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A freight transport demand, energy and emission model with technological choices

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A freight transport demand, energy and emission model with technological choices

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Abstract: Reducing energy consumption and emissions from freight transport plays an important role in climate change mitigation. However, there remains a need for enhanced policymaking and research to explore a low carbon future of freight transport. This research establishes a freight transport model to simulate transport demand (tonne kilometre), energy consumption and emissions. The model incorporates macroeconomic factors, policy indicators, technological characteristics, detailed profiles of the vehicle stock and travel distances, and behavioural parameters with discrete based choices. This model is applied to the freight transport sector in Ireland with scenarios running out to 2050. The results show that overall freight transport demand increases substantially from 2015 to 2050. Economy-wide climate policies (i.e. carbon tax) and high fuel prices result in modest reductions in energy consumption and CO₂ emissions in freight transport, compared to a baseline. Sectoral measures, such as European CO₂ emission performance standards, that aim to improve new vehicle fuel efficiency/emission rates can potentially lead to significant reductions, but such measures face a lag in greening the goods vehicle stock in the short/mid term, and uncertainties in policy compliance and technical barriers in the long run. Notably, in spite of few commercially mature vehicle technologies, adoption of biofuel and alternative freight vehicles are expected to bring additional reductions in future energy consumption and emissions. In all, for a transition to a low carbon future for freight transport, a comprehensive and dynamic policy agenda should be developed to promote low or zero emission vehicles, especially for heavy goods vehicles.

Keywords: Freight transport, CO₂ emission, Energy consumption, Carbon tax, CO₂ emission performance standard, goods vehicle

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A Freight Transport Demand, Energy and Emission Model with Technological Choices

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Abstract

Reducing energy consumption and emissions from freight transport plays an important role in climate change mitigation. However, there remains a need for enhanced policy making and research to explore a low carbon future of freight transport. This research establishes a freight transport model to simulate transport demand (*tonne – kilometre*), energy consumption and emissions. The model incorporates macroeconomic factors, policy indicators, technological characteristics, detailed profiles of the vehicle stock and travel distances, and behavioural parameters with discrete based choices. This model is applied to the freight transport sector in Ireland with scenarios running out to 2050. The results show that overall freight transport demand increases substantially from 2015 to 2050. Economy-wide climate policies (i.e. carbon tax) and high fuel prices result in modest reductions in energy consumption and CO₂ emissions in freight transport, compared to a baseline. Sectoral measures, such as European CO₂ emission performance standards, that aim to improve new vehicle fuel efficiency/emission rates can potentially lead to significant reductions, but such measures face a lag in greening the goods vehicle stock in the short/mid term, and uncertainties in policy compliance and technical barriers in the long run. Notably, in spite of few commercially mature vehicle technologies, adoption of biofuel and alternative freight vehicles are expected to bring additional reductions in future energy consumption and emissions. In all, for a transition to a low carbon future for freight transport, a comprehensive and dynamic policy agenda should be developed to promote low or zero emission vehicles, especially for heavy goods vehicles.

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emission performance standard, Goods vehicle

1 Introduction

Globally, the transport sector accounts for more than 50% of total oil consumption (IEA, 2016). Road freight transport¹ has the second-largest share at 18% of oil consumption after road passenger transport (IEA, 2017). From 2010 to 2015, oil consumption of road freight transport almost tripled, accounting for more than 35% of the net total oil consumption increase (IEA, 2017). Furthermore, road freight transport (light good vehicles (LGVs) and heavy good vehicles (HGVs)), primarily uses carbon-intensive oil products - diesel and petrol, which represents a challenge for decarbonization. Approximately, one-third of transport-related CO₂ emissions come from fuel combustion in road freight transport (Muncrief and Sharpe, 2015). Thus, curtailing emissions from road freight transport plays an crucial role in climate change mitigation.

Economy-wide policies, such as carbon taxes, fuel taxes and biofuel blending mandates have been implemented in the transport sector to incentivize broad carbon emission reductions. While sectoral policies such as CO₂-based vehicle taxes, and fuel economy/CO₂ emission performance standards have been applied to private passenger cars to reduce energy consumption and emissions, much less attention has been paid to freight transport policies. Without strong policies to support adoption of fuel saving technologies, HGVs' fuel efficiency has almost stagnating over the past 15 years (EC, 2016). The EU first introduced a CO₂ emission performance standard on new heavy-duty vehicles only

¹The sectors are road passenger, road freight, aviation, maritime, other transport, steam and process heat, petrochemical feedstocks, buildings, power generation and others. Road freight transport consists of light goods vehicles (unladen weight less than 2 tonnes or gross weight less than 3.5 tonnes in the EU term) and heavy goods vehicles (unladen weight more than 2 tonnes or gross weight more than 3.5 tonnes)

in 2019(EC, 2019a). Furthermore, some countries (e.g. Ireland) subsidize fossil fuel use for freight transport to compensate negative impacts of climate policies on the competitiveness of local industries. There is a need to explore pathways to achieve low emission freight transport and to inform future policy development.

