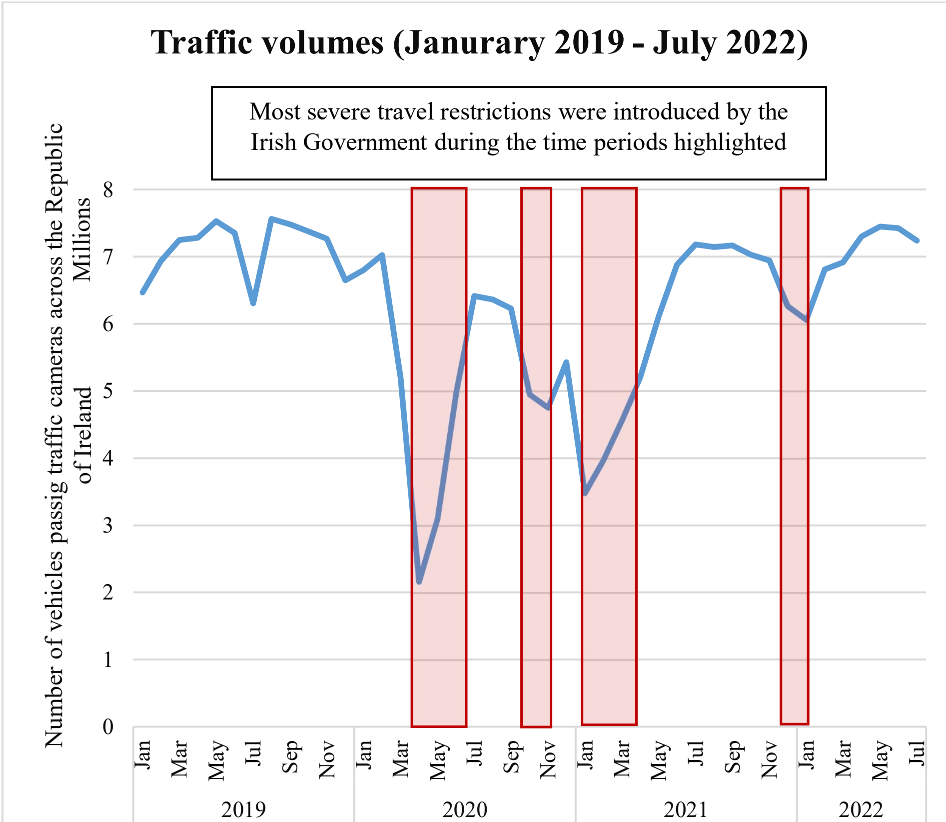

Figure 33: Traffic volumes of vehicles (all types) passing road traffic counters (J–nuary 2019 - May 2022)

Overall road traffic for 2020 experienced a 26% decrease across all types of freight and passenger vehicles on Irish roads. In 2020, Car, motorbike, and caravan traffic reduced by 29%, 23%, and 3% respectively when compared to 2019 volumes.

For 2021, car and motorbike traffic were 19% and 22% lower than 2019 levels. However, in 2021, Caravan traffic was 19% *higher* than the 2019 traffic levels.

From January to May 2022, car volumes were 4% lower than 2019 levels, and motorbike traffic volumes were 9% lower than 2019 levels. Caravan traffic was 20% higher than 2019 traffic levels, sustaining the growth observed in 2021.

The monthly traffic volume index for January 2020 – May 2022 of traffic volumes for cars, caravans, and motorbikes on Irish roads compared to 2019 is shown in Figure 34.

