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Evaluating transport decarbonisation policies under carbon budget constraints: The role of carbon pricing and ICE bans

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Evaluating Transport Decarbonisation Policies under Carbon Budget Constraints: The Role of Carbon Pricing and ICE Bans

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Abstract: This paper develops and applies I3E-Transport, a new passenger transport model for Ireland that integrates behavioural, technological, and macroeconomic drivers to assess the effectiveness of two decarbonisation policies—carbon taxation and internal combustion engine (ICE) phase-outs—on emissions from private cars and public transport by bus, rail, and light rail. The model is linked to the Ireland Environment–Energy–Economy (I3E) Computable General Equilibrium framework, allowing for a comprehensive evaluation of how policy measures affect transport demand, vehicle stock composition, energy consumption, and emissions within the constraints of Ireland's carbon budgets. Simulation results for 2024–2050 show that, under a business as usual baseline scenario, emissions are projected to increase steadily through 2040, driven by income and population growth. A modest decline follows between 2040 and 2050, reflecting gradual uptake of alternative vehicles and improvements in fuel efficiency. However, 2050 emissions are projected to still exceed current levels, indicating limited overall progress without further policy intervention. A carbon tax delivers only marginal abatement, while a comprehensive ICE vehicle ban from 2035—including hybrids—reduces CO_2 emissions by nearly six million tonnes relative to the baseline by 2050. Nevertheless, the sector remains off course for compliance with its 2030 abatement target and carbon budgets ceilings for 2031–2035 and 2036–2040, reaching them only in the late 2030s even under the most ambitious scenario. Earlier implementation and accelerated public transport electrification could advance compliance modestly but not fully bridge the gap. The findings highlight that timely and coordinated policy action—combining regulatory, fiscal, and behavioural instruments—is essential to align Ireland's transport sector with its long-term climate commitments.

Keywords: Transport decarbonisation; ICE bans; Carbon taxation; Passenger transport modelling; Vehicle stock; Electric vehicles; Carbon budgets; Ireland

JEL codes: Q54, Q58, R41, R48, C63

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Introduction

Transport is the largest energy-consuming sector in Ireland, accounting for 37.6% of national greenhouse gas (GHG) emissions in 2023—well above the EU average and second only to agriculture (SEAI, 2024). Although total emissions have declined in recent years, transport emissions have continued to rise, placing Ireland at risk of exceeding its sectoral carbon budgets and undermining the government's long-term target of reducing total emissions by 51% by 2030 (relative to 2018) and achieving carbon neutrality by 2050 (Department of the Taoiseach, 2025). Projections from the Environmental Protection Agency (2023) indicate that, under current trajectories, Ireland's emissions will fall by only 29% by 2030—well short of the 51% target. Furthermore, Ireland's EU commitments under the Effort Sharing Regulation (ESR) requires a reduction in GHG emissions of at least 42% by 2030 for non-ETS sectors including transport. Non-compliance with EU targets is expected to carry substantial fiscal penalties, estimated at €3.5 billion by 2030 and approximately €0.7 billion annually thereafter (Casey & Carroll, 2023). Decarbonising transport is therefore critical not only to meeting Ireland's domestic and EU obligations but also to contributing to the Paris Agreement objective of limiting global warming to well below 2°C above pre-industrial levels.

The challenge of decarbonising transport is compounded by structural characteristics of the sector. Transport demand is closely linked to economic and demographic growth, making sustained reductions in emissions difficult to achieve as both drivers tend to increase travel demand (IEA, 2023; Pietzcker et al., 2014). A range of policy instruments have been implemented to curb transport demand and emissions, including carbon pricing, technology mandates, and behavioural and spatial planning measures. Yet reducing transport emissions on the scale required demands a coherent policy mix and transformative interventions that move beyond conventional approaches such as carbon pricing and efficiency standards. Reflecting the scale of ambition required, the European Union (EU) has legislated that all new passenger cars sold from 2035 must be zero-emission (European Parliament, 2023). Although vehicles registered before 2035 may continue to operate, the regulation effectively mandates a transition towards battery electric and other zero-emission technologies. Such measures have brought internal combustion engine (ICE) phase-outs to the centre of policy debate, yet empirical evidence on their broader implications for transport demand, energy consumption, and emissions remains limited.

Assessing the implications of such policies requires robust analytical tools. A large literature has examined pathways for transport decarbonisation using a variety of modelling frameworks. Top-down models, such as the IEA Mobility Model (MoMo) and the EU's PRIMES model, embed transport within energy–economy systems, allowing for analysis of cross-sectoral feedbacks and economy-wide outcomes (Fulton et al., 2009; Syri et al., 2001). By contrast, bottom-up models such as the UK Transport Carbon Model (UKTCM) and TIMES provide greater sectoral and technological detail, capturing the role of infrastructure provision, technology choice, and behavioural drivers (Brand et al., 2012; Daly et al., 2014). Both approaches face limitations: top-down models may lack technological specificity, while bottom-up models often understate macroeconomic interactions and consumer heterogeneity (Horne et al., 2005). Hybrid frameworks have emerged to address these shortcomings, integrating macroeconomic consistency with sectoral detail, as in the Canadian CIMS model or global integrated assessment models such as GCAM, MESSAGE-Transport, and

IMACLIM-R (Horne et al., 2005; Kyle & Kim, 2011; McCollum et al., 2016; Waisman et al., 2013).

Within this broad literature, considerable attention has been devoted to carbon pricing and fuel efficiency standards. Carbon pricing is widely recognised as a cornerstone of climate policy, but transport has proven less responsive than other sectors due to long capital lifetimes and low short-run elasticities. Studies consistently find that while carbon taxes can deliver incremental reductions in emissions, they are insufficient alone to drive the large-scale technological transitions required for deep decarbonisation (Girod & van Vuuren, 2012; Pietzcker et al., 2014; Tvinnereim & Mehling, 2018). Fuel-efficiency standards also reduce emissions per kilometre but are vulnerable to rebound effects, whereby lower operating costs stimulate additional travel (Ajanovic & Haas, 2012; Dimitropoulos et al., 2018). Meta-analyses suggest rebound effects of 10–12% in the short run and up to 26–29% in the long run (Dimitropoulos et al., 2018). These findings indicate that while carbon pricing and efficiency mandates remain essential, they require complementary measures to deliver durable emissions reductions.

Among such measures, bans on new ICE car sales have recently attracted some scholarly attention. Research highlights their potential to achieve transformative emissions reductions, though outcomes are highly sensitive to the design of the ban with respect to timing and scope. Brand and Anable (2019) show that in the UK only an early and comprehensive ban, including hybrids, achieves emissions reductions consistent with long-run climate goals. Similarly, Pirie et al. (2020) find that advancing the phase-out from 2035 to 2030 reduces cumulative emissions by 191 Mt CO_2 between 2020 and 2040. Evidence from Sweden further demonstrates that comprehensive ICE bans outperform alternative measures such as biofuel deployment (Morfeldt et al., 2021).

Irish research has addressed a range of decarbonisation policies for the transport sector. Daly and Ó Gallachóir (2011, 2012) projected that efficiency improvements could flatten growth in car energy demand, but deep reductions required deployment of EVs, biofuels, and behavioural change, achieving up to a 22% cut in non-ETS emissions relative to 2009. Giblin and McNabola (2009) showed that reforming vehicle taxation based on CO_2 intensity reduced the emissions profile of new cars. More recent system-level modelling with TIMES-Ireland has emphasised regional and spatial dimensions: Aryanpur et al. (2022) demonstrate that EV incentives remain important but insufficient without demand-side measures to limit car use, while Gaur et al. (2024) highlight that dispersed settlement patterns drive significantly higher per-capita transport emissions. City-level studies have also suggested the potential for targeted interventions: Ghosh et al. (2018) estimate that banning new diesel car sales in Dublin from 2025 would halve NOx and $PM_{2.5}$ emissions by 2030, with associated health and economic benefits.

Despite these contributions, evidence remains limited on the implications of internal combustion engine (ICE) phase-outs for achieving Ireland's long-term emission-reduction targets and sectoral carbon budgets. Moreover, no study has systematically compared their effectiveness with carbon taxation or with integrated policy approaches. This gap is particularly important given Ireland's binding EU obligations and the substantial fiscal risks associated with non-compliance. Addressing it requires a modelling framework that simultaneously captures technological detail, behavioural dynamics, and macroeconomic feedbacks.

This paper introduces I3E-Transport, a newly developed passenger transport model for Ireland. This model covers transportation by private car, bus, rail and light rail, which represents approximately just under half of the total transport sector in Ireland. The model is designed to evaluate technological and behavioural decarbonisation policies and is integrated with the Ireland Environment–Energy–Economy Computable General Equilibrium (CGE) (I3E) Model, enabling analysis of how transport policies interact with fuel prices and broader macroeconomic activity. I3E-Transport employs a nested multinomial logit framework to capture decision-making across multiple levels—mode choice, fuel type, engine size, and vehicle vintage—while incorporating features such as vehicle scrappage, age-related distance decay, and changes in efficiency. The model is calibrated on detailed Irish data for the period from 2008 to 2023, including travel behaviour, vehicle stock, fuel prices, taxation, and energy performance.