To explore future pathways for climate policies in the freight transport sector, this paper deploys a freight transport model to project future freight transport activities (*tonne – kilometre, tkm*), energy consumption and emissions given economic, technological and policy factors. To reach this objective a model combining economic, environment and energy is needed (Schäfer, 2012; Venturini et al., 2019).

Further research is needed to (i) improve transport modelling, especially for freight transport, with details of vehicle technologies at a national level where transport policies are generally implemented, (ii) incorporate responses of transport demand to market and cost changes, and (iii) integrate behavioural realism in transport (energy) models to strengthen the representation of competition between transport modes and vehicle technologies. To make contributions to existing transport modelling research, this paper aims to address these issues. Specifically, the paper simulates freight transport activities using a detailed profile of vehicle stock, annual distance travelled, and energy consumption. Historical vehicle data are disaggregated by fuel type, unladen weight band and year of registration. Car age (year of registration) is an important dimension, as it is associated with transport-related behaviours in terms of vehicle scrappage, travelling distance decay, engine deterioration, and fuel economy improvements of new vehicles. Several studies focused on behavioural aspects using multinomial logit (MNL)-type equations in their models to simulate choices (Kyle and Kim, 2011; Girod et al., 2013). The model in this paper uses

the MNL-type equations to model the demand competitions between transport modes and vehicle technologies in the freight transport model. This transport freight model contributes to an empirical estimation of parameters in the MNL-type equations based on a historical vehicle demand profile, but also an integration of a detailed vehicle stock model in the transport demand modelling. The model allows demand shifts between transport modes and vehicle technologies in response to changes of vehicle costs. This is a novel contribution to the literature where other national transport energy models do not consider this (e.g., Brand et al. (2012); Daly and Gallachóir (2011)).

This paper demonstrates a long-term view of the decarbonization of freight transport through simulating freight transport activities in Ireland, though the modelling framework can be applied to other countries too. Scenarios for Irish freight transport are constructed to compare the effectiveness of policies on freight transport and explore possible options with limited resources in the face of future uncertainties, rather than providing precise and comprehensive projections of future outcomes. Ireland stands as an interesting case as it is among the EU countries with the highest transport emissions per capita². Dispersed spatial development and a priority on infrastructural investment in roads (DCCAE, 2017) has led to high reliance on road transport for freight in Ireland. The rail freight sector carries less than 1% of total freight movement, while the contributions of domestic aviation and shipping to total freight transport demand are negligible (DTTAS, 2018). Meanwhile, few policies have focused on energy consumption and emissions reduction in the freight transport sector, especially for HGVs.

The modelling results show that with continuous growth in economic activity, overall

²Eurostat data: https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=env_ac_ainah_r2&lang=en

freight transport demand will substantially increase from 2015 to 2050. Economy-wide climate policies (e.g., an carbon tax up to €80 per tonne) and high fuel prices result in modest reductions in energy consumption and CO₂ emissions in the freight transport; a 3%-5% reduction for the carbon tax scenario and a 4%-8% reduction for energy price scenario compared to a baseline in the long run. Sectoral measures, such as European CO₂ emission performance standard, that aim to improve vehicle fuel efficiency/emission rates could potentially lead to significant reductions, but such measures face uncertainties in policy compliance and technical barriers, such as uncertain return on investments in new technologies. This study also finds that fuel efficiency improvements of new vehicles have dominant direct effects on energy consumption reduction, compared to the rebound effects of energy consumption that are induced by corresponding decreased transport prices (€/tkm).

However, comparing scenarios, the improvements of new vehicle fuel efficiency do not lead to lower transport energy consumption than increases in carbon taxes/fuel prices in the short/mid term due to a lag of updating vehicle stock with new technologies. Since the Paris Agreement urges a greenhouse gas (GHG) emissions peak as soon as possible, multiple policy instruments (mandated standards and pricing tools) should be considered in a dynamic way. Notably, in spite of few commercially mature vehicle technologies, adoption of biofuel and alternative freight vehicles are expected to bring additional reductions in future energy consumption and emissions. In all, for a low carbon future for freight transport, integrated efforts are needed to develop a comprehensive policy agenda and promote low or zero emission vehicle technologies, especially for HGVs.