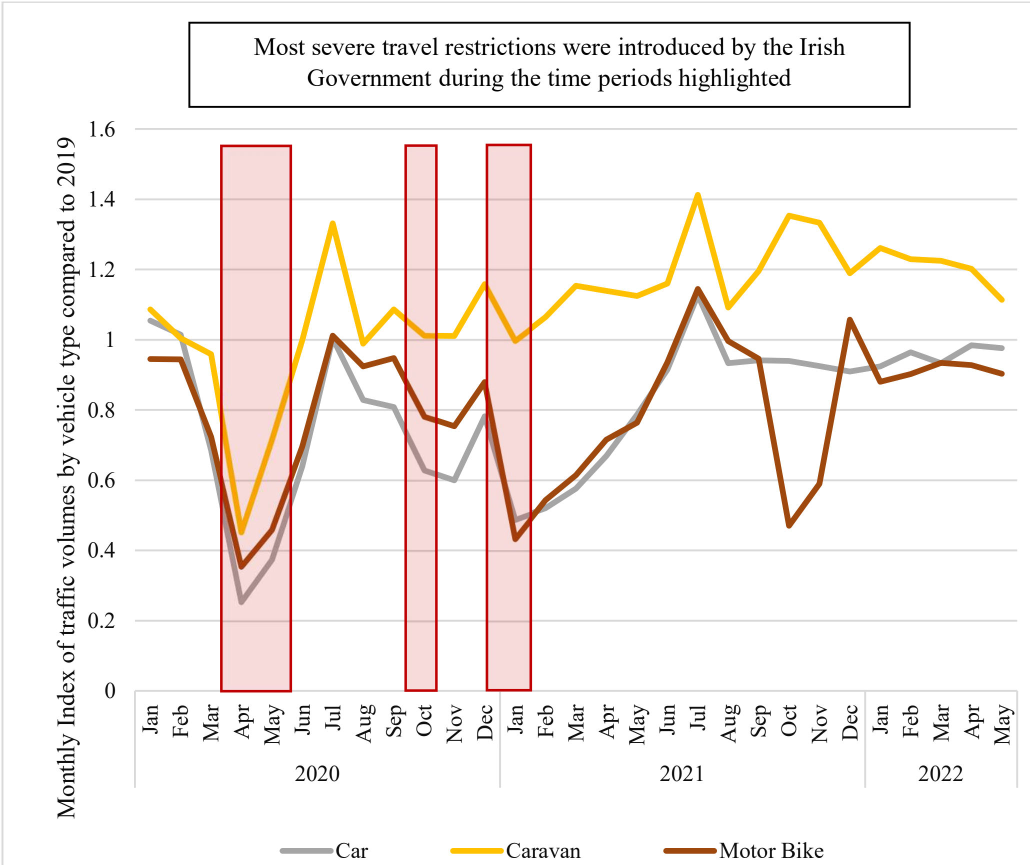

Figure 34: Monthly Index of traffic volumes by vehicle type compared to 2019

Bicycle counter data from Dublin City Council shows that on average, bicycle count numbers across the 6 sites, has been increasing beyond 2019 values in 2022. Bicycle count numbers dropped below 2019 levels during the COVID-19 related travel restrictions.

The monthly passenger numbers for public transport, and bicycle counter data were indexed to monthly figures for 2019 and are shown in Figure 35.

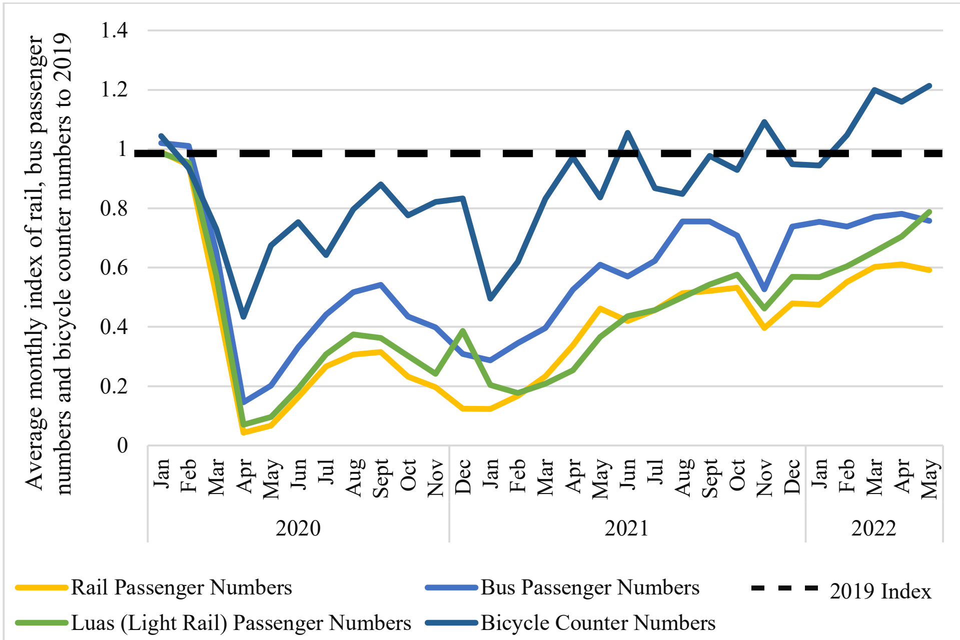

Figure 35: Average monthly index of bicycle counts in Dublin City indexed to 2019

The bicycle counter data used to inform the indexes in included in the Appendices (Appendix F.A). Total passenger numbers for bus, rail, and light rail transport over the period of January 2019 – May 2022 are included in the appendixes (Appendix F.B). The traffic activity indexes were aggregated on an annual basis, and 2022 figures are based on performance from January – May 2022.

Irish rail passenger numbers reduced by 64% in 2020. Rail, DART (Dublin Area Rapid Transit) and Luas passenger numbers were like 2020, with passenger numbers again 64% lower than 2019 levels. For January to May 2022, the number of rail trips increased from 2021, but were yet to reach pre-pandemic levels, with 2022 passenger numbers from January to May 2022 being 43% lower than 2019 levels over the same period.