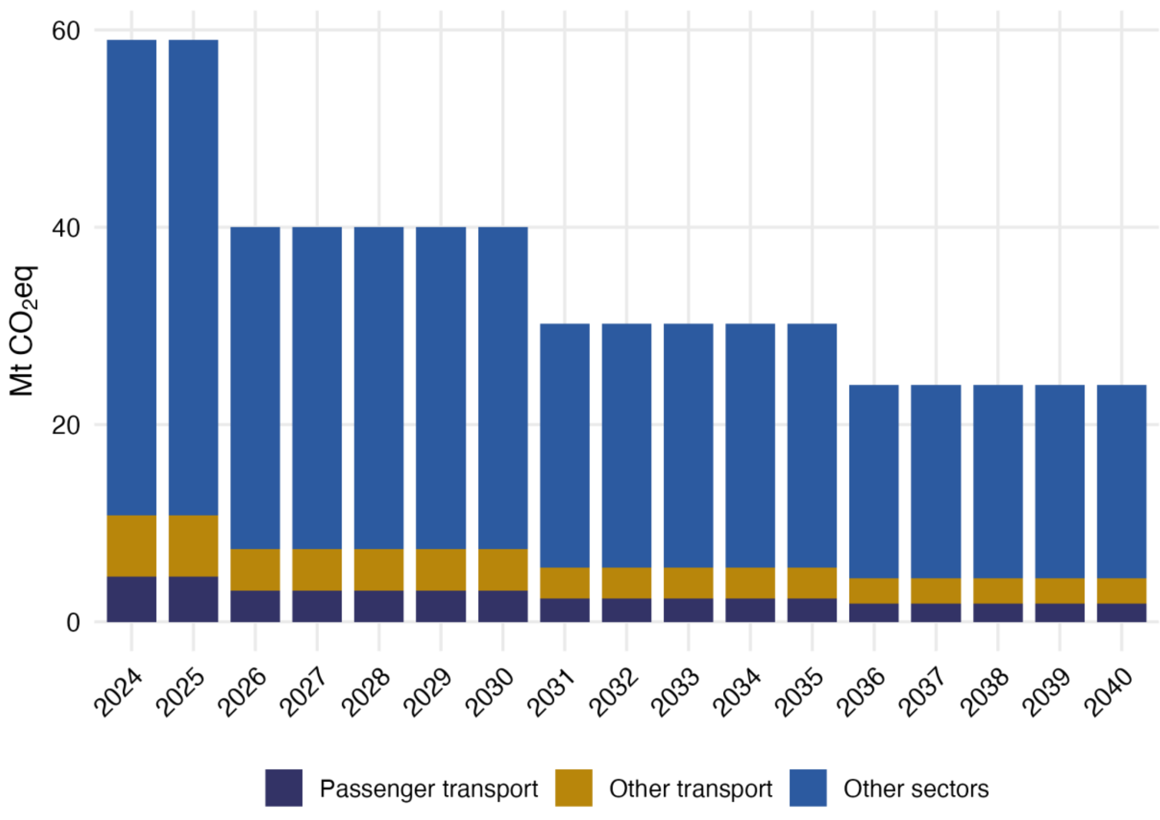
We apply this framework to a set of policy scenarios for 2024–2050. These include a business-as-usual baseline, Ireland's planned carbon tax trajectory, and ICE phase-out policy scenarios, both with and without hybrid vehicles, which also include planned changes in the level of carbon taxation. The results provide new insights on the effectiveness of these approaches in reducing demand, energy consumption, and emissions, and in aligning Ireland's transport sector with national carbon budgets and long-run climate targets. The paper proceeds as follows. Section 2 provides the policy context outlining Ireland's emissions targets, carbon budgets and sectoral ceilings in transport. Section 3 describes the model structure and methodology. Section 4 details the data sources used in the model calibration process. Section 5 presents the scenario results and discusses their implications for Irish decarbonisation and emission reduction targets. Section 5 concludes with policy recommendations.

Policy Context

Under the Climate Action and Low Carbon Development (Amendment) Act 2021, and in line with the EU Green Deal, Ireland is legally committed to achieving climate neutrality by 2050 (Department of the Taoiseach, 2021; European Commission, 2019). Advancement toward this long-term objective is anchored by an interim milestone requiring a 51% reduction in total greenhouse gas emissions by 2030 relative to 2018 levels. These statutory commitments are given practical effect through a series of five-year carbon budgets, which set legally binding limits on the cumulative volume of greenhouse gas emissions, expressed in tonnes of CO_2 equivalent, that may be released within each budgetary period (Climate Change Advisory Council, 2024; Department of Climate, Energy and the Environment, 2022a). The budgets are designed both to guide emissions trajectories towards the 2030 target and to continue constraining emissions thereafter on the pathway to net zero by mid-century. The first two carbon budgets — covering 2021–2025 and 2026–2030 — have been formally adopted, with a provisional third budget for 2031–2035 also in place. These budgets are set at 295 Mt CO_2eq, 200 Mt CO_2eq, and 151 Mt CO_2eq, respectively, implying approximate annual ceilings of 59, 40, and 30.2 Mt CO_2eq if emissions are distributed evenly across each year (Department of the Taoiseach, 2025). The Climate Change Advisory Council has also published a provisional carbon budget for the 2036-2040 period, set at 120 Mt CO_2eq for the full period, implying an equal annual budget of 24 Mt CO_2eq for each year from 2036-2040 (Climate Change Advisory Council, 2024).

Within Ireland's carbon budgeting system, the total permissible volume of national GHG emissions is apportioned across sectors of the economy, establishing sectoral emissions ceilings that define the maximum emissions each sector may produce within a given budget period (Department of Climate, Energy and the Environment, 2022b). These ceilings, determined by the relevant departments and approved by government, have been formally set for the first two carbon budget periods (Environmental Protection Agency, 2025). For the transport sector, the ceilings were set at 54 Mt CO_2eq for 2021–2025 and 37 Mt CO_2eq for 2026–2030 (Department of Climate, Energy and the Environment, 2022b). For the subsequent budget periods, where no sectoral ceilings have yet been established, we infer equivalent limits by maintaining the transport sector's historical share of total national emissions—approximately 18.3%. Applying this proportion to the national carbon budgets yields indicative ceilings of 27.6 Mt CO_2eq for 2031–2035 and 21.96 Mt CO_2eq for 2036–2040. As shown in Figure 1, assuming an equal annual allocation across each period, these correspond to annual sectoral ceilings of 10.8, 7.4, 5.52, and 4.39 Mt CO_2eq, respectively.

Figure 1: Carbon budget allocation estimates



This study focuses on passenger transport, which represents approximately just under half of the total transport sector as defined under Ireland's carbon budgets. Passenger transport comprises travel by private car, as well as by bus, rail, and light rail services. To derive an implied emissions ceiling for this portion of the sector, we use mode-specific energy and emissions shares reported in the Sustainable Energy Authority of Ireland's (SEAI, 2024) Energy in Ireland report, which disaggregates total transport emissions by sub-sector. In 2023, private cars accounted for 39.3% of total transport energy use and emissions, while rail and bus services contributed 1.0% and 2.4%, respectively. Based on these shares, the analysis assumes that passenger transport accounts for 42.7% of the transport sector's total emissions ceiling. Applying this proportion yields estimated carbon budgets for passenger transport of 23.0 Mt CO_2eq, 15.8 Mt CO_2eq, 11.8 Mt CO_2eq, and 9.38 Mt CO_2eq for the respective periods 2021–2025, 2026–2030, 2031–2035, and 2036–2040. Assuming an even annual distribution across each period, these correspond to annual ceilings of 4.6, 3.2, 2.4, and 1.9 Mt CO_2eq, respectively.

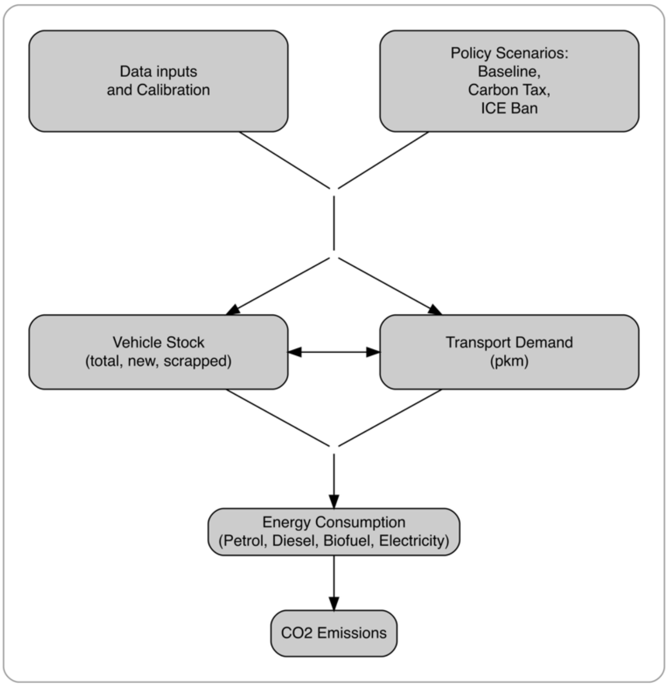
Ireland's total greenhouse gas (GHG) emissions fell below 1990 levels for the first time in 2023, recording 54.93 Mt CO_2eq—1.4% lower than in 1990 and 6.8% below 2022 levels—marking an initial turning point in the national emissions trajectory (Environmental Protection Agency, 2025). Despite this progress, Ireland faces substantial challenges in meeting its legally binding climate targets. Current projections indicate that emissions will decline by only 29% by 2030 relative to 2018, well short of the 51% reduction required under the Climate Action and Low Carbon Development (Amendment) Act 2021. The fiscal implications of non-compliance are significant, with estimated costs of approximately €0.35 billion per year until 2030 and €0.7 billion annually thereafter (Casey & Carroll, 2023; Walker et al., 2023).

