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How and Why We Travel – Mobility Demand and Emissions from Passenger Transport

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Working Paper

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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 paper 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 paper quantifies energy consumption and emissions intensities, and for the first time for Ireland, passenger transport occupancy rates. The findings quantify missed targets in walking and cycling uptake rates. Light rail has the lowest CO2 emissions per passenger kilometres among motorized modes. In 2019, travel for work purposes contributes the greatest to overall passenger transport demand (30%) followed by shopping (19%) and companion journeys (16%). Journeys under 8 kilometres were responsible for 37% of passenger transport emissions.

Keywords

Transport emissions modelling, CO2 emissions, energy systems modelling, occupancy, public transport, walking, cycling

Highlights

- Method of calculating passenger transport demand and CO2 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., 2021b)

1. Introduction
1.1 Global context

Globally, the transport sector is responsible for 23% of total energy-related CO2 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 study, the authors develop a spreadsheet model linking passenger kilometre demand by mode type, trip purpose and trip distance with CO2 emissions. This allows readers to draw greater insights of the contributions of transport mode type, trip purpose and occupancy has on passenger transport CO2 emissions.

2 Literature Review
2.1 Global Context

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 optimization 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).

2.2. 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, 2019). 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. We 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, Fulton and Staub, 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 CO2 emissions for 22 world regions/countries together forming the world (Fulton, Cazzola and Cuenot, 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 paper looked at final energy and CO2 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, Usher and Strachan, 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 a 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 optimization 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 and 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 CO2 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.

2.3 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 CO2 emissions intensity and a reduction in annual tax revenue of €191 million (Giblin and McNabola, 2009). Other ex-ante studies of the car tax change included a total life-cycle cost model (Hennessy and Tol, 2011). This ex-ante analysis anticipated that the cost of carbon dioxide emissions abatement per tonne would be “high, if not very high,” with a recent ten-year ex-post analysis of the 2008 car tax reporting that the average cost of abatement over the period of 2008 to 2018 was €684 per tonne of CO2 [In submission]. 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 gCO2/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, Rogan and Gallachóir, 2017), and factors influencing EV uptake (Mukherjee and 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 and 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.

2.4. *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 paper is structured as follows; section 2 covers the methods and data sources used to develop the IPTEM model, section 3 covered the results, Section 4 covers the uncertainties, implications and use cases for the results, section 5 discusses the results, and section 6 covers concluding remarks on the relevance and novelty of the IPTEM model.

3 *Methods and data*

In response to the growing need for a comprehensive look at how and why we travel, this paper 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 et al., 2021a) 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 paper 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 CO2 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 incorporates 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 1 (below).