Bus passenger transport numbers decreased 48% below 2019 levels in 2020. There was little recovery for bus transport in 2021 (trips were 46% lower than in 2019). In 2022, bus transport increased, but trips were 24% lower than in 2019, thus bus transport in Ireland had been more resilient than rail to the pandemic-related behavioural change in travel in the post-restriction era.

A summary of the of annual Ierformance indicator by transpIode are included in Table 109.

Table 109: Summary of annual performance indicator by transport mode

Passenger transport mode	Performance indicator description	2020	2021	2022
Private car	Percent reduction of traffic volumes with respect to 2019	-29%	-19%	-4%
Bus	Percent reduction of passenger numbers with respect to 2019	-48%	-46%	-24%
Rail/Dart/Luas	Percent reduction of passenger numbers with respect to 2019	-64%	-64%	-43%
Cycling	Percent reduction bicycle counter volumes with respect to 2019	-27%	-27%	-18%
Motorcycle/Other	Percent reduction of traffic volumes with respect to 2019	-23%	-22%	-9%
Caravan	Percent reduction of traffic volumes with respect to 2019	-3%	+19%	+20%

Passenger Kilometre Demand, Mode Shares, and CO_2 Emissions from Transport

The passenger kilometre demands for 2020, 2021 and 2022, were calculated based on Equations 24, 25, 26 as described in the Methodology section. The percentage of passenger kilometre demand met by each mode is described as the “mode share”. The mode share for private car increased from 82% in 2019 to 86% in 2022. The share of passenger transport met by rail, DART (intercity rail), or Luas (light rail) transport fell from 6% in 2019 to 3.7% in 2022. The mode share of bus passenger transport was also affected, falling from a 5.5% share in 2019, to a low of 2.8% in 2021, rebounding to a 4.6% share in 2022. The mode share of cycling transport also fell from 0.4% in 2019 to 0.2% in 2022. A summary of the passenger transport mode shares over the period of 2019 – 2022 is shown in Table 110: Passenger transport mode shares (2019 - 2022)(below).

Table 110: Passenger transport mode shares (2019 - 2022)

Passenger Transport mode shares (2019 – 2022)				
Mode type	Year			
	2019	2020	2021	2022
Private car	82.1%	85.5%	86.8%	85.5%
Bus	5.5%	4.2%	3.9%	4.6%
Rail/Dart/Luas	6.0%	3.2%	2.8%	3.7%
Cycling	0.4%	0.2%	0.2%	0.2%
Motorcycle/Other	5.1%	5.7%	5.2%	5.0%
Walking	0.5%	0.7%	0.6%	0.5%

The passenger kilometre demands for both the “COVID-19” passenger transport an” the “No COVID-19" reference were combined with technology stock data from the Irish Car Stock model, the Irish Passenger Transport Emissions and Mobility (IPTEM) model, and fuel carbon intensity data from the Technology and Environment database (TED) in LEAP (Heaps, 2022), to calculate the carbon dioxide emissions from passenger transport. LEAP enables scenario comparison. It provides an overview of the total CO_2 emissions for 2018 – 2022 in the COVID-19 passenger transport scenario, which models what happened in real-time with traffic counter, bicycle counter, and public transport passenger numbers and the changes in annual CO_2 emissions coming from that. It also provides a view at what could have happened in a “No COVID-19” counterfactual scenario case. These results from the LEAP Ireland model scenarios are shown in Table 111 (below).

Table 111: Overview of net differences in CO_2 emissions between COVID-19 and Passenger Trans“ort scenari” and "No COVID-19" counterfactual scenario

	2018	2019	2020	2021	Jan-May 2022	Total
	$MtCO_2$					
COVID 19	6.7	6.5	4.5	5.0	5.9	
No COVID-19 Reference	6.7	6.5	6.6	6.6	6.5	
Net CO_2 emissions saving	-	-	2.1	1.5	0.6	**4.2**

The greatest reductions in emissions were from private car transport, followed by rail, bus, and taxi transport. As active modes of travel are emission free, changes in the activity levels in these modes of transport on their own does not change emissions from the sector, however modal shift from carbon emitting modes of transport to active modes of travel like walking and cycling would cause a reduction in activity and emissions from other modes of transport over the same period. The net reductions in carbon dioxide emissions by year and mode share is highlighted in Figure 36.