These shortfalls are already reflected in the management of Ireland's carbon budgets. After three years of the first five-year budget period, 63% of the allowable emissions have been used, implying that average annual reductions of nearly 5% would be required in the remaining years to remain within the limit (Environmental Protection Agency, 2025). Sectoral performance mirrors this position. Emissions in the transport sector increased by 0.3% in 2023, despite the need for sustained reductions. The sector remains particularly difficult to decarbonise: improvements in vehicle efficiency have been largely offset by rising travel demand, which is closely correlated with national income growth (Climate Change Advisory Council, 2025). Passenger transport emissions from private cars, buses, and rail have nearly returned to pre-pandemic levels following temporary declines during the COVID-19 period (SEAI, 2024). The Climate Change Advisory Council (2025) now projects that the transport sector will exceed its emissions ceilings by 4 Mt CO_2eq in the first carbon budget period and by 15.5 Mt CO_2eq in the second, even under optimistic assumptions. Given its position as the largest energy-consuming sector in the economy and a key determinant of Ireland's overall emissions trajectory, the transport sector's persistent underperformance highlights the urgency of implementing robust and effective policy interventions to ensure alignment with national climate objectives.

Model Description

This section describes the structure of the I3E-Transport model, detailing the interaction between its four core modules and the key input variables—such as mode- and vehicle-specific costs, consumer preferences, energy efficiencies, and emission factors—which are crucial in shaping policy outcomes. As illustrated in Figures 2 and 3, the I3E-Transport model integrates: (1) a transport demand module, which projects total passenger-kilometres (pkm) travelled and allocates this across different transport modes and vehicle technologies based on socioeconomic drivers; (2) a vehicle stock module which endogenously estimates the composition and size of the vehicle fleet to 2050; (3) an energy consumption module, which uses projected travel demand, fleet characteristics, energy efficiency, and fuel prices to estimate fuel use; and (4) an emissions module, which translates fuel consumption estimates into future CO_2 emissions. Together, these modules provide a comprehensive framework for simulating the dynamic interaction between demand, technology, energy use, and environmental outcomes under alternative policy settings.

Figure 2: I3E-Transport model structure

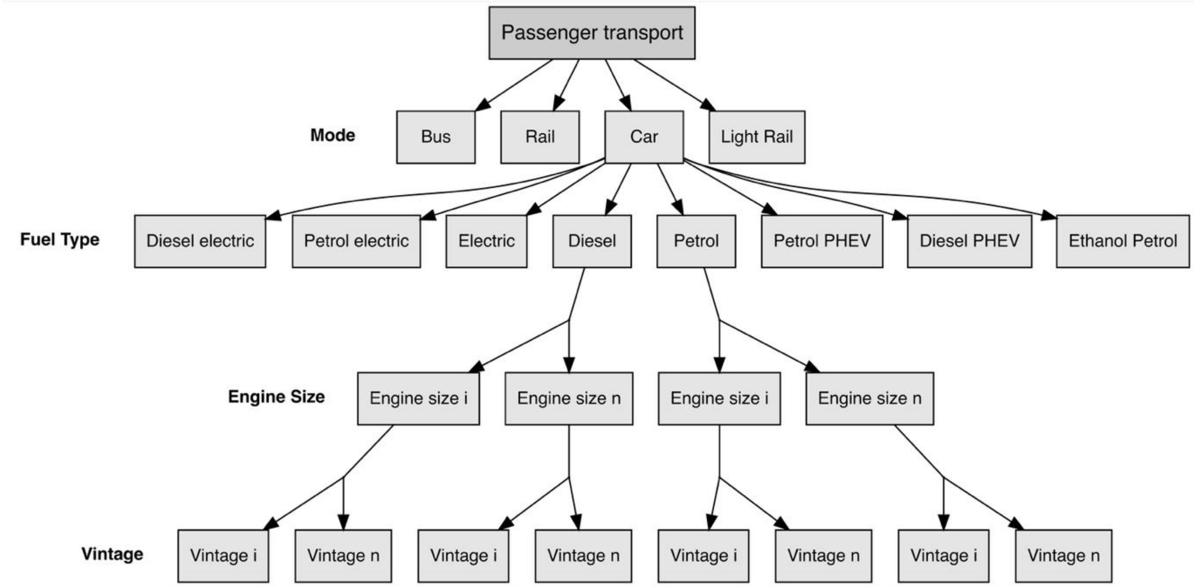


Total demand for passenger transport services in the I3E-Transport model is determined by macroeconomic and transportation cost drivers, consistent with the structure of comparable transport models (Kyle and Kim, 2011; Pietzcker et al., 2014; Zhang et al., 2018). Specifically, as shown in Equation 1, the model uses projected growth trends in national income, population, and fuel costs—used here as a proxy for generalised transport costs—to forecast aggregate travel demand:

$$TD_t = TD_{t-1}(1 + \eta^Y \frac{Y_t - Y_{t-1}}{Y_{t-1}})(1 + \eta^P \frac{P_t - P_{t-1}}{P_{t-1}}) \tag{1}$$

In this formulation, *TD* denotes aggregate national transport demand in year *t*. The variables *Y and* P, represent income per capita and fuel prices respectively. Projections for these variables, including population, are sourced from the I3E CGE model, establishing a soft link between the I3E-Transport model and the broader I3E framework, ensuring consistency between transport sector dynamics and macroeconomic developments. The parameters η^Y and η^P are elasticity coefficients that measure the responsiveness of transport demand to changes in income per capita and fuel prices. Each coefficient reflects the percentage change in aggregate transport demand resulting from a 1% change in the corresponding variable. Consistent with values reported in the literature, these are set to 0.55 and −0.3 respectively (Dunkerley et al., 2014; AECOM and ESRI, 2020).

Figure 3: I3E-Transport model nested structure



To allocate projected passenger transport demand across modes and vehicle technologies, we employ a nested multinomial logit (MNL) framework grounded in discrete choice modelling—a well-established method in the transport modelling literature (Girod et al., 2012; Mittal et al., 2017). The hierarchical structure of the model is illustrated in Figure 3, with mode choice occupying the top level, followed by fuel type, engine size, and vehicle vintage (year of registration) within the car mode. At each decision level, demand shares are determined using MNL-type equations that depend on the generalised cost of transport for each alternative and calibrated preference parameters that capture non-cost influences. For the mode choice level, the calculation also incorporates the monetary value of travel time, capturing both direct monetary travel costs and the monetary cost of time.

The share of total passenger transport demand allocated to each mode is determined using an MNL-type specification, as shown in equation 2.

$$SMODE_{t,m} = \frac{\alpha_m * PMODE_{tm}^{\beta^{mode}}}{\sum_{m\epsilon M}(\alpha_m * PMODE_{tm}^{\beta^{mode}})} \tag{2}$$

In this framework, $SMODE_{t,m}$ denotes the share of projected total transport demand in year *t* allocated to mode *m*. The allocation depends on the generalised price of each mode, *PMODE*, expressed in euros per passenger kilometre (€/pkm), and a mode-specific preference parameter, α_m, which captures the influence of non-cost factors such as infrastructural availability, technological barriers and social norms on mode choice. The price sensitivity is governed by the parameter β^{mode}, which reflects how responsive demand shares are to changes in the generalised price. The parameters α_m and β^{mode} are calibrated on historical data from 2008 to 2023, by regressing relative demand shares on relative prices across modes.

Generalised prices are calculated either as weighted averages of the generalised costs of options within lower levels of the nested choice structure, as is the case for private transport modes, or by dividing total revenue by total demand for a given public transport mode.

$$PMODE_{tm} = \sum_{f \epsilon F} \left(SFUEL_{tmf} * PFUEL_{tmf} \right) + PTIME_{m} \tag{3}$$

For the car mode, as shown in equation 3, the generalised price, *PMODE*, is computed by weighting the generalised cost of each fuel type, *PFUEL*, by their respective demand shares, *SFUEL*. At mode level the generalised price of the car mode is adjusted to account for the differences in the monetary cost of travel time, $PTIME_m$, across modes.

At lower levels of the I3E-Transport model hierarchy, choices among competing car technologies are represented using similar nested multinomial logit (MNL) structures. These nests reflect sequential decisions within the car mode, progressing from fuel type (level 3, denoted k), to engine size (level 2, j), and finally to vehicle vintage (level 1, i). At each level of the nesting structure, transport demand is disaggregated from the level above, to an alternative, a, on the current level of the nested structure according to a calculated demand share, such that $TD_{tmla} = TD_{tml+1} * S_{tmla}$. The share S_{tmla} is derived using an MNL-type formulation, where demand shares are determined by the generalised price P_{tmla}, an associated preference parameter $\alpha_{ma^{(l)}}$, and a level-specific price sensitivity coefficient $\beta^{(l)}$. Specifically,

$$S_{tma^{(l)}} = \frac{\alpha_{ma^{(l)}} * P_{tma^{(l)}}^{\beta^{(l)}}}{\sum_{a'^{(l)} \epsilon A^{(l)}} (\alpha_{ma'^{(l)}} * P_{tma'^{(l)}}^{\beta^{(l)}})} \tag{4}$$

in turn, generalised prices at each level are computed as share-weighted averages of generalised costs at the next lower level, following

$$P_{tma^{(l)}} = \sum_{a^{(l-1)} \epsilon A^{(l-1)}} \left(S_{tma^{(l-1)}} * P_{tma^{(l-1)}} \right) \tag{5}$$

Parameters α and β are calibrated using Irish market data from 2008 to 2023. An exception is made for the alternative specific parameters at the fuel-type level for conventional and alternative fuel vehicles, which are calibrated using more recent data from 2023 to reflect evolving preferences and the rising market share of alternative technologies in Ireland (Department of Transport, 2022). We further assume that preferences for alternative vehicles improve by 5% per annum reflecting improvements in non-cost factors such as increased availability of charging facilities and greater range capabilities. The price sensitivity parameter $\beta^{(l)}$ is estimated at both the fuel-type and engine-size levels using historical relative price and demand data for petrol and diesel technologies options.