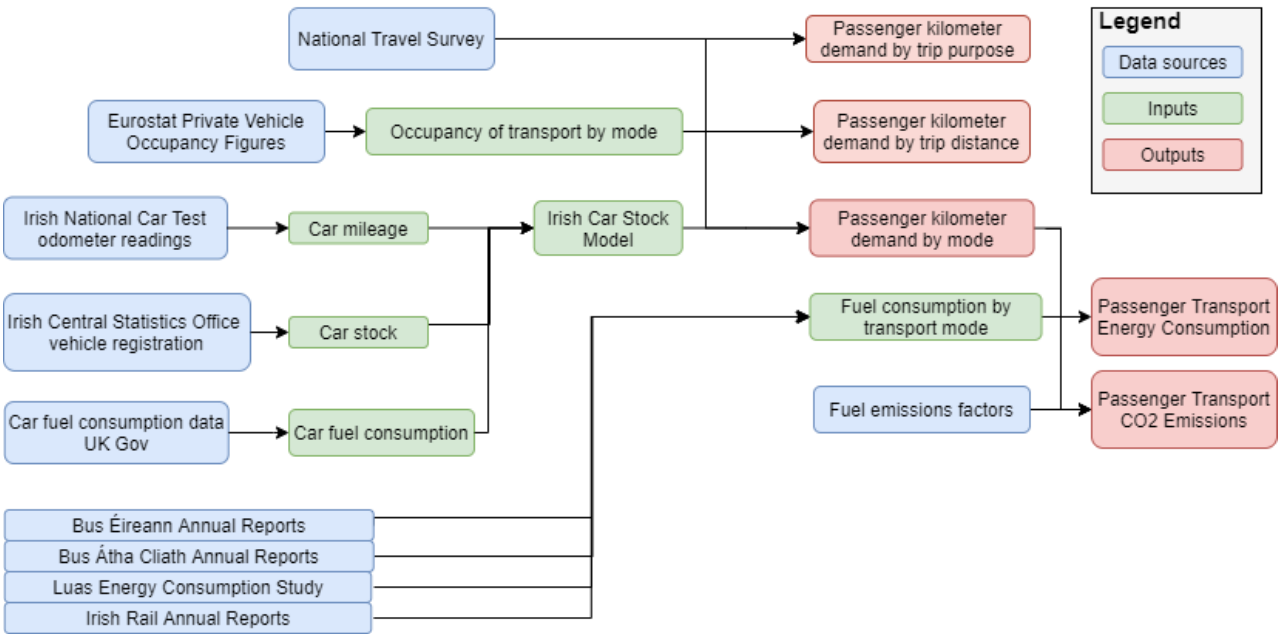

Figure 1: Overview of the Irish Passenger Transport Emissions and Mobility (IPTEM) Model

3.1. 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 (Daly and Ó Gallachóir, 2011a). The model used in this paper is a technology stock simulation model, which relies on revealed preferences of car choice. This was selected over a cost optimization 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 optimization 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. An overview of the private car transport model is provided in Figure 1 (below), which includes the relationship between the inputs (left), 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 Irish Car Stock model is available on Zenodo (O'Riordan et al., 2021a). An overview of the Irish Car Stock Model is highlighted in Figure 2 (below).

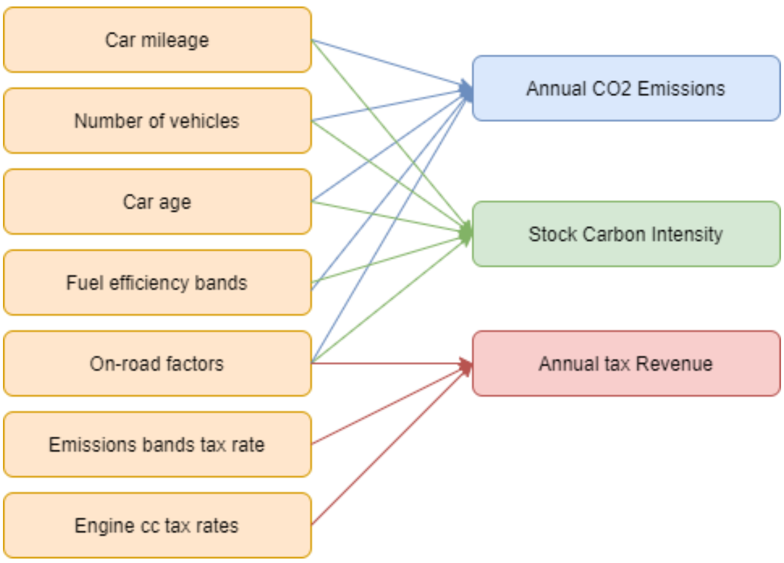

Figure 2: Overview of the Irish Car Stock Model

For the IPTEM Model, the total vehicle kilometres travelled by private cars is used (see Fig. 2). The total vehicle kilometres (Vkm) travelled by the private car fleet is calculated from the Irish Car Stock Model as described in Equation 1.

$$Vkm = Number\ of\ vehicles_{f,v,e} \times Average\ odometer\ reading\ (km)_{f,v,e} \quad (1)$$

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 complimenting this paper.

3.2. 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.

3.3. 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 Passenger kilometres by trip distance

The passenger kilometres (Pkm) are calculated as shown in Equation 2.

$$Pkm = Vkm \times Occupancy \quad (2)$$

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-kilometer category was calculated through calibration with the Irish Car Stock Model.

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.

3.5 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 1.):

Table 1: 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 3 (below). 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.

$$Weighting\ factor_{mode,year} = \frac{Average\ distance\ of\ all\ journeys_{mode,year}}{Average\ distance\ for\ private\ car - driver_{year}} \quad (3)$$

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 3, 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 3 are included in the Data in Brief complimenting this paper.