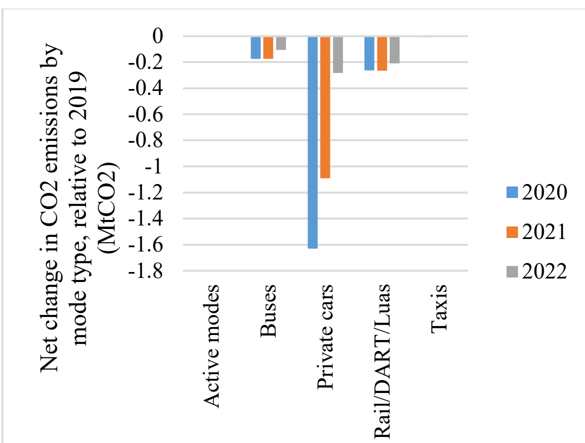

Figure 36: Net change in CO_2 emissions by mode type and year, relative to 2019 ($MtCO_2$)

Based on the changes in a) passenger kilometre demand, and b) mode shares of passenger transport, it is possible to determine which modes were most affected by travel restrictions in Ireland in both the initial stages and the aftermath. An overview of the modes most impacted by the initial lockdown (based on the monthly reductions in traffic counts and passenger numbers) and the modes that have most rebounded or exceeded pre-pandemic traffic or passenger levels by 2022 is shown in Figure 37.

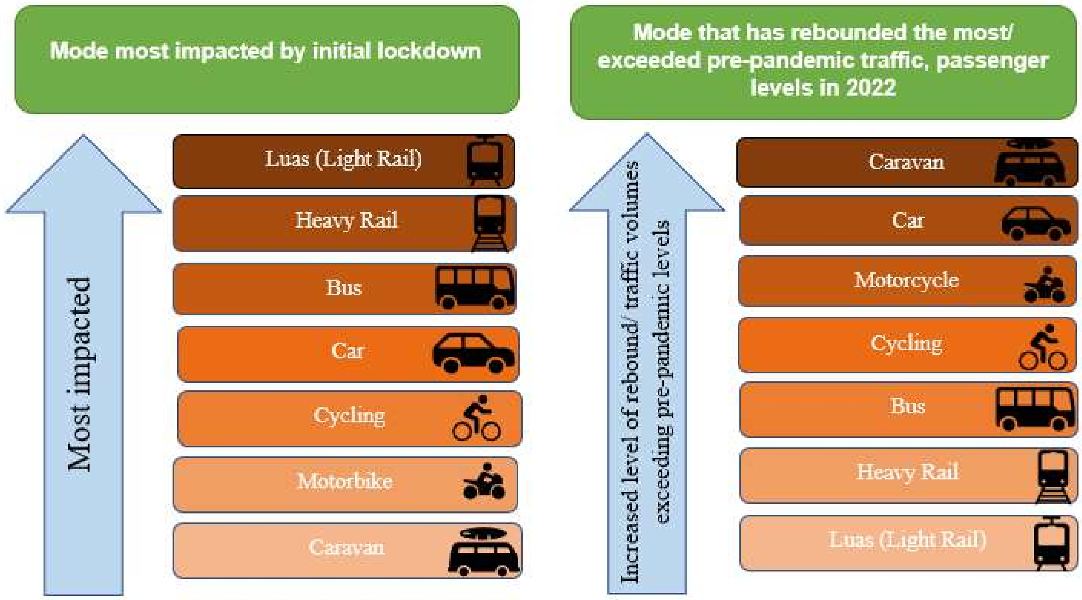

Figure 37: Modes most impacted by initial lockdown (left) and modes that have rebounded the most/exceeded pre pandemic traffic or passenger levels in 2022 (right)

Discussion

Uncertainty

This study used traffic counter data to estimate traffic volumes. However, this data should be used with caution and should be updated when concrete fuel sales data and car odometer reading data become available. Gensheimer et al. examined the inconsistencies with applying traffic counter data and satellite-based tracking devices to national and regional emissions and overall mobility models. Based on studies of several cities, there was a moderate range of error depending on the data source used, noting errors of up to 60% when using these data sets, and recommended a cautious approach when using these data sets (Gensheimer et al., 2021). In the short term, they can be helpful indicators of the general direction of traffic patterns and driving behaviour, but subsequent updates to the "pandemic restrictions" scenario will be required to give a better representation based on fuel consumption and car odometer data from the period being studied.

Bus and rail passenger numbers were based on information gathered from ticketed sales, and transit card swipes from public transit providers. In the received data sets from Transport Infrastructure Ireland, there are null entries for time periods of data loss and estimates for these entries were based on the average values from the preceding and following data entries. These estimated values are highlighted in the Supplementary Information (Appendix F). The bus and rail passenger numbers are aggregated on a month-by-month basis for the purposes of the index calculation The aggregated values are included in Appendix F.B. When calculating the changes in passenger kilometre demand for rail and bus from passenger numbers, journey distances were not captured in the data and thus are not factored into changes passenger journeys for public transport. Future work could benefit from information on the journey distances completed by each of the passengers onboard.