At the most disaggregated level of the model, transport demand shares are estimated across vehicle vintages. This bottom-level specification serves as the foundation for the weighted calculations of demand shares and generalised prices used at higher levels of the nested structure. The vintage-level shares are derived using detailed data on surviving vehicles registered in previous years, incorporating information on scrappage-adjusted car stocks, average annual distances travelled per vehicle, and load factors (i.e. the average number of occupants per car). These elements allow for a granular representation of transport activity associated with each vintage.

The share of transport demand attributable to each vehicle vintage is calculated as a proportion of total demand across all vintages, conditional on mode, fuel type, and engine size. This is given by:

$$SVINTAGE_{tmfev} = \frac{TD_{tmfev}}{\sum_{v \epsilon V} TD_{tmfev}} \tag{6}$$

where $SVINTAGE_{tmfev}$ denotes the demand share for vintage, *v*, and TD_{tmfev} represents total transport demand associated with that vintage. The subscripts, *t*, *m*, *f*, and *e* refer to year, mode (restricted here to cars), fuel type, and engine size, respectively. Demand for each vintage is determined by multiplying the number of cars in the fleet CNO_{tmfev} by the average annual vehicle distance travelled VD_{tmfev} and the load factor, which is defined as the number of occupants per vehicle LF_{tmfev}:

$$TD_{tmfev} = CNO_{tmfev} * VD_{tmfev} * LF_{tmfev} \tag{7}$$

This formulation indicates that vintage-level demand shares reflect not only fleet composition but also variation in usage intensity across vehicle cohorts.

The generalised cost at the vintage level is defined as the annualised service price per vehicle, incorporating key cost components associated with vehicle ownership and usage. It is calculated as:

$$PVINTAGE_{tmfev} = \frac{APC_{tmfev} + ACT_{tmfev} + FC_{tmfev}}{SVD_{tmfev}} \tag{8}$$

where $PVINTAGE_{tmfev}$ denotes the generalised cost per vehicle for vintage v in year *t*, conditional on mode (*m*), fuel type (*f*), and engine size (*e*). The numerator comprises the average annualised purchase cost APC_{tmfev}, average annual motor taxation ACT_{tmfev}, and annual average fuel cost FC_{tmfev} per car within each vintage category, while the denominator SVD_{tmfev} reflects the average annual service distance travelled per vehicle i.e., the product of vehicle distance and the load factor.

The annualised purchase cost includes the vehicle's pre-tax price, value-added tax (VAT), vehicle registration tax (VRT), and any relevant grants or VRT reliefs for alternative fuel vehicles. Vehicle cost is annualised over a 12-year service life using a 5% discount rate to reflect the time value of money:

$$APC_{tmfev} = PC * \frac{r(1+r)^n}{(1+r)^n - 1} \tag{9}$$

where *PC* is the up-front purchase cost, *r* = 0.05 is the discount rate, and *n* = 12 is the assumed vehicle lifetime. Annual car taxation is included as a policy-defined rate that depends on fuel type, engine size, and CO_2 emissions. Finally, the fuel cost component of the generalised cost numerator is calculated for each vintage category as the product of total kilometres travelled VD_{tmfev}, average fuel efficiency ε_{mfev}, in litres per kilometre or kWh per kilometre, and the applicable fuel price P_t^{fuel} in euros per litre or euros per kWh, divided by the number of vehicles in the corresponding vintage category VS_{tmfev}. Equation 10 presents this calculation for single-fuel vehicles—including petrol, diesel, electric, ethanol–petrol, petrol–electric hybrid, and diesel–electric hybrid—while Equation 11 sets out the corresponding specification for petrol and diesel PHEVs, where fuel costs are computed using a 60:40 weighting between fossil fuels and electricity consumption.

$$FC_{tmfev} \frac{VD_{tmfev} * \varepsilon_{mfev} * P_t^{fuel}}{VS_{tmfev}} \tag{10}$$

$$FC_{tmfev} \frac{0.6\left(VD_{tmfev} * \varepsilon_{mfev} * P_t^{fuel}\right) + 0.4\left(VD_{tmfev} * \varepsilon_{mfev} * P_t^{fuel}\right)}{VS_{tmfev}} \tag{11}$$

The transport demand module is directly integrated with the car stock module, which simulates the evolution of the national vehicle fleet over time. The car stock is disaggregated by fuel type, engine size, and vintage, allowing for detailed analysis of how different policy interventions influence vehicle ownership patterns and usage profiles across car types. The vehicle module is constructed in a similar manner to other vehicle stock models in the literature (Girod et al., 2012; Hugosson et al., 2016) and accounts for vehicle scrappage and age-related reductions in average distance travelled (driving decay), and endogenously determines annual additions to the fleet, with the composition by vehicle type determined by discrete choice based frameworks. New vehicle entries in each year are computed as the difference between projected total transport demand and the aggregate distance travelled by the existing stock, the latter being estimated using average driving intensities by vehicle category.

Formally, the total number of cars in any given year is defined by Equation 12, which determines the total car stock by fuel type and engine size level, TCS_{tmfe}, as the sum of the surviving car stock from the previous year, ECS_{tmfe}, and newly purchased vehicles in the current year, NCS_{tmfe}:

$$TCS_{tmfe} = ECS_{tmfe} + NCS_{tmfe} \tag{12}$$

The existing car stock, ECS_{tmfe}, is calculated by applying historical average scrappage rates across age groups to the previous year's stock. Scrappage rates vary by fuel type, engine size, and vintage, where vehicle age *a* is defined as the difference between the year of evaluation *t* and the year of first registration *v*. The surviving stock is thus computed as:

$$ECS_{tmfe} = \sum_{v \epsilon V} TCS_{t-1mfe} * SR_{amfe} \tag{13}$$

The scrappage rate SR_{amfe} is defined as the product of the average scrappage rate by age, fuel type, and engine size ASR_{amfe}, and the percentage change in total car stock between periods:

$$SR_{amfe} = ASR_{amfe}(\frac{TCS_{tmfe} - TCS_{t-1mfe}}{TCS_{t-1mfe}}) \tag{14}$$

The number of new cars of a given fuel type and engine size, where vintage *v* corresponds to year *t*, is calculated as the annual change in total car stock at the relevant fuel type and engine size level. Formally, new car stock NCS_{tmfev} is defined as the difference between the total car stock in year *t*, TCS_{tmfe}, and the total stock in the preceding year, TCS_{t-1mfe}:

$$NCS_{tmfev} = TCS_{tmfe} - TCS_{t-1mfe} \tag{15}$$

This formulation enforces consistency in the model's stock-flow accounting, where all newly registered vehicles are associated with a specific vintage and added to the stock of cars of the corresponding fuel type and engine size in the year of purchase. The new stock for vintage *v* in year *t* is determined endogenously as the proportion of projected transport demand not met by the existing stock carried over from the previous year, after accounting for scrappage and the decay in annual driving distance with vehicle age. This ensures coherence between the transport demand module and the vehicle stock module, such that the evolution of the vehicle fleet reflects developments in transport demand.

Projections from both the Transport Demand and Vehicle Stock modules are integrated into an Energy Consumption module to estimate future energy use arising from passenger transport activity. Energy consumption is computed using projected travel demand, vehicle stock disaggregated by fuel type, engine size, and vintage, and mode- and vehicle-specific energy efficiency statistics. This approach is consistent with methodologies adopted in other established transport-energy models (Meyer et al., 2007; Mittal et al., 2017; Zhang et al., 2018). Energy consumption is projected across all modes and aggregated to national totals by fuel type (petrol, diesel, electricity, and biofuels). For non-car modes, total energy consumption in year *t* is given by the product of the total projected service distance ($SVD_{t,m}$) and the average mode-specific energy intensity (EF_m) per passenger-kilometre:

$$EC_{tm} = SVD_{tm} * EF_m \tag{16}$$

For private cars, energy consumption is calculated by summing the consumption of both newly registered and surviving vehicles from previous vintages, allowing us to account for declining efficiency in older vehicles and technological improvements in newer models. The formulation is as follows:

$$EC_{tm} = \sum_{v \in V} (OC_{tmfev} * VDOC_{tmfev} * EFOC_{tmfev}) + \sum_{v \in V} (NC_{tmfev} * VDNC_{tmfev} * EFNC_{tmfev}) \tag{17}$$

where *OC* and *NC* denote the existing and new car stock, *VD* represents annual vehicle distance travelled, and *EF* denotes the respective energy efficiency. We then convert our energy consumption estimates to fuel-specific consumption figures by applying fuel-usage weights. This approach allows us to account for biofuel blending with conventional fuels. We use the 2023 blending rates, with petrol containing 4.2% ethanol and diesel containing 8.5% biodiesel.[1] Furthermore, for hybrid vehicles, consumption is allocated using a 40:60 ratio in favour of electricity. Final fuel consumption estimates by fuel type—diesel, petrol, electricity, and biofuels—are then obtained by aggregating the results across all vehicle types and adding values from the non-car modes. For non-car modes, energy consumption intensities (MJ/pkm) are taken from Banister (2003), with values of 0.92 for bus, 1.69 for rail, and 0.91 for light rail.