This paper is laid out as follows. Section 2 reviews existing literature. Section 3 illustrates

the methods. Section 4 presents the data and model calibration. Section 5 presents and discusses simulation results, which is followed with conclusions in Section 6.

2 Literature review

In this section existing modelling research on the representation of the transport sector in models that combine energy, environment and economy, and also transport-focused models are reviewed.

Global Change Assessment Model (GCAM) is a multi-region dynamic-recursive partial equilibrium model with a technology-rich representation of different sectors, including freight and passenger transport (Kyle and Kim, 2011). The passenger transport model in GCAM is further expanded by Zhang et al. (2018) and Mishra et al. (2013). In their transport models, total transport service demand is driven by GDP, an index price for transportation, and population. The competition between transport modes and vehicle technologies is based on a nested-logit function where the shares of mode/vehicle demand are determined by levelized transport costs. Other multi-sector models, such as MESSAGE (McCollum et al., 2017), WITCH (Carrara and Longden, 2017), and REMIND (Luderer et al., 2015), differ in the way they represent the transport sector. For example, the total transport demand in the REMIND transport model is endogenously calculated through a nested CES (constant elasticity of substitution) function, while total transport demand in the WITCH transport model is exogenously projected based on GDP and car ownership. In these three models, the competition between transport mode and vehicle technologies are determined through a least-cost approach.

Different from the multi-sector models, a global transport-focused model, Mobility Model (MoMo) relies on expert judgement and detailed country-specific transport profiles of vehicle characteristics, sectoral policies, energy consumption and emissions in the passenger and freight transport sectors (Fulton et al., 2009). However, it is not possible for MoMo to endogenously simulate changes in travel demand and shifts between transport modes and technologies in response to market and cost changes.

To evaluate impacts of climate and transport policies on the transport sector, national transport energy models have been established with considerable technological details of transport systems, but most models focus on modelling passenger transport and lack responses to market and cost changes for the choices between transport modes and technologies (Brand et al., 2012; Kloess and Müller, 2011; Merven et al., 2012; Mulholland et al., 2016; Daly and Gallachóir, 2011; Whyte et al., 2013).

Currently in Ireland practitioners rely on running separate models with different modelling frameworks, such as private car model (Daly and Gallachóir, 2011; Alam et al., 2017), LGVs model (Mulholland et al., 2016), and HGVs model (Whyte et al., 2013). Daly and Gallachóir (2011) developed a private passenger car fleet model with car profiles by fuel type, engine size and age. Projected overall transport demand is disaggregated by fixed weight factors that are estimated proportionally based on historical data and do not respond to cost changes directly. Another Irish passenger car model by Alam et al. (2017) calculates Tank-to-Wheel (T2W) and Well-to-Wheel (W2W) CO₂ emissions. Mulholland et al. (2016) apply a similar modelling framework as Daly and Gallachóir (2011) to simulate the Irish LGV fleet. Instead of relying on exogenous variables (income and its elasticities), Mulholland et al. (2016) project vehicle sales based on the level

of stock required to satisfy total transport activities. For HGVs Whyte et al. (2013) model transport demand (*tonne – kilometres*) and energy consumption (*MJ/tonne – kilometre*) using an commodity-based approach without detailed technological profiles of HGVs (e.g., vehicle stock and activities). Lastly, apart from these Irish transport simulation models which describe transport systems based on its logical representation and historical data-driven assumptions, the Irish TIMES energy system model (Gallachóir et al., 2012) determines optimal configurations for the Irish energy and transport system.

In all, most existing transport models focus on private passenger cars. There is a similar policy need to model and analyse freight transport in a comprehensive way. Different from passenger transport modelling, freight transport modelling is subject to more heterogeneities among decision makers (e.g. suppliers, shippers, wholesalers, retailers and consumers), vehicle types, and cargo units. Further research on modelling transport is needed to i) improve transport modelling, especially for freight transport, with technological details at national level where specific transport-related policies are usually implemented, ii) incorporate responses of transport demand to market and cost changes, iii) integrate behavioural realism in the transport (energy) model to strengthen the representation of competition between transport modes and vehicle technologies. The present study establishes a transport model that includes these three aspects to explore future paths of energy consumption and emissions for freight transport.

3 Methodology

3.1 Model overview

In this paper, a national freight transport model is developed to analyse the freight transport sector and its emissions by incorporating transport modes and vehicle technological details by fuel type, unladen weight and year of registration (age). As shown in Figure 1, the model consists of four modules: vehicle stock module, transport demand module, fuel consumption module and emission module. The model calculates and projects freight transport activities (*kilometre (km)* or *tonne – kilometre (tkm)*), and estimates the associated energy consumption (*litre (l)* or *megajoule (MJ)*), CO₂ emissions (*tonne*) and air pollutants (*tonne*). The freight transport model is calibrated based on historical data.