Information for traffic counter, passenger rail and bus information were available up to May 2022. Estimates for 2022 are based on figures from the January to May period of 2022. As more information becomes available, the methods developed in this study can be used to monitor passenger transport mode shares for the rest of 2022 and beyond.

Missing entries and null values are also evident in the raw data from the bicycle counters. During the pandemic additional bicycle counters were added, but as they did not have a 2019 data set to reference to monitor traffic changes, they were not used. As with bus and rail passenger numbers, averages of the neighbouring months for traffic counts, to balance out seasonal fluxes, were used to estimate values of missing entries. Estimated entries are highlighted in the supplementary information. Another source of uncertainty is that the bicycle counters only from Dublin City Centre, and they may only be representative of some of the country.

The EPA provides annual emissions inventories from the transport sector which are compared against the emissions calculations from the LEAP model. The SEAI provides annual accounts of energy consumption based on fuel use by each sector and thus develops emissions inventories for all sectors, including the passenger transport sector. A comparison of the estimates provided by the SEAI and the EPA and the results from this study are provided below (Table 112).

Table 112: Emissions for private transport sector comparison between SEAI, EPA, and LEAP "COVID-19" passenger transport sector

Total Fuel Consumption (TFC) ktoe					
	SEAI Sub-sectors	LEAP Sub-sectors	SEAI	LEAP	% Difference
2019	Road Private Car	Private Transport\Road Private Cars	2,080	2,007	-3%
2019	Public Passenger Services	Private Transport\Buses + Rail	183	198	8%
2020	Road Private Car	Private Transport\Road Private Cars	1,528	1,398	-8%
2020	Public Passenger Services	Private Transport\Buses + Passenger Rail	154	88	-43%
2021	Road Private Car	Private Transport\Road Private Cars	1,794	1,564	-13%
2021	Public Passenger Services	Private Transport\Buses + Rail	152	90	-41%
Total CO_2 Emissions ($ktCO_2$)					
Year	EPA Sub-sectors	LEAP Sub-sectors	EPA	LEAP	% Difference
2019	Road transportation	Road Freight + Fuel Tourism (Diesel) + Fuel Tourism (Petrol) + Buses + Road Private Cars + Taxis + unspecified petrol, diesel	11,509	11,236.2	-2%
2019	Railways	Rail Freight + Passenger Rail	122	233.6	91%
2020	Road transportation	Road Freight + Fuel Tourism (Diesel) + Fuel Tourism (Petrol) + Buses + Road Private Cars + Taxis + unspecified petrol, diesel	9,593	8,793.3	-8%
2020	Railways	Rail Freight + Passenger Rail	97	86.5	-11%
2021	Road transportation	Road Freight + Fuel Tourism (Diesel) + Fuel Tourism (Petrol) + Buses + Road Private Cars + Taxis + unspecified petrol, diesel	10,194	9,559.7	-6%
2021	Railways	Rail Freight + Passenger Rail	105	86.2	-18%

Future Implications and Policy insights

The passenger transport sector shows strong signs of recovery based on the traffic volume rebound that occurred in the second half of 2021, following the end of travel restrictions as shown in Figure 33. Once travel restrictions were ended in Ireland, the traffic volumes quickly reverted to levels closer to 2019.

While there were widespread reports of increased bicycle sales (Brooks et al., 2020), and much attention drawn in other regions to the emergence of cycling transport as an alternative transport mode, the bicycle counter data shows that counts of bicycles past those particular sites did not increase overall during the pandemic.

The Luas transport system typically has high occupancy rates compared to bus transport (O'Riordan, Rogan, Ó Gallachóir, Mac Uidhir, et al., 2022b), with passengers standing as typical for light rail transport. This could explain the rapid decline in passenger transport number seen during the travel restriction period of the COVID-19 pandemic, as social distancing aboard light rail was not possible, so people switched to other modes of transport. Given that the 2020 - 2022 passenger transport savings are accounted to be 4.2 MtCO_2, this reduction due to COVID-19 travel restrictions can help contribute towards the legally binding carbon budget sectoral ceilings under the Climate Action Bill 2021 (Government of Ireland, 2021a). However, it only serves as a short-term strategy for what needs to be a carefully managed long-term GHG reduction plan consistent with carbon budgets. As mentioned in the introduction, Forster et al. noted that while the emissions reductions during the restriction era of COVID-19 would have little impact over an extended period of 50+ years. There needs to be a focus on continued interventions to reduce GHG emissions on a global scale to a similar extent met during the initial stages of the COVID-19 pandemic.