Our estimates of total energy consumption by specific fuel types are subsequently passed to the Emissions module to generate annual projections of CO_2 emissions from the passenger transport sector. Emissions are computed as the product of total energy consumption and fuel-specific CO_2 emission factors. For CO_2 emissions, we calculate total emissions in year t as:

$$TCO2_t = (TDC_t * EFD) + (TPC_t * EFP) \tag{18}$$

where $TCO2_t$ is total CO_2 emissions at time *t*, TDC_t and TPC_t, are total diesel consumption and total petrol consumption at time *t*, and *EFD* and *EFP* are respective specific emission factors for diesel and petrol.

Data and Model Calibration

In this section we present and describe the data used for parameter estimation, projections and model calibration within the I3E-Transport model. The projection data used to estimate total Irish passenger transport demand are sourced from the I3E CGE model. Specifically, the projections of real national income, fuel prices, and population—key inputs to the estimation of aggregate passenger transport demand as specified in equation 1—are drawn from a

[1] See SEAI (2024) for biofuel blending rates.

business-as-usual scenario within the I3E framework. While annual growth rates vary over time, the average annual changes between 2023 and 2050 are 3.3% for national income, 0.8% for population, and -0.03% for fuel prices, with petrol prices serving as a proxy for the latter. The modest decline in fuel prices reflects the assumption that energy markets gradually stabilise following the elevated prices observed from 2022 as a result of wartime impacts on energy supplies.

These macroeconomic trajectories underpin the transport projections in the baseline scenario, anchoring them in a policy-neutral economic outlook. In contrast, under the carbon tax scenario, the trajectories of key projection inputs are adjusted to reflect both the direct and indirect effects of the pricing policy. The incremental increase in the carbon tax—rising by €7.60 per tonne annually until 2030 (OECD, 2021)—has a direct upward effect on fuel prices and an indirect influence on broader macroeconomic conditions, including national output growth. As a result, the average annual rate of change in fuel prices shifts from -0.03% in the baseline to +0.22% under the carbon tax scenario, while the average annual growth rate of real GDP decreases from 3.31% to 3.09%. These changes capture the economy-wide feedback effects of climate policy and ensure that the economic environment under this policy scenario is appropriately reflected in the transport demand projections.

Data use in the calibration process on transport demand for the car mode, measured in vehicle kilometres travelled, are sourced from the Central Statistics Office (CSO) of Ireland. These data provide disaggregated estimates of passenger car activity by fuel type, and further by engine size and vehicle vintage. Corresponding data on the car stock, disaggregated at similar levels, are also obtained from the CSO. However, due to the aggregation of alternative fuel vehicles into a single category within the CSO data, more granular information on the composition of alternative fuel vehicle types—such as hybrids, plug-in hybrids, and battery electric vehicles—is sourced from multiple editions of the Irish Bulletin of Vehicle and Driver Statistics, published annually by the Department of Transport (DoT).[2] This additional data allows for a more detailed characterisation of the alternative fuel vehicle fleet in the model.

Following the introduction of emissions-based vehicle taxation in mid-2008, Irish car stock and mileage data reveal a marked shift in consumer preference from petrol to diesel vehicles. From July 2008, VRT and annual motor tax were redefined based on CO_2 emissions rather than engine size, substantially reducing the tax liability for diesel vehicles, especially those with larger engines (Hennessy and Tol, 2010). This policy change catalysed a significant reallocation in the composition of the vehicle fleet. In 2008, diesel vehicles comprised just 19% of the 1.9 million passenger car stock, compared to 80.7% for petrol, and accounted for 26.5% of the 31 billion vehicle-kilometres travelled, relative to 73.1% for petrol. Diesel shares continued to grow, peaking in 2021 at 57.3% of the 2.2 million car fleet and 68.4% of the 30.4 billion kilometres travelled, while petrol shares fell to 36.6% and 26.5% respectively. Since 2021, both diesel and petrol shares have declined modestly as alternative fuel vehicles have gained market share. Among these, conventional petrol-electric hybrids now constitute the largest group, reaching 5.2% of the vehicle stock and accounting for 4.7% of mileage by 2023.

[2] For past editions of the Irish Bulletin of Vehicle and Driver Statistics see: https://www.gov.ie/en/department-of-transport/publications/bulletin-of-vehicle-and-driver-statistics/#2022

Data on vehicle costs are compiled from multiple sources, reflecting the distinct components of ownership costs, including vehicle purchase prices, VRT, annual motor tax, and fuel expenses. Vehicle price data are sourced from the Society of the Irish Motor Industry (SIMI) price guides, which provide comprehensive listings of vehicle prices disaggregated by make, fuel type, and engine size. To construct representative purchase prices, we compute weighted averages by engine size category, subsequently aggregating these by fuel type using market shares of new vehicle registrations by make and engine size, as reported by the CSO. For petrol and diesel vehicles, engine size is categorised into five bands: under 1000 cc, 1001–1400 cc, 1401–1600 cc, 1601–2000 cc, and over 2000 cc. Due to data limitations, alternative fuel vehicles are not disaggregated by engine size. Over the period 2008–2023, average prices for the most commonly purchased diesel vehicles increased by just under €10,000, while petrol vehicle prices rose by approximately €8,000. Price trajectories for alternative fuel vehicles were more variable, reflecting both a broader range of available specifications and the entry of higher-specification models into the market over time.

Taxation data for this study are sourced from the annual editions of the ACEA Tax Guide, published by the European Automobile Manufacturers' Association (ACEA), which provide comprehensive information on VRT and annual motor tax for Ireland and other European countries over the full calibration estimation period, 2008–2023.[3] As previously noted, a major reform of the Irish vehicle taxation system was implemented in mid-2008, shifting both VRT and annual car tax from a structure based on engine capacity to one based on CO_2 emissions. VRT is levied as a tax-inclusive ad valorem charge, calculated as a percentage of the open market selling price of the vehicle, inclusive of the tax itself. Prior to the reform, the applicable rate was determined by engine size, while post-reform rates are based on a vehicle's initial CO_2 emissions. For the post-2008 period, we match average emissions data for new passenger cars by fuel type and engine size—sourced from the European Environment Agency (EEA) database—with the corresponding tax brackets to compute average VRT and annual motor tax liabilities.[4] In addition, the ACEA guides provide data on VRT exemptions and vehicle grants applicable to alternative fuel vehicles over the sample period, which are incorporated where relevant.

Fuel costs per vehicle are calculated using data on average annual mileage by fuel type, engine size, and vintage, combined with corresponding estimates of energy efficiency and fuel prices. Mileage and vehicle stock data, as described previously, are used to derive average distance travelled per car, while energy efficiency—measured in litres per kilometre for combustion vehicles and kilowatt-hours per kilometre for electric vehicles—is disaggregated by fuel type, engine size, and vintage. Fuel price data, expressed in euro per litre or per kilowatt-hour, are obtained from the CSO, while energy efficiency data are sourced from the EEA. To account for vehicle ageing, an annual deterioration rate of 0.3% and 0.9% is applied to energy efficiency for ICE and EVs respectively, reflecting the year-on-year increase in fuel consumption per kilometre for used vehicles (Van den Brink and Van Wee, 2001; Yang et al., 2018). Furthermore, the impact of technological progress is captured by assuming an average annual improvement in the fuel efficiency of newly registered vehicles of 2%, based on observed historical trends.