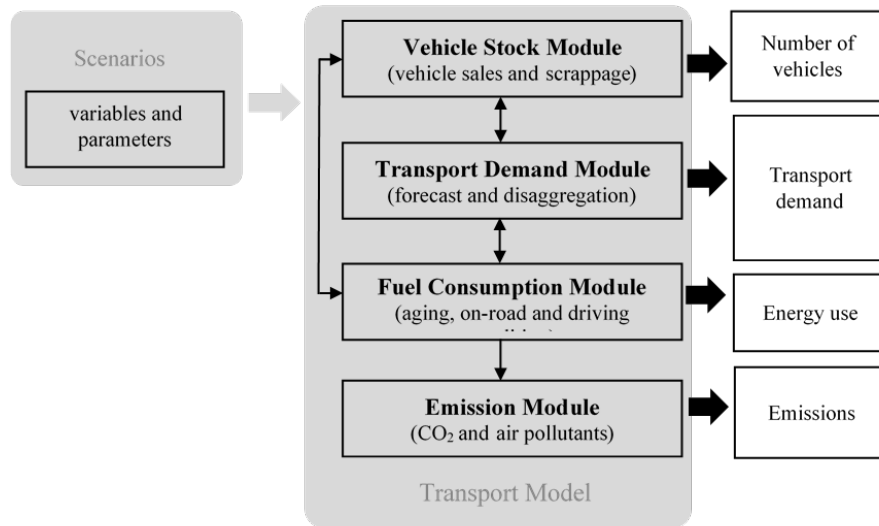


Figure 1: The modelling framework.

Figure 2 displays the nested structure of the freight transport model, which reflects the competition between transport modes and between vehicle technologies. Vehicles are

disaggregated into groups on each level. The model includes all freight transport modes; road, rail, aviation and shipping. For road freight transport, transport demand and goods vehicle stock are disaggregated by vehicle fuel types, unladen weight and year of registration. In this multi-level structure, transport demand is projected with a top-down approach from total sectoral freight transport demand to demand by vehicles types. The demand disaggregation is based on the costs of transport modes/vehicles types, including vehicle prices, taxes and fuel costs. The costs are calculated as weighted averages with a bottom-up approach from specific goods vehicles types, to transport modes, and to the whole sector of freight transport.

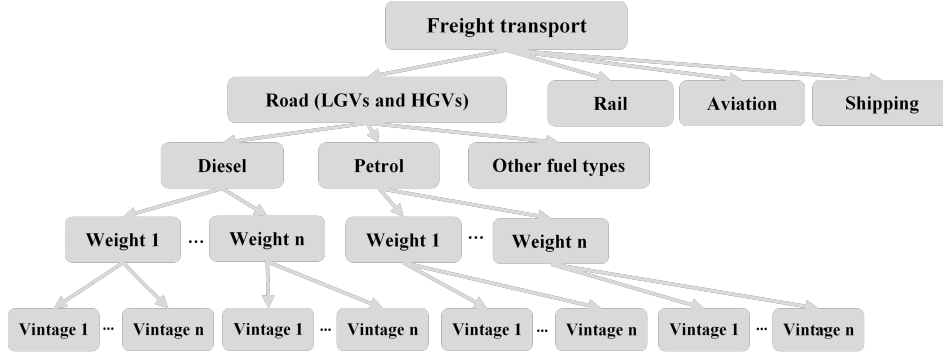


Figure 2: The nested structure of transport demand by mode and vehicle technology.

3.2 Freight transport model

The equations in the following subsections are used to calibrate the freight transport model. The full list of variables and parameters and their descriptions are given in Table 4 in the Appendix.

3.2.1 Transport demand module

Overall freight transport

Conventionally, the growth of overall freight transport demand (*tkm*) is determined by changes in economic activities (e.g., GDP) and fuel prices (Brand et al., 2012; Mishra et al., 2013; IEA, 2017). In Equation 1, overall freight transport demand, TD_t is derived as an econometric equation of exogenous variables (GDP and fuel price) and their respective elasticities of demand. Where, t represents the year, ΔGDP is the year-on-year percentage change in GDP and ΔFP is the year-on-year percentage change in fuel price. The elasticities, φ_{GDP} and φ_{FP} , represent percentage changes in transport demand corresponding to a change of 1% in GDP and fuel prices, respectively.

$$TD_t = TD_{t-1} \times (1 + \Delta GDP \times \varphi_{GDP}) \times (1 + \Delta FP \times \varphi_{FP}) \quad (1)$$

Freight transport by transport mode

Overall sectoral freight transport demand consists of demand by modes – rail, road (LGVs & HGVs), shipping and aviation. The demand breakdown by modes is calculated by applying demand shares of transport modes in the overall transport demand in Equation 2. TD_{tm} is transport demand by mode, and SD_{tm} is the demand share by mode with m representing transport modes.