3.6 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 3 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.

3.7 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 4.

$$Share\ of\ Bus\ Pkm_{bus\ provider} = \frac{No.\ of\ Passengers_{bus\ provider} \times Vkm_{bus\ provider}}{\sum_{i=1}^{n} No.\ of\ Passengers \times Vkm} \quad (4)$$

Occupancy for the bus transport providers is derived from the passenger kilometres and vehicle kilometres, as illustrated earlier in Equation 2 (above).

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 5.

$$Share\ of\ Rail\ Pkm_{rail\ provider} = \frac{Passengers\ serviced_{rail\ provider} \times Vkm_{rail\ provider}}{Passenger\ serviced \times Vkm} \quad (5)$$

Occupancy is calculated in the same method as described for bus travel in Equation 2. 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 6 (below).

$$Capacity\ Factor = \frac{Total\ Vehicle\ Kilometres}{Vehicle\ Seat\ Kilometres} \times 100 \qquad (6)$$

3.8. 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 7:

$$\text{Energy Intensity}\left(\frac{\text{kWh}}{\text{pkm}}\right) = \frac{Energy\ intensity\ per\ kWh_{f,t} \times Energy\ consumption\ per\ year_{f,t}}{Pkm_t} \qquad (7)$$

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 8:

$$\text{Carbon Intensity}\left(\frac{\text{gCO2}}{\text{pkm}}\right) = \frac{Carbon\ intensity\ per\ kWh_{f,t} \times Energy\ consumption\ per\ year_{f,t}}{Pkm_t} \qquad (8)$$

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 et al., 2021a). 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 and Ó Gallachóir, 2013), (Dineen, Ryan and Ó Gallachóir, 2018).

4 Results

4.1. Passenger kilometres by trip distance, mode type and trip purpose

Passenger kilometres by trip distance, mode type and trip purpose are shown in Figure 3. (below). 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.