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[3] ACEA Tax Guides are available at: https://www.acea.auto/nav/?content=publications

[4] EEA $C0_2$ emissions from new cars database is available at: Monitoring of CO2 emissions from passenger cars

Results and Discussion

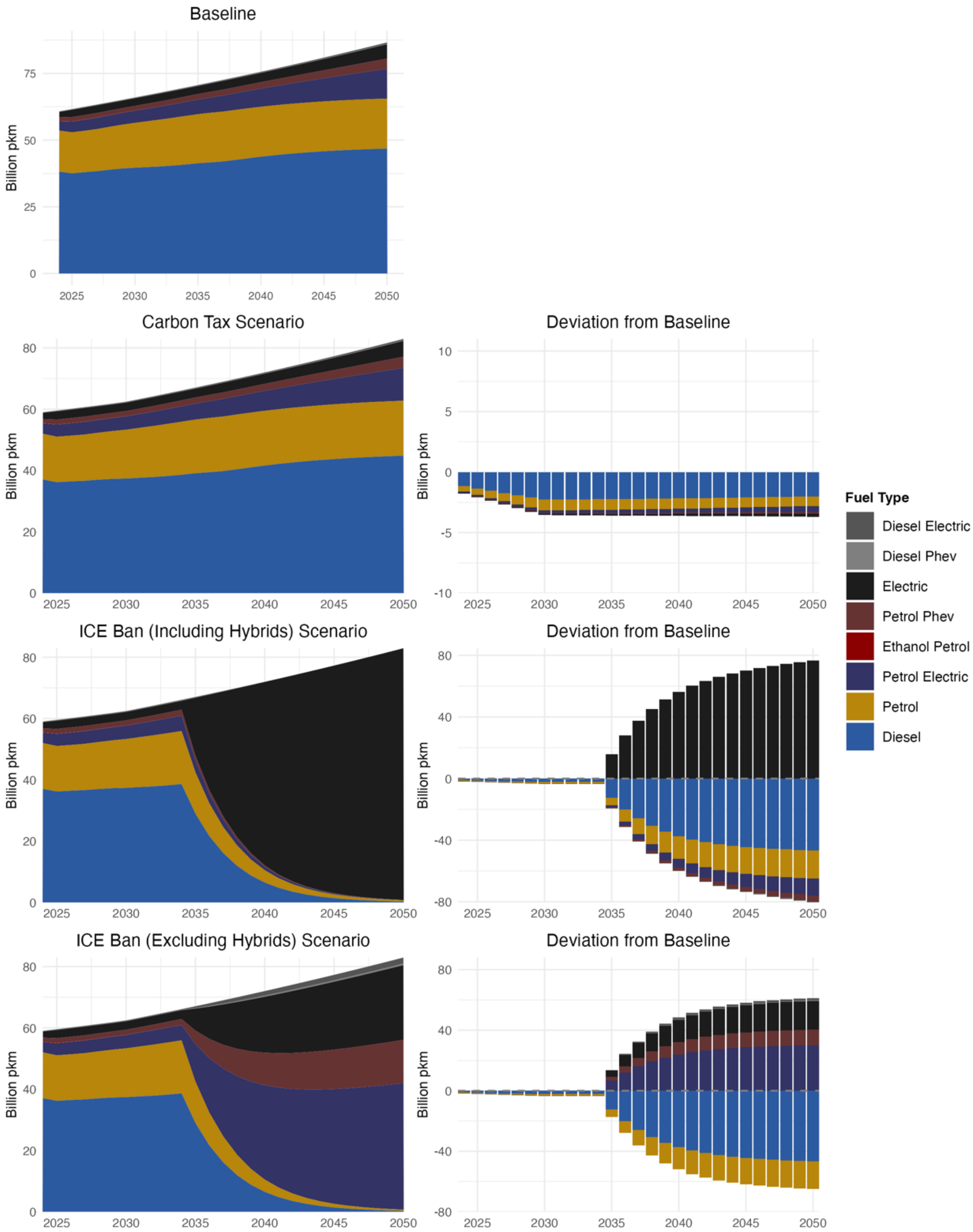
I3E-Transport Model projections

To understand the impact of an ICE ban on transportation emissions, we implement several scenarios. The first scenario is the *baseline*, which represents the estimated growth path for transport demand without additional policy interventions. The second scenario implements an increase in the carbon tax in line with the government's commitments. We include two different specifications of the ICE ban, one which allows hybrids and one which does not, both also include planned changes in the level of carbon taxation. Figure 4 presents the estimated transport demand for the car mode which accounts for over 85% of transport demand across the scenarios, while Figure 5 shows projections for the vehicle stock, both split by fuel type.

In the absence of additional policy measures (the baseline), projected growth in national income and population drives a sustained expansion in passenger transport activity. Total passenger transport demand is projected to rise from 69 billion pkm in 2024 to 98 billion pkm by 2050. The additional demand is met predominantly by private cars, with the modal composition remaining broadly unchanged over the projection period: cars account for 87% of total demand, buses for 8%, rail for 4%, and light rail for 1%.This expansion translates into higher energy use, which grows from 27 TWh in 2024 to over 32 TWh by the mid-2030s before falling back to 30 TWh in 2050, reflecting greater energy efficiency and a greater penetration of hybrid alternative vehicles, as shown in Figure 5. Petrol and diesel remain the primary fuels, accounting for over 90% of total energy consumption, reflecting minimal fleet transformation. Consequently, CO_2 emissions increase from six and a half million tonnes in 2024 to over seven and a half million tonnes by 2040, before alternative vehicle uptake and improved energy efficiency levels reduce emissions to just over seven million tonnes as shown in Figure 6. This baseline trajectory serves as a reference point for evaluating the effectiveness of alternative decarbonisation policies.

Increasing carbon taxation delivers only marginal reductions in transport demand and emissions (see carbon tax scenario). Total passenger transport activity falls by just under five billion pkm relative to the baseline, lending support to assertions in the literature that carbon pricing as a policy lever in transport mainly operates incrementally at the margin rather than as a transformative instrument (Tvinnereim and Mehling, 2018). Emissions reductions remain modest—no more than 0.4 million tonnes below the baseline by 2050—illustrating the limited capacity of relatively small price signals alone to induce structural change in the passenger transport sector.

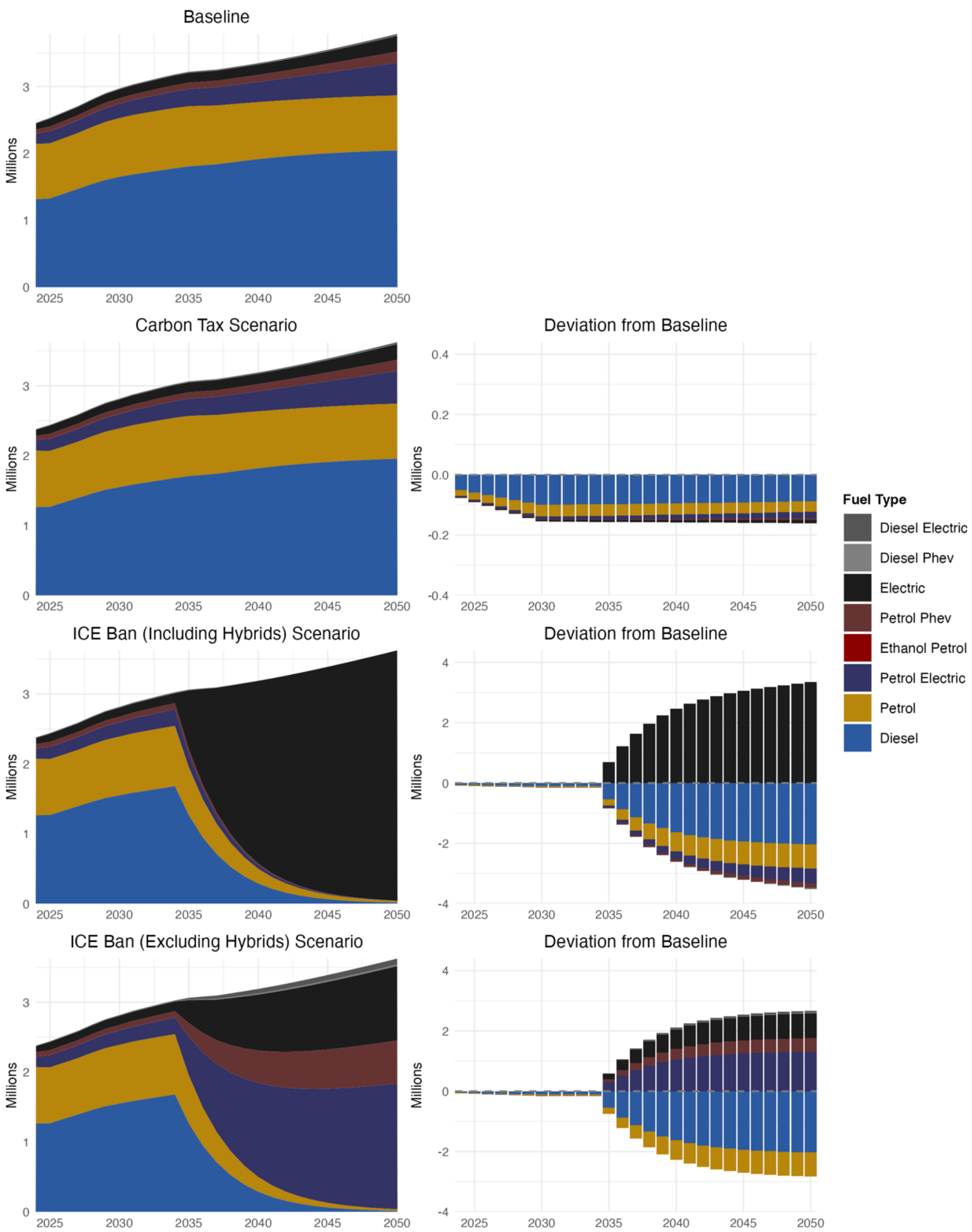
Figure 4: Transport Demand Projections



Note: pkm is calculated using a load factor of 1.65.