The determination of demand shares by mode depends on indices of transport prices by modes (€/tkm) which embraces costs related to vehicle purchase and use and by intangible factors, such as availability of infrastructures, location and time of delivery. The

calculation of demand shares is shown in Equation 3. SD_{tm} is determined by price index - generalized price by mode, GP_{tm} ($\text{€}/tkm$). GP_{tm} can be obtained either by dividing the total revenue of a transport mode (e.g., rail transport) by the total demand, or by aggregating prices of vehicles (e.g., road transport) by fuel type, unladen weight band and year of registration. In Equation 3, the representation of competition between transport modes uses a modified logit equation, following similar applications of this equation by Mittal et al. (2017) and Zhang et al. (2018) in their global passenger models³. Later, the revised logit equation is also applied in Equation 6 and Equation 9 to represent the competition between vehicle technologies.

In Equation 3, α_m is a set of alternative-specific coefficients that are calibrated to the base year. Each alternative-specific coefficient captures specific preferences for a particular choice alternative (a transport mode or a vehicle technology) (Mishra et al., 2013). The preference may be caused by existing infrastructure, industrial preference, social and technological barriers to the market. β^{mode} is a price coefficient for all modes. The price coefficient determines the scales of differences in demand shares by modes caused by the price differences (Mishra et al., 2013). Different from Mishra et al. (2013), the price coefficient in this research is estimated empirically by OLS regression with historical data based on Equation 3⁴.

Generalized prices are defined as weighted average prices based on generalized prices of the elements in the level below in the nested structure (Figure 2). In Equation 4, the

³The original logit (choice) equation is formulated as $s = \alpha_i \times \exp(\beta \times p_i) / \sum_{i \in I} \alpha_i \times \exp(\beta \times p_i)$ (Mishra et al., 2013). i represents one of the alternatives and I is a set of alternatives. Compared to the original form, the revised logit equation (Equation 3) is much less sensitive to incremental differences in the choice indicator. For instance, with this revised equation, it takes more time to eliminate uncompetitive old technologies and adopt new technologies, such as electric vehicles.

⁴The revised logit equation $SD = (\alpha_i \times GP_i^\beta) / \sum_{i \in I} (\alpha_i \times GP_i^\beta)$ can be transformed to $\ln(SD_i / SD_j) = \beta \times \ln(GP_i / GP_j) + \ln(\alpha_i / \alpha_j)$ to estimate β . $j \in J$, but $i \neq j$.

generalized prices of road freight by mode are calculated by summing the products of the generalized prices by mode and fuel type, GP_{tmf} and transport demand share by mode and fuel type, SD_{tmf} . F is a set of vehicle fuel types within each mode.

$$TD_{tm} = TD_t \times SD_{tm} \quad (2)$$

$$SD_{tm} = \frac{\alpha_{tm} \times GP_{tm}^{\beta^{mode}}}{\sum_{m \in M} (\alpha_{tm} \times GP_{tm}^{\beta^{mode}})} \quad (3)$$

$$GP_{tm} = \sum_{f \in F} (SD_{tmf} \times GP_{tmf}) \quad (4)$$

Road freight transport by vehicle fuel type

Road freight transport modes are specified with their fleets in this model. The transport demand of road freight (LGVs & HGVs) by mode can be further divided into demand by mode and fuel type, TD_{tmf} , in Equation 5. In Equation 6, the shares of transport demand by transport mode and fuel types, SD_{tmf} are determined by generalized prices by mode and fuel type (GP_{tmf}), a price coefficient (β^{fuel}) and a set of alternative-specific coefficients (α_{mf}) for all vehicles by mode and fuel types. GP_{tmf} is calculated as the sum product of generalized prices by mode, fuel and unladen weight, GP_{tmfw} , and demand shares by mode, fuel type and unladen weight, SD_{tmfw} in Equation 7. W is a set of vehicle unladen weight bands within each fuel type.