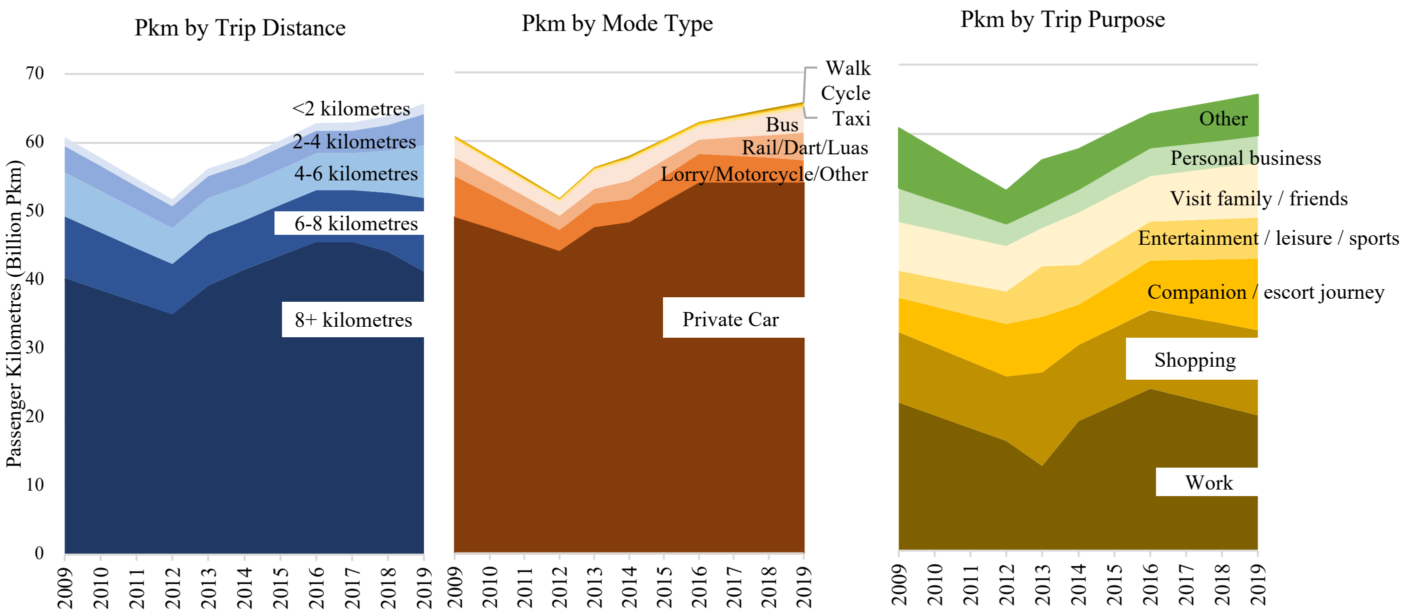

Figure 2: Passenger Kilometres by trip distance, mode type and trip purpose

Tabulated data can be found in the Data in Brief complementing this paper, and calculations are available from the open-source repository of the IPTEM model on Zenodo (O'Riordan et al., 2021b).

4.2. Occupancy, energy consumption and carbon intensity of passenger transport

The average occupancy of each of the public transport mode types is highlighted in Table 2. 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 5 in the Methods section.

Table 2: 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 4. The capacity factor for private cars is based on a 1.5 persons occupancy based on figures from Eurostat is included for illustrative purposes. 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, 2021) and is included for illustrative purposes.

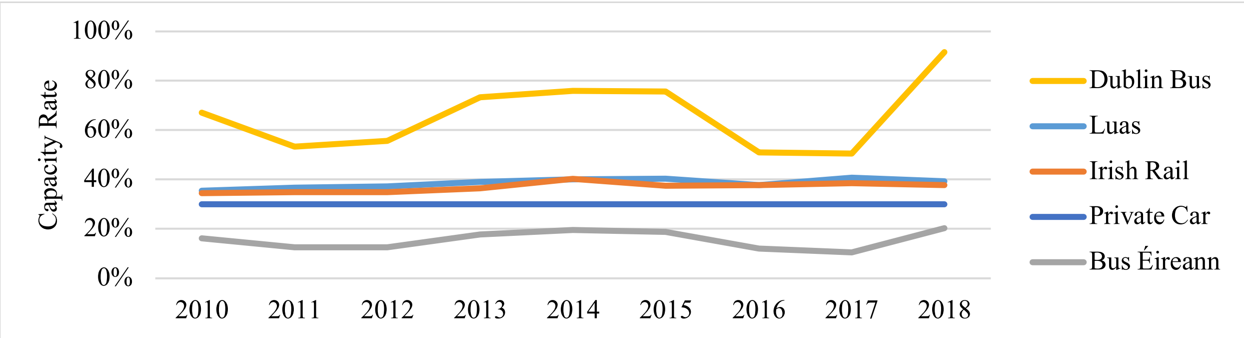

Figure 3: Capacity rates by transport mode

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.

4.3. 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 5.