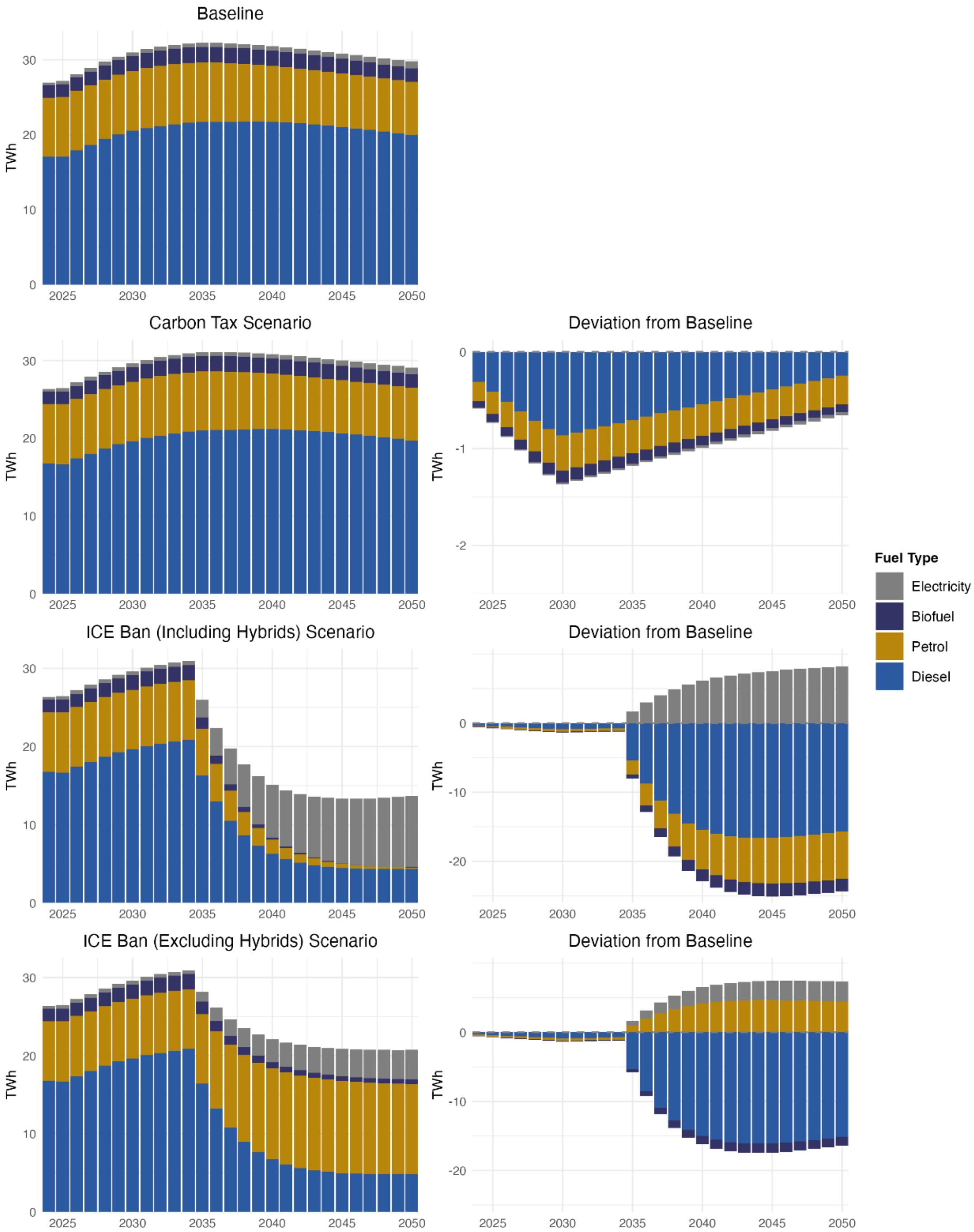
Policies that regulate the composition of new vehicle sales have a far more pronounced impact. The scope of the ban—whether hybrids are included—emerges as a critical determinant of outcomes. Under a partial ban, where hybrids remain permitted, demand shifts substantially towards them after the ban's introduction in 2035. By 2050, conventional petrol hybrids account for nearly 50% of car passenger-kilometres, plug-in hybrids for 17%, and battery-electric vehicles (BEVs) for 30%. This preference for hybrids sustains high levels of petrol consumption, which reaches 56% of total energy use by 2050, while electricity accounts for just 18%. Consequently, emissions reductions are diluted: although emissions fall by almost 2.9 million tonnes relative to the baseline, they remain too high with less than a 50% reduction on today's levels, underscoring the limitations of hybrid-focused strategies.

Figure 5: Vehicle Stock Projections



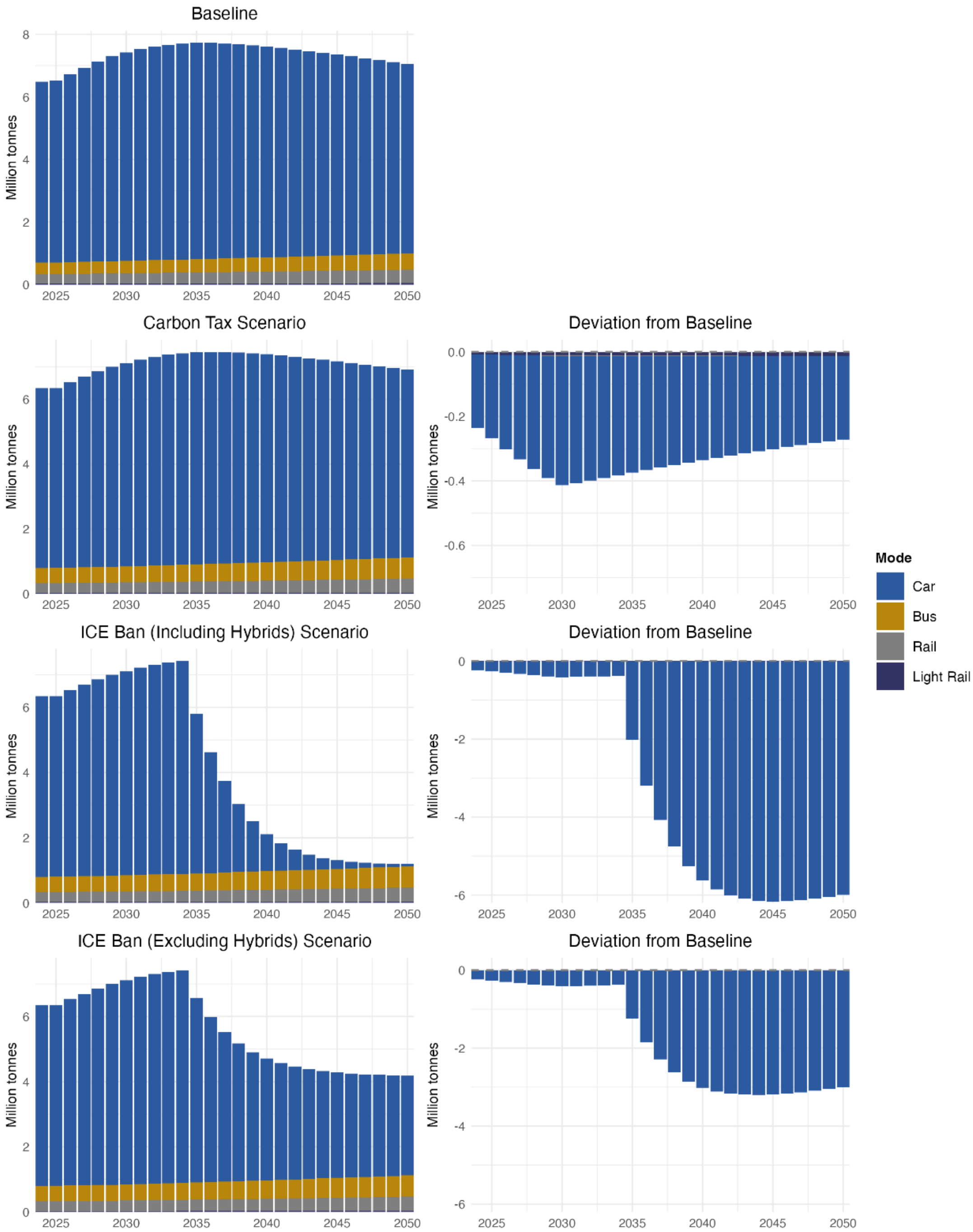
Extending the ban to include hybrids (a comprehensive ban) fundamentally alters the trajectory. From 2035 onwards, the car fleet transitions entirely to BEVs, driving deep decarbonisation. Electricity's share of energy use rises to 67% by 2050, while fossil fuel consumption declines sharply. Emissions fall below 2.5 million tonnes by 2040 and reach approximately 1.2 million tonnes by 2050—more than 5.8 million tonnes lower than the baseline. This scenario demonstrates that stringent regulatory instruments, combined with broad technological coverage, are essential for achieving near-complete decarbonisation.

Figure 6: Energy Consumption Projections



Across all scenarios, the results highlight that incremental measures such as carbon taxation cannot deliver the scale of emissions reduction required. In contrast, comprehensive ICE bans drive transformative change, while partial bans or fuel-efficiency mandates that encourage hybridisation fail to achieve deep decarbonisation. Policy design—particularly the inclusion or exclusion of hybrids—emerges as a decisive factor in shaping long-term emissions outcomes.