$$TD_{tmf} = TD_{tm} \times SD_{tmf} \quad (5)$$

$$SD_{tmf} = \frac{\alpha_{mf} \times GP_{tmf}^{\beta^{fuel}}}{\sum_{f \in F} (\alpha_{mf} \times GP_{tmf}^{\beta^{fuel}})} \quad (6)$$

$$GP_{tmf} = \sum_{w \in W} (SD_{tmfw} \times GP_{tmfw}) \quad (7)$$

Road freight transport by vehicle fuel type and unladen weight band

The road freight transport demand by mode and fuel types is further broken down into demand by mode, fuel type and unladen weight, TD_{tmfw} in Equation 8. In Equation 9, the calibration of SD_{tmfw} depends on GP_{tmfw} . β^{weight} is a price coefficient by transport mode, fuel type and weight band. α_{mfw} are alternative-specific coefficients by mode, fuel type and weight band. In Equation 10, GP_{tmfw} is calculated. GP_{tmfw} is the generalized price by mode, fuel type, weight band and year of registration. SD_{tmfwv} is the share of transport demand by mode, fuel type, weight band and year of registration. V is a set of years for each weight band of vehicles.

$$TD_{tmfw} = TD_{tmf} \times SD_{tmfw} \quad (8)$$

$$SD_{tmfw} = \frac{\alpha_{mfw} \times GP_{tmfw}^{\beta^{weight}}}{\sum_{w \in W} (\alpha_{mfw} \times GP_{tmfw}^{\beta^{weight}})} \quad (9)$$

$$GP_{tmfw} = \sum_{v \in V} (SD_{tmfwv} \times GP_{tmfwv}) \quad (10)$$

Road freight transport by vehicle fuel type, unladen weight band and year of registration

The disaggregation by fuel, weight and year of registration is on the bottom level of the nested structure (Figure 2). The demand shares and generalized prices by fuel, weight and year of registration, SD_{tmfwv} and GP_{tmfwv} , are calculated in Equations 11 - 13.

$$SD_{tmfwv} = \frac{TD_OLD_{tmfwv}}{\sum_{v \in V} TD_OLD_{tmfwv}} \quad (11)$$

$$TD_OLD_{tmfwv} = OldVehicle_{tmfwv} \times VD_OLD_{tmfwv} \times LF_{tmfw} \quad (12)$$

In Equation 11, the demand share by fuel, weight and year of registration is calculated intuitively as a portion of the overall demand. TD_OLD_{tmfwv} is the total freight transport demand by transport mode, fuel, weight and year of registration for existing vehicles survived from the previous year. The total freight transport demand (tkm) is defined as the product of the number of vehicles, annual kilometre travelled per vehicle (km) and average load factor (tonnes carried per vehicle) in Equation 12. TD_OLD_{tmfwv} is annual vehicle distance travelled per vehicle for existing vehicles. $OldVehicle_{tmfwv}$ is the number of existing vehicles survived from the previous year. LF_{tmfw} is average load factor for good vehicles by fuel type and weight band.

When calculating GP_{tmfw} and SD_{tmfwv} , only existing vehicles are included. It is assumed

that new vehicles purchased in the current year do not affect current GP_{tmfw} since new vehicles comprise a relatively small share of the total freight vehicle stock. Another reason is that the numbers of new vehicle sales in the current year are unknown. The new vehicle sales are projected endogenously with the transport demand in the transport model.

In Equation 13, GP_{tmfwv} is calculated as the sum of different cost components - vehicle prices ($Carprice_{tmfwv}$), purchase taxes ($PurchaseTax_{tmfwv}$), fuel cost ($FuelCost_{tmfwv}$), and annual ownership taxes ($OwnershipTax_{tmfwv}$)⁵. The fuel cost is calculated as the product of vehicle distance (km), fuel efficiency (l/km) and fuel price ($€/l$). Vehicle prices and purchase taxes are one-off payments. They are annualized with assumptions on vehicle life time and discounting rate.

$$GP_{tmfwv} = Carprice_{tmfwv} + PurchaseTax_{tmfwv} + OwnershipTax_{tmfwv} + FuelCost_{tmfwv} \quad (13)$$

In the transport demand module, the referred vehicle distance and car number in Equation 12 and Equation 13 are obtained from the vehicle stock module of the freight transport model in Section 3.2.2

3.2.2 Vehicle stock module

The vehicle stock module models vehicle stock by fuel type, weight band and year of registration. The module provides the number of freight vehicles (LGVs and HGVs) and

⁵Fuel cost represents the main differences in operational costs between vehicle technologies (Sharpe, 2017).

annual vehicle distance travelled. This module enables evaluations of economic, technical and policy effects on the ownership and use of different vehicle types.

The population of freight vehicles changes every year due to the scrappage of existing vehicles and purchases of new vehicles. In Equation 14, the total number of vehicles by fuel and weight, $TotalVehicles_{tmfw}$, in the current year is equal to the sum of existing vehicles, $OldVehicles_{tmfw}$, survived from the previous year and new vehicles, $NewVehicles_{tmfw}$, purchased in the current year.