Monitoring the impact of COVID-19 travel restrictions on emissions informs future planning for Ireland's legally binding carbon budgets.

Overall CO_2 emissions fell during the pandemic because of travel restrictions, with this activity effect resulting in CO_2 reductions of 2.1, 1.5 and 0.6 MtCO_2 in 2020, 2021 and 2022 respectively. The passenger transport emissions reductions have helped contribute approximately a 2.1 MtCO_2 reduction (accounting for 2021 and 2022 only) towards meeting Ireland's legally binding Sectoral Emissions Ceiling for the transport sector, for the first carbon budget period which is defined as having a total of a 54 $MtCO_2$ emissions limit from the transport sector overall from the period of 2021 – 2025 (inclusive).

In this study, I found that car, caravan, and motorbike traffic volumes reduced significantly during the initial stages of the pandemic but have returned to pre-pandemic levels. The mode share of car transport has increased from 82.1 % of passenger kilometres travelled in 2019 to 85.5% of passenger kilometres travelled in 2022. Passenger numbers from bus transport experienced a reduction of 48% in 2020. While the mode share of passenger kilometres met by bus transport is trending back towards a return to pre-pandemic levels, over the period January to May 2022, the share of Irish passenger kilometres met by bus transport mode share was 4.6% during January – May 2022 - still below the level in 2019 (5.5%). The share of passenger kilometres serviced by heavy and light rail decreased more than bus travel over the pandemic period and is also not back to the pre-pandemic mode share of passenger kilometres. COVID-19 appears to have set back progress in this respect as cycling rates are lower than pre-pandemic levels at the five sites monitored, and public transport passenger numbers are still lower than pre-pandemic levels.

Ireland has stated policy goals to increase the number of trips completed by walking, cycling and public transport as part of its Climate Action Plan 2023. As increasing public transport, walking, and cycling is a stated goal of the Department of Transport, monitoring monthly fluctuations and tracking mode shares across all mode types is important to show whether Ireland is ‘on track’.

This study shows that the unprecedented changes in personal mobility brought about by travel restrictions and changes in work practices related to COVID-19 achieved significant and immediate reductions in transport emissions. This illustrates the potential for demand reduction as a key lever to complement vehicle electrification and biofuels, which have been the main mitigation levers planned to date for the sector. However, the reduction in car activity has not been sustained: Travel restrictions driven by public health concerns do not address the fundamental and structural drivers of traffic, which is dispersed settlement patters, low availability of public transport and low levels of active travel (Laverty et al., 2020). This indicates that car traffic volumes and associated emissions will continue to grow in 2022 beyond 2019 levels until the structural drivers of transport activity are addressed as a priority for climate mitigation. All these changes have led some authors to put forward the idea that the COVID-19 crisis may be an opportunity to change the transport choices through new proposals such as promoting responsible transport (Budd and Ison, 2020). This opportunity is slipping away.

Using the methods developed in this study, it is possible to monitor and model the situation into 2022 and continue to compare with the "No COVID-19" scenario. While work from home rates have increased, from 23% prior to the pandemic to 65% in November 2021 (Central Statistics Office, 2022a), the private transport demand has rebounded, this indicates that that the trip purposes driving our transport demand have changed also. Commuting was responsible for 30% of passenger transport emissions in 2019. Future work could investigate changes in travel times, trip purposes and trip distances following the "work-from-home" policies and widespread calls to encourage remote work and flexible working policies. Effects such as a rebound in activity with increased population, people making more non-commuting trips, or people making longer, less frequent, commuting trips to compensate for the reduced need for daily commuting may be possible explanations. Understanding the structural legacy of the pandemic on why we travel is an important area for future work and could be possible with future National Travel Surveys and updates to the Irish Passenger Transport Emissions and Mobility Model beyond 2019.

Conclusions

This study developed a methodology which combines traffic/bicycle counter data with bus and rail passenger numbers to inform passenger kilometre demand inputs. These inputs are used in an energy systems simulation model to calculate CO_2 emission reductions and changes in the private passenger transport sector during the COVID-19 pandemic. Performance indicators of road traffic volumes, bicycle counter data, and passenger transport numbers of informed calculations on mode shares, and emissions reductions when combined with LEAP Ireland and the Irish Passenger Transport Emissions and Mobility model. Overall travel has returned to pre-pandemic levels – therefore the activity effect was temporary – but the modal share of cars is higher. This will make meeting carbon budgets more challenging, as private car transport, with the prevalence of fossil fuel cars remaining in the fleet for years to come, is more carbon intensive than high occupancy public transport and zero carbon active travel alternatives. There was a net emissions reduction of 4.2 $MtCO_2$ from March 2020 – May 2022. While the COVID-19 travel restrictions have directly contributed a calculated 2.1 $MtCO_2$ savings over the 2021 – 2025 1st Carbon Budget period of 54 $MtCO_2$, activity levels have largely returned to pre-pandemic levels. The mode share of public transport, walking and cycling was reduced over this period. It will require the policy system to prioritise improving public transport provision urgently to meet transport sectoral emission ceiling goals as outlined by the Climate Action Plan 2023 (Government of Ireland, 2022b).