Figure 7: CO2 Emissions Projections



Meeting emission reduction targets: carbon budgets and sectoral ceilings

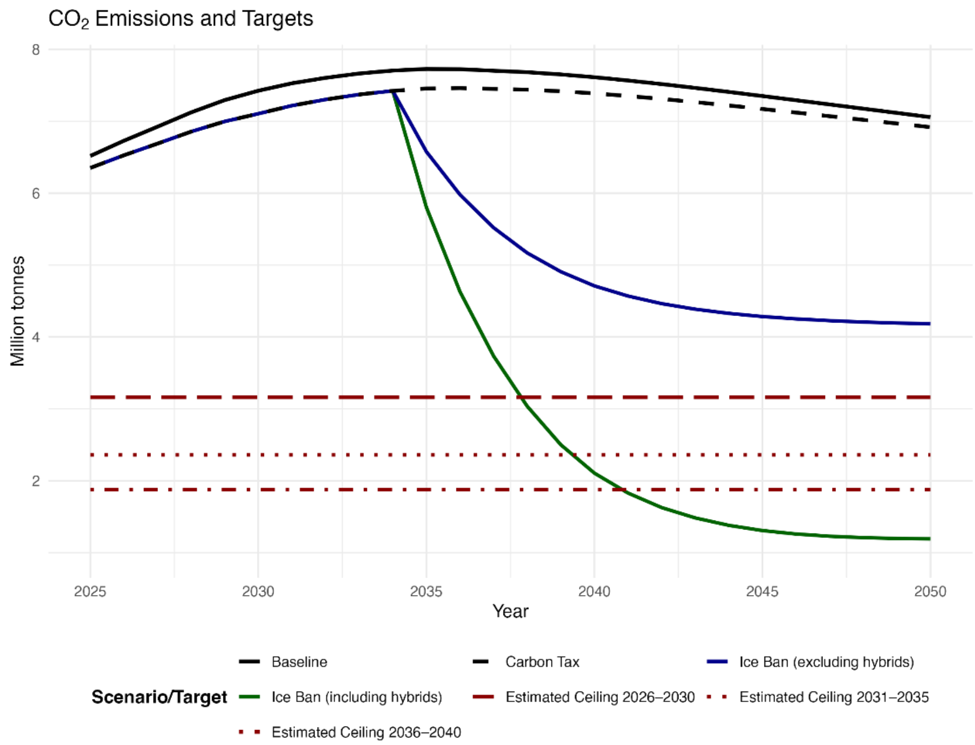
The projected trajectory of passenger transport emissions across all scenarios from 2024 to 2050, benchmarked against the estimated emissions reduction targets for the sector is illustrated in Figure 8.[5] The derivation of these implied targets is outlined in Section 2. These

[5] In our analysis, the five-year carbon budgets are allocated evenly across each year within the carbon budget period. The analysis does not adjust these annual allocations for potential overruns in earlier budget periods, even though exceedances would, in practice, reduce the volume of emissions permitted in subsequent periods.

targets correspond to the carbon budget periods 2026–2030, 2031–2035, and 2036–2040, and are calibrated to align with Ireland's 2030 national objective of a 51% reduction in total greenhouse gas emissions relative to 2018 levels. Accordingly, the emissions ceiling for the 2026–2030 budget period serves as the anchor point for achieving the 2030 target within the passenger transport component of the transport sector.

Figure 8 shows that, across all scenarios examined, Ireland's passenger transport sector fails to meet the implied emissions reduction targets consistent with either the 2030 national objective or the corresponding estimated sectoral ceilings under the carbon budgeting framework. Even in the most ambitious scenario—featuring a comprehensive ban on internal combustion engine (ICE) vehicles encompassing petrol, diesel, and all hybrid variants—the 2030 target is not achieved until 2038, implying a delay of approximately eight years. No additional policy measures to decarbonise public transport are assumed in these simulations. However, if complementary interventions—such as large-scale electrification of bus and rail fleets—were implemented alongside a strict ICE ban, the 2030-equivalent emissions level could be reached just a year earlier in 2037, contingent on near-complete decarbonisation of public transport.

Figure 8: Projected CO2 Emissions and Targets



A similar pattern is observed for later carbon budget periods. The model suggests that emissions compatible with the 2031–2035 and 2036–2040 budgets would only be achieved by 2040 and 2041, under the most ambitious scenario—implying target delays of up to five years and a year respectively. Even with accelerated public transport decarbonisation under this scenario, the 2031–2035 ceiling would be met only two years earlier. However, combining a ban with public transport decarbonisation could enable the 2036–2040 ceiling to be achieved from 2038 (not shown in the figure). Overall, the findings contribute to the growing literature evaluating the effectiveness of ICE bans, highlighting that their capacity to deliver timely emissions reductions depends critically on the timing of implementation. From a policy standpoint, a ban taking effect in 2035 appears insufficient to align Ireland's passenger transport emissions with its climate targets.

Although this study does not explicitly assess the impact of binding energy-efficiency mandates, the results nonetheless offer insights into their likely effectiveness. Stricter fuel-efficiency standards can incentivise a shift towards hybrid vehicles, reflecting both technological constraints and the already high efficiency levels of modern internal combustion engines. In the scenario where a less stringent ICE ban is implemented—permitting hybrid engines–the persistence of emissions from these vehicles prevents compliance with any of the carbon budget reduction targets. This outcome holds even when a carbon tax is applied and public transport is assumed to be fully decarbonised. These findings reinforce the broader evidence in the literature suggesting that the scope and stringency of ICE bans are pivotal to their effectiveness (Pirie et al., 2020). Policies that allow hybrid vehicles within the definition of "zero-emission" transport risk locking in residual emissions, thereby undermining the achievement of sectoral and national climate objectives.

Taken together, the results demonstrate that none of the policy scenarios modelled place Ireland's passenger transport sector on a trajectory consistent with national or sectoral emissions reduction targets. Even the most ambitious scenario—introducing a full internal combustion engine (ICE) ban that includes hybrid vehicles—achieves the 2030-equivalent emissions reduction level only by 2038, nearly a decade late. Earlier compliance would require the combined effect of a strict ICE ban and the near-complete decarbonisation of public transport, however this would advance achievement of the 2030 target by only one year due to the relative size of public transport emissions to private car emissions. The timing of policy implementation therefore emerges as a critical determinant of effectiveness: a ban introduced in 2035 occurs too late to ensure alignment with the 2030 national target or subsequent estimated carbon budget ceilings. Moreover, the findings indicate that policies focused primarily on fuel-efficiency improvements or partial ICE bans—those allowing hybrid engines—are insufficient, as residual emissions from hybrid vehicles prevent compliance even under optimistic assumptions. Overall, the results highlight that early and comprehensive regulatory action of private transport covering a mix of all of these policies—complemented by the rapid decarbonisation of public transport—is essential if Ireland is to meet its legally binding climate commitments within the prescribed timeframe.

Conclusion

This paper developed and applied I3E-Transport, a new passenger transport model for Ireland that integrates technological, behavioural, and macroeconomic drivers to assess the effectiveness of decarbonisation policies. The model captures interactions between transport demand, vehicle stock composition, energy use, and emissions, providing an internally consistent framework for evaluating national climate policies within the structure of Ireland's legally binding carbon budgets.

The results indicate that, in the absence of additional policy measures, rising income and population growth will drive increases in passenger transport demand, vehicle stock, energy use, and emissions between 2025 and 2050. Carbon taxation alone delivers only marginal abatement, highlighting the limited responsiveness of the sector to price-based instruments. By contrast, bans on the sale of new internal combustion engine (ICE) vehicles exert a transformative influence on fleet composition and emissions outcomes. However, the scope and timing of these bans are decisive. A partial ban—allowing hybrid vehicles—produces a substantial shift towards hybridisation but fails to achieve compliance with sectoral ceilings or the 2030 national target. Only a comprehensive ICE ban, prohibiting all hybrid sales from 2035, achieves deep decarbonisation, reducing passenger transport emissions by more than 5.8 million tonnes relative to the baseline by 2050.

Even so, the analysis shows that Ireland's passenger transport sector will not reach its implied 2030 emissions target until the late 2030s and will continue to overshoot the 2031–2035 and 2036–2040 carbon budgets by several years. Accelerated electrification of public transport alongside a comprehensive ban in 2035 would still leave Ireland behind its statutory trajectory however it may bring forward compliance modestly and potentially help to achieve later sectoral ceiling targets. These findings suggest that policy timing is critical: an ICE ban commencing in 2035 is too late to align the sector with Ireland's near-term obligations.

The study also highlights the risk that policies focused primarily on fuel-efficiency mandates or partial electrification will lock in residual fossil-fuel use through expanded hybrid deployment. Deep decarbonisation requires a combination of early regulatory intervention, rapid infrastructure deployment, and complementary measures that support behavioural change and public transport electrification.

More broadly, the results emphasise that no single policy is sufficient to align the passenger transport sector with Ireland's climate objectives. Deep decarbonisation will require a comprehensive policy mix that combines regulatory, fiscal, and behavioural instruments. ICE bans will likely need to be complemented by carbon pricing, which reinforces relative cost signals across the vehicle fleet, as well as by biofuel blending mandates and fuel-efficiency standards that lower residual emissions from the existing stock. Equally, policies that reduce transport dependence will likely be required—including investment in public transport, active travel infrastructure, and urban planning that promotes shorter travel distances—are essential to constrain total demand growth. Coordinated implementation of these measures can generate synergies: fiscal instruments can accelerate behavioural change, efficiency and biofuel standards can limit emissions from legacy fleets, and infrastructure investment can shift travel towards sustainable modes. Achieving Ireland's sectoral and national climate targets will therefore depend not only on technological substitution, but on a coherent strategy that integrates demand reduction, modal shift, and clean technology adoption within a unified policy framework. This is consistent with broader assessments indicating that meeting Ireland's climate objectives will require a system-wide shift in how transport is organised and used, rather than reliance on a limited set of policy instruments (OECD, 2022).

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