The number of existing vehicles in the current year is calculated by subtracting the number of vehicles scrapped from the number of all vehicles in the previous year. To calculate the existing vehicle stock, $OldVehicles_{tmfw}$, Equation 15 is applied to each vehicle technology by fuel, weight and year of registration across age groups, a . Age is defined as the difference between year of registration, v , and year of calculation, t . The scrappage rate, $ScapRate_{a,mfw}$ is calculated as an average scrappage rate by fuel, weight, and age based on historical vehicle registration profiles (Daly and Gallachóir, 2011), as shown in Equation 16.

$$TotalVehicles_{tmfw} = OldVehicles_{tmfw} + NewVehicles_{tmfw} \quad (14)$$

$$OldVehicles_{tmfw} = \sum_{v \in V} TotalVehicles_{t-1,mfww} \times ScapRate_{a,mfw} \quad (15)$$

$$ScapRate_{a,mfw} = Average_{a,mfw} \left(\frac{TotalVehicle_{tmfw} - TotalVehicle_{t-1,mfw}}{TotalVehicle_{t-1,mfw}} \right) \quad (16)$$

This freight transport model determines the number of new vehicles, $NewVehicle_{tmfw}$, endogenously, instead of relying on exogenous variables, such as income, fuel price and population in many other transport models. The number of new vehicles is calculated as the number of vehicles that are needed to fulfil the part of transport demand that the existing vehicles cannot provide. The calculation of new vehicle sales is in Equation 17. VD_NEW_{tmfw} is the annual vehicle distance travelled per vehicle for new vehicles by fuel and weight. VD_NEW_{tmfw} is unchanged over time, while annual distance travelled by existing cars, VD_OLD_{tmfw} (in Equation 12), declines with increasing age of vehicles.

$$NewVehicle_{tmfw} = \frac{TD_{tmfw} - TD_OLD_{tmfw}}{VD_NEW_{tmfw} \times LF_{tmfw}} \quad (17)$$

3.2.3 Energy and emission modules

Overall energy consumption, TF_t , and emissions, TE_t , from freight transport are calculated for all modes. Non-road freight transport modes are not specified with their fleets in this model. Average energy efficiency (l/tkm) and emission rates (g/tkm) are applied directly to calculate their energy consumption and emissions. As for road freight transport mode, vehicle specific fuel efficiency (MJ/km) and emission rates (g/km) are used.

Overall energy consumption and emissions are calculated as the sum of total energy

consumption and emissions by vehicle fuel type, weight band and year of registration for both existing vehicles and new vehicles. Total energy consumption (or emissions) is the product of the number of vehicles, annual distance travelled and fuel efficiency (or emission rates) in Equation 18 and 19. $FE_OLD_{tmf_{wv}}$ and $ER_OLD_{tmf_{wv}}$ are fuel efficiency and emission rates for existing vehicles. $FE_NEW_{tmf_{wv}}$ and $ER_NEW_{tmf_{wv}}$ are fuel efficiency and emission rates for new vehicles. $VD_OLD_{tmf_{wv}}$ and $VD_NEW_{tmf_{wv}}$ are annual distance travelled per vehicle for existing and new vehicles.

Fuel efficiency (emission rates) of existing vehicles increases as vehicles get older due to engine deterioration, while those of new vehicles have been reduced with technological progress and technical regulations. The variables for fuel efficiency and emission rates for new and existing vehicles vary by year. Therefore, the variables are labelled with a subscript, t .

$$TF_t = \sum_{v \in V} (OldVehicles_{tmf_{wv}} \times VD_OLD_{tmf_{wv}} \times FE_OLD_{tmf_{wv}}) + \sum_{v \in V} (NewVehicles_{tmf_{wv}} \times VD_NEW_{tmf_{wv}} \times FE_NEW_{tmf_{wv}}) \quad (18)$$

$$TE_t = \sum_{v \in V} (OldVehicles_{tmf_{wv}} \times VD_OLD_{tmf_{wv}} \times ER_OLD_{tmf_{wv}}) + \sum_{v \in V} (NewVehicles_{tmf_{wv}} \times VD_NEW_{tmf_{wv}} \times ER_NEW_{tmf_{wv}}) \quad (19)$$

4 Data and model calibration

The freight transport model is applied to land (rail and road) freight transport sector in Ireland. The demand of domestic aviation and shipping are negligible in Ireland. In the model, road freight transport is specified with its vehicle fleet, including two fuel types⁶, ten weight bands⁷ and vehicle year of registration from 1999.