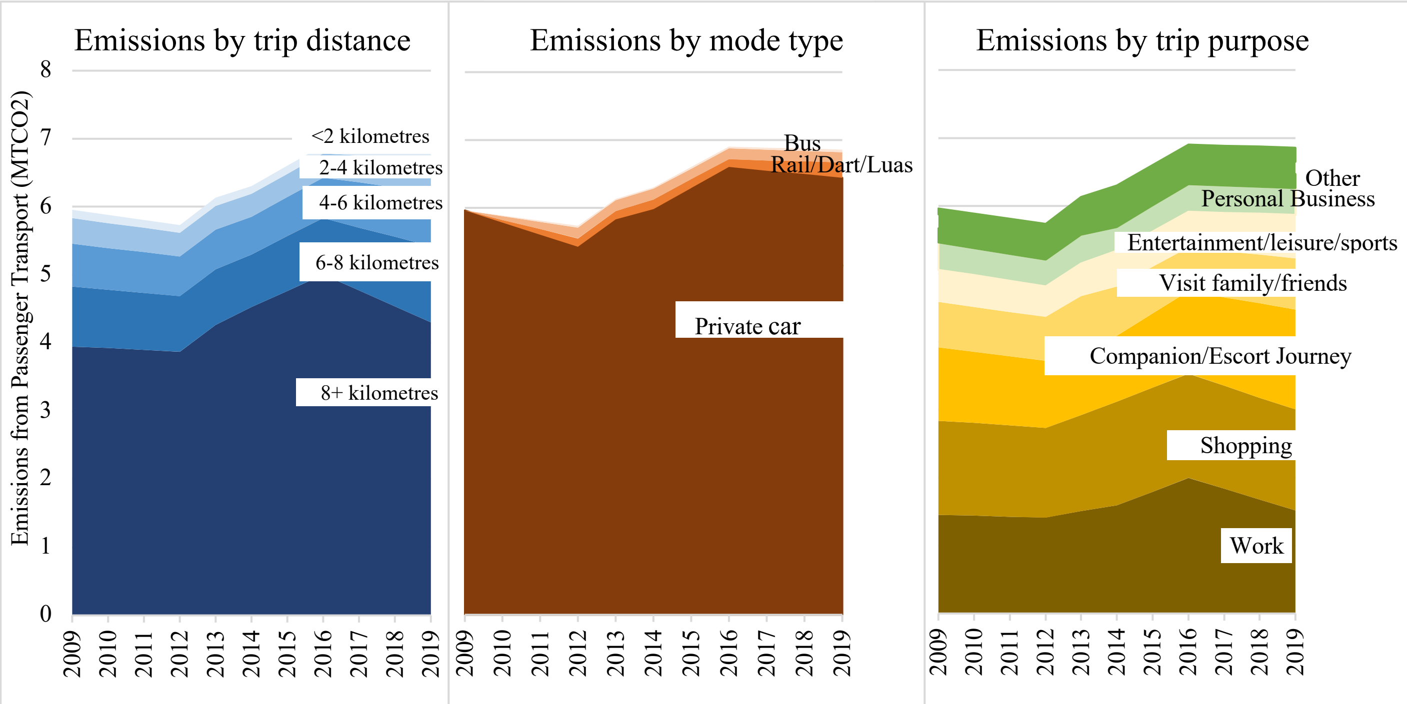

Figure 5: Carbon Dioxide Emissions from Passenger Transport by trip distance, mode type and trip purpose[1]

Emissions intensity by mode type and trip purpose category is shown in Figure 6 (below). This provides an insight into the grams of carbon dioxide (gCO2) per passenger kilometre (pkm) serviced over the period of 2009 – 2019.

[1] Emissions for the "Lorry/Motorcycle/Other" category are not included in this section due to a mixing of the technology types in this category and an uncertain emissions intensity per passenger kilometre as a result