Acknowledgements

The authors would like to thank Transport Infrastructure Ireland, the National Transport Authority, and Dublin City Council for their help and for sharing valuable data that informed the findings in this study.

Appendix F: Supplementary Information for "Passenger Transport Demand, Mode Share, and CO_2 Emissions following COVID-19 Travel Restrictions: A Case Study of Ireland"

Appendix F.A: Luas (light rail) passenger numbers, January 2019 - May 2022

Year	Month	Luas passenger numbers
2019	Jan	3,378,507
2019	Feb	4,019,078
2019	Mar	3,985,084
2019	Apr	3,941,792
2019	May	3,807,002
2019	Jun	3,961,044
2019	Jul	3,869,484
2019	Aug	3,820,845
2019	Sep	4,170,972
2019	Oct	4,346,070
2019	Nov	4,468,849
2019	Dec	4,578,534
2020	Jan	3,335,564
2020	Feb	3,835,096
2020	Mar	2,290,562
2020	Apr	276,985
2020	May	368,123
2020	Jun	761,583
2020	Jul	1,193,301
2020	Aug	1,433,682
2020	Sep	1,512,397
2020	Oct	1,316,250
2020	Nov	1,081,853
2020	Dec	1,770,659
2021	Jan	692,327
2021	Feb	713,847
2021	Mar	830,291
2021	Apr	1,002,419

2021	May	1,393,207
2021	Jun	1,732,091
2021	Jul	1,769,090
2021	Aug	1,910,657
2021	Sep	2,268,357
2021	Oct	2,504,918
2021	Nov	2,063,407
2021	Dec	2,608,705
2022	Jan	1,918,976
2022	Feb	2,431,674
2022	Mar	2,609,085
2022	Apr	2,781,274
2022	May	3,000,994

Appendix F.B: Dublin Bus, Bus Éireann, and Private Bus passenger numbers (January 2019 - May 2022)

		Dublin Bus	Bus Eireann	Private Bus
2019	Jan	10,026,080	2,830,523	1,061,127
2019	Feb	11,712,034	3,217,032	1,229,585
2019	Mar	11,636,857	3,265,442	1,236,912
2019	Apr	11,832,166	3,264,615	1,238,358
2019	May	11,037,198	3,104,202	1,193,661
2019	Jun	11,099,948	3,121,493	1,222,496
2019	Jul	11,292,503	3,226,551	1,293,615
2019	Aug	10,863,761	3,153,894	1,277,797
2019	Sept	11,214,362	3,312,492	1,317,047
2019	Oct	12,299,820	3,707,788	1,470,211
2019	Nov	12,098,590	3,571,498	1,429,751
2019	Dec	12,433,460	3,572,889	1,436,948
2020	Jan	10,105,580	2,900,360	1,195,590
2020	Feb	11,707,745	3,268,032	1,354,039
2020	Mar	7,542,601	2,111,685	903,480
2020	Apr	1,657,077	491,401	231,257
2020	May	2,148,652	637,897	311,656
2020	Jun	3,552,097	1,059,535	507,259
2020	Jul	4,807,310	1,501,586	676,971
2020	Aug	5,422,054	1,731,282	750,734
2020	Sept	5,855,570	1,931,067	809,865
2020	Oct	5,264,393	1,620,660	729,934
2020	Nov	4,642,282	1,509,316	667,398
2020	Dec	6,214,709	1,900,967	842,688
2021	Jan	2,976,106	905,314	418,810
2021	Feb	3,200,403	986,452	463,561
2021	Mar	3,805,619	1,202,185	572,093
2021	Apr	4,375,743	1,423,117	666,762
2021	May	5,490,426	1,781,328	790,932
2021	Jun	6,375,318	2,148,203	894,821
2021	Jul	6,063,939	2,116,349	839,682
2021	Aug	6,491,761	2,174,573	872,363
2021	Sept	8,193,863	2,689,592	1,077,224
2021	Oct	9,163,284	2,874,351	1,162,744
2021	Nov	8,458,167	2,617,769	1,035,516
2021	Dec	6,428,352	2,005,493	755,421
2022	Jan	7,366,996	2,245,431	882,294
2022	Feb	8,602,519	2,373,023	970,887
2022	Mar	8,981,767	2,449,434	1,005,893
2022	Apr	9,243,592	2,504,496	1,026,540
2022	May	8,297,179	2,402,685	937,226