4.1 Transport demand

The yearly data (from 2008 to 2017) of freight transport demand are used to calibrate this model. Rail freight transport demand data are obtained directly from the Central Statistics Office (CSO)⁸ Ireland. Road freight transport demand (tkm) is calculated with annual vehicle distance travelled (km per vehicle), average load factors ($tonnes$ carried per vehicle) (Table 5 of Appendix), and the numbers of vehicles which is explained later in Section 4.2. The data of annual vehicle distance travelled by vehicle fuel type, weight band and year of registration are obtained from the Sustainable Energy Authority of Ireland (SEAI)⁹ and the CSO. Further data descriptions are given in Table 8 of Appendix. For LGVs, average load factors follow the assumptions in the UK transport carbon model (UKTCM) (Brand et al., 2012). For HGVs, average load factors by weight band are estimated from the CSO Road Freight Transport Survey dataset, which has a valid sample

⁶Goods vehicles stock and new sales are dominated by diesel powered vehicles which historically accounts for more than 99% of the total numbers.

⁷Goods vehicles are divided into five light goods vehicles, LGVs, ($<1017\ kg$, $1017-1270\ kg$, $1271-1524\ kg$, $1525-1778\ kg$, and $1779-2032\ kg$) and five heavy goods vehicles, HGVs, ($2033-5080\ kg$, $5081-7112\ kg$, $7113-10160\ kg$, $10161-12192\ kg$ and $>12193\ kg$).

⁸<https://www.cso.ie/en/index.html>

⁹<https://www.seai.ie/>. Data are originally from Department of Transport, Tourism and Sport in Ireland and Commercial Vehicle Roadworthiness Test (CVRT)

size of around 10,000 HGVs.

Overall freight transport demand is projected with future changes in GDP and fuel prices are estimated by an Irish computable general equilibrium (CGE) model (named I3E) (De Bruin, 2019). The long-run GDP and fuel price elasticities of demand (*tonne – kilometre*) are assumed to be 0.66 and -0.18 based on a review of traffic-related elasticities research (de Jong et al., 2010; Dunkerley et al., 2014; Dimitropoulos et al., 2018). Diesel price is used to represent the fuel price due to the dominance of diesel-powered goods vehicles in the Irish freight transport sector. The annual distance travelled by new vehicles in the future is assumed to be the same as the distance data for new vehicles in the base year. The historical average decay rates of annual distance travelled by existing vehicles are estimated to be -2.5% for LGVs and -0.3% for HGVs.

4.2 Vehicle stock

The number of goods vehicles is disaggregated by fuel, weight and year of registration. The vehicle registration data from 2008 to 2017 are from Department of Transport, Tourism and Sport (DTTAS) in Ireland for both LGVs and HGVs. The scrappage rates of vehicles by weight band and age (Appendix Figure 8) are estimated based on the historical data.

4.3 Fuel efficiency and emissions rates

The vehicle fuel efficiency data used in the model are by fuel type, weight band and year of registration. The data are assembled from different datasets from the SEAI and the Environmental Protection Agency (EPA) in Ireland. The fuel efficiency data from the

EPA assumes an average HGV load rate of 50% . In this study, a 20% on-road factor is considered for the manufacture-labelled vehicle fuel efficiency. Further data descriptions are in Table 8 in the Appendix. In addition, the annual deterioration rate of goods vehicles' engines is assumed to be 0.3% to represent the year-on-year increase in the fuel consumption per kilometre of used vehicles, as (Van den Brink and Van Wee, 2001) estimate for cars. The average rate of fuel efficiency improvement for new vehicles is estimated to 2.0% for LGVs and 0.4% for HGVs based on historical data.

The CO₂ emission rates for petrol and diesel are assumed to be 70.0 g/MJ and 73.3 g/MJ ¹⁰. Weighted CO₂ emission rates (g/MJ) are assumed considering 6% blending of biofuel (biodiesel and bioethanol) in 2015 (base year for projection in the model), as required by the Irish Biofuels Obligation Bill 2015.

4.3.1 Other variables and parameters

Vehicle prices of LGVs are collected as recommended prices from manufacturers' websites and HGV prices follow the assumptions in the UKTCM model (Brand et al., 2012). Vehicle tax rates and fuel prices are from the ACEA tax guide (ACEA, 2016) and the CSO. In addition, to discount future vehicle costs, the expected vehicle lifetime is assumed to be 15 years and the discount rate is 5%. For calculating rail generalized price, annual freight transport revenue data are taken from the Irish Rail annual reports ¹¹.

Apart from generalized prices