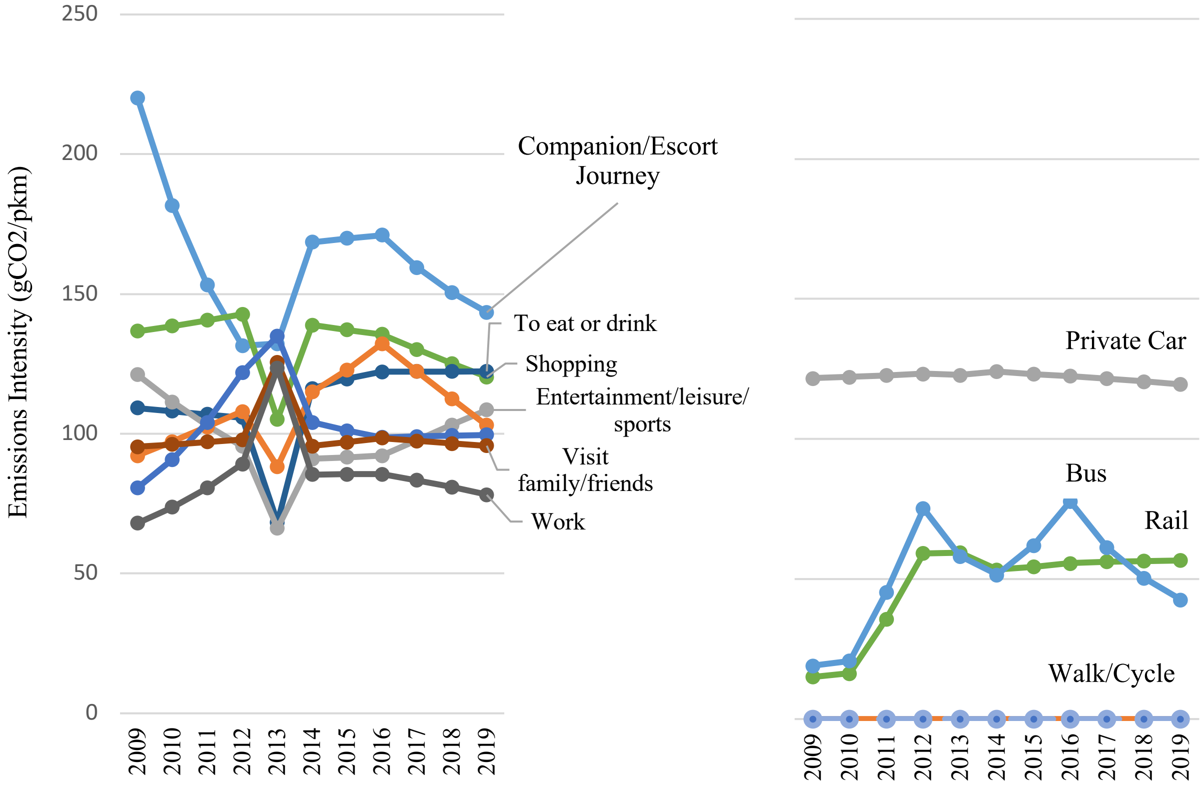

Figure 4: Emissions Intensity by trip purpose and mode type (gCO2/pkm)

Emissions intensity by trip purpose notes that trips for companion/escort journeys are among the highest. Lower occupancy is responsible for the high emissions across all sectors. While emissions by mode type are lower on average, higher occupancies skew on a trip-purpose basis. Walking and cycling rates are extremely low (~1%, Figure 5), and the use of private car transport is widespread. Occupancy rates for companion/escort journeys may also be lower. Private car emissions decrease gradually towards 2019, however they have a marginal impact on emission by trip purpose. 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.

A breakdown of trip purpose and mode type from total passenger kilometres is shown in Figure 7 (below) based on values from 2019.