Appendix F.C: Bicycle counter data from Dublin City Council

Year	Month	Charleville Mall	Grand Canal Cycle	Grove Road Totem	Guild Street	North Strand Rd N/B	North Strand Rd S/B
2019	Jan	3,328	194,504	95,612	34,092	37,746	32,142
2019	Feb	3,335		92,653	33,052	37,813	31,341
2019	Ma	3,931	195,875	95,818	34,589	38,257	32,064
2019	Apr	4,142	200,022	95,915	34,844	40,093	34,413
2019	May	5,043	236,817	111,071	39,538	47,862	38,992
2019	Jun	4,847	213,974	88,015	38,620	42,446	37,991
2019	Jul	5,768	246,220	108,362	46,975	51,724	47,278
2019	Aug	5,170	204,592	103,512	42,185	45,457	41,652
2019	Sep	5,266	167,519	110,503	43,284	48,113	41,448
2019	Oct	4,888	208,289	111,545	43,576	45,241	38,862
2019	Nov	3,670	186,616	101,418	38,343	38,313	31,708
2019	Dec	2,892	148,342	75,876	28,617	29,990	24,178
2020	Jan	3,537	189,821	98,939	38,721	39,386	32,632
2020	Feb	3,116	178,293	88,749	34,761	32,389	27,503
2020	Ma	2,853	146,921	66,832	25,949	27,607	23,709
2020	Apr	2,388	98,974	39,845	12,227	15,017	13,530
2020	May	4,520	140,990	67,785	24,193	30,937	27,014
2020	Jun	4,071	125,381	69,891	27,506	33,194	30,517
2020	Jul	4,132	119,027	73,682	30,799	34,011	31,373
2020	Aug	6,269	111,171	69,749	36,262	34,391	30,540
2020	Sep	7,020	132,290	79,012	39,852	36,956	31,408
2020	Oct	6,116	126,243	69,529	36,867	31,089	25,212

2020	Nov	5,195	115,150	62,815	33,714	27,602	21,494
2020	Dec	3,910	77,405	55,491	25,796	23,035	17,528
2021	Jan	3,213	32,888	40,383	20,704	16,810	11,651
2021	Feb	3,529	4,484	43,922	22,045	17,993	13,461
2021	Ma	5,839	96,554	64,152	33,298	27,149	21,640
2021	Apr	6,757	157,500	71,712	38,299	31,921	26,512
2021	May	7,515	142,849	72,284	38,442	30,631	25,750
2021	Jun	8,874	145,682	82,647	44,372	36,884	32,552
2021	Jul	9,241	136,171	80,134	43,648	36,361	32,065
2021	Aug	8,281	110,205	70,713	38,788	31,149	27,600
2021	Sep	9,494	123,668	82,314	45,747	36,554	31,706
2021	Oct	8,965	128,535	77,352	42,210	32,812	28,754
2021	Nov	8,734	128,141	77,798	42,053	30,430	26,149
2021	Dec	5,958	78,150	53,258	26,909	21,412	18,170
2022	Jan	7,120	106,027	63,137	33,292	26,183	20,965
2022	Feb	7,592	103,798	62,339	32,966	24,268	20,298
2022	Mar	10,157	145,009	79,299	44,057	33,476	28,705
2022	Apr	10,027	144,145	77,133	45,199	34,070	29,645
2022	May	12,465	148,049	89,716	54,192	37,975	5,215
2022	Jun	12,660	151,482	86,731	53,010	37,068	
2022	Jul	12,769	156,256	88,379	54,856	34,012	
2022	Aug	1,277	14,316	7,963	5,094	-	

Appendix F.D: Passenger Kilometre demand for Ireland by mode (2019 - 2022)

Mode Type	**Year**			
	2019	2020	2021	2022
	Passenger Kilometres (Pkm)			

Private car - Driver	43,130,427,324	30,622,603,400	34,935,646,133	41,405,210,231
Private car - Passenger	10,792,465,210	7,662,650,299	8,741,896,820	10,360,766,602
Private car	53,922,892,534	38,285,253,699	43,677,542,953	51,765,976,833
Walk	303,409,409	303,409,409	303,409,409	303,409,409
Bus	3,642,740,747	1,894,225,188	1,967,080,003	2,768,482,968
Cycle	233,080,616	83,909,022	83,909,022	132,855,951
Rail/Dart/Luas	3,948,009,846	1,421,283,545	1,421,283,545	2,250,365,612
Taxi/hackney	302,040,793	214,448,963	244,653,042	289,959,161
Lorry/Motorcycle/ Other	3,335,786,464	2,568,555,578	2,601,913,442	3,035,565,683
Total	65,687,960,410	44,771,085,403	50,299,791,416	60,546,615,617