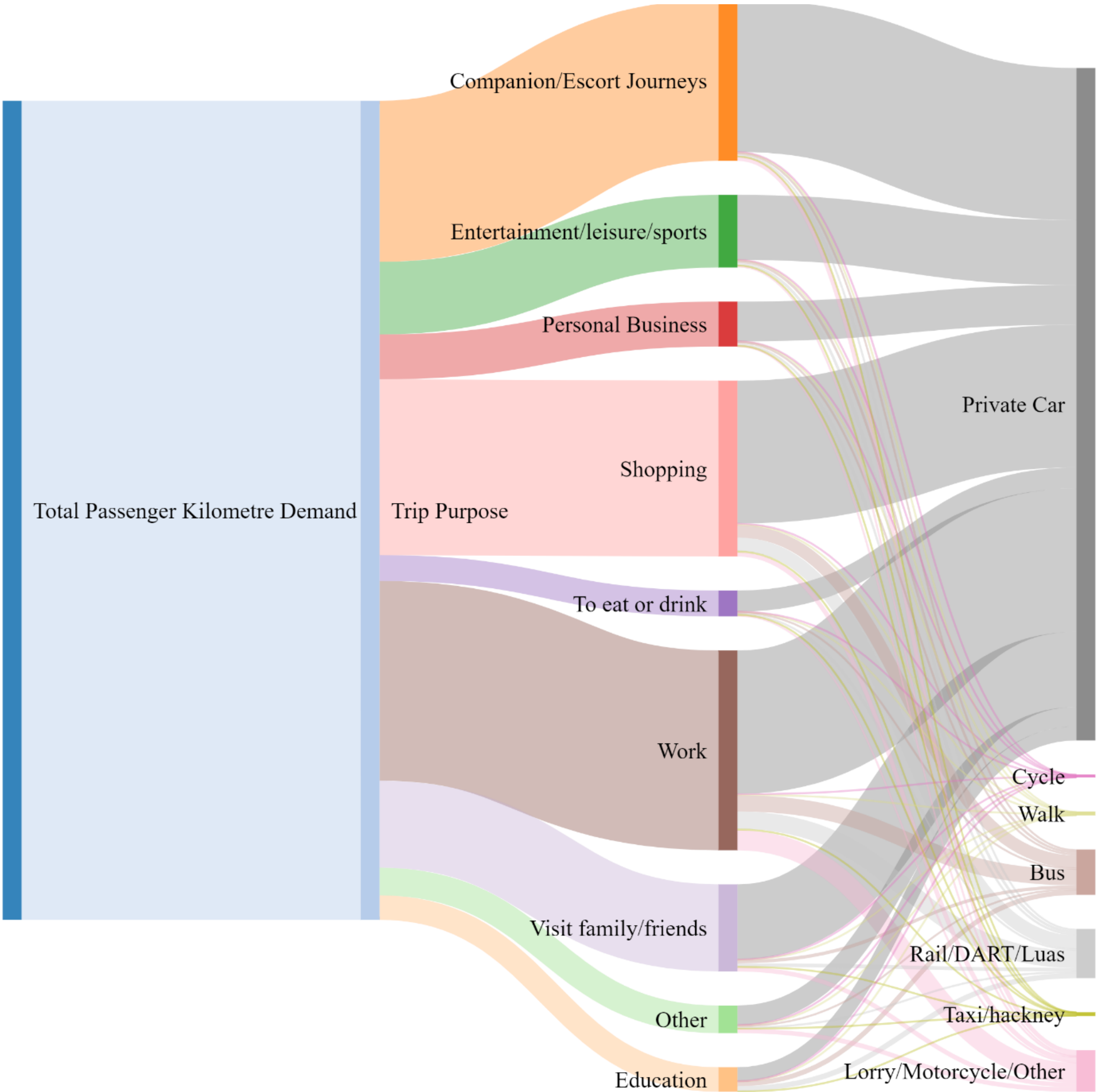

Figure 5: Breakdown of Passenger Kilometre trip purpose and mode type for 2019

For illustrative purposes, a comparison of passenger kilometre demand and emissions for 2012 with 2019 is made by trip distance, trip purpose and mode type. In Figure 6, the absolute values are compared, whereas in Table 3, 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 3 illustrates this.

Table 3: 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 4: 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 4 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 3). This indicates an increase in efficiency from bus transport. We know from Fig. 4 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 has 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.

5 Discussion

5.1. Uncertainty

Slight discrepancies occur due to the percentages not adding up to 100% for responses from the National Travel Survey. 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 and 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 of 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, 2021). 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 2. 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 on car transport in Ireland is explored within the Irish Car Stock Model (Daly and Ó Gallachóir, 2011a; b; O'Riordan et al., 2021a).

5.2. Key Insights

This paper calculates for the first time, passenger transport demand and carbon dioxide emissions by mode type, trip purpose and trip distance. 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, Rogan and Gallachóir, 2020), 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). We now know from the IPTEM model that these targets were not achieved as Figure 3 quantifies the proportion of cycling of passenger kilometres to be ~1%.

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 and 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 land public 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, 2021).

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, 2021). 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 3) and emissions (Figure 5) 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. 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. 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. 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 3.

Capacity rates are also quantified. Figure 4, 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 5 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 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 4, 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 paper can usefully inform research on what public transport people use and where the opportunities for increased capacity lie. Initial findings from this paper 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 7, where private car transport is responsible for greater than four out of five passenger kilometres driven 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, and companion/escort journeys were the most popular characteristics of passenger transport demand.

From Table 3, 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 4, 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 3 and Table 4 are developed with a reference to the 2012 year, and thus develop narratives with respect to the year 2012. For example, while Table 3 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, 2016).

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. We 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 4.1, in the uncertainty section. Empirical data gaps for passenger transport occupancy, and the unprecedented COVID-19 pandemic and its impact on transport behaviour will no doubt be a confounding factor in future passenger transport modelling calculations. COVID-19 resulted in an unprecedented reduction in passenger transport due to the national travel restrictions. This has been the subject of discussion for several studies. 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 [COVID 19 and Passenger Transport - In Submission]. 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.

6 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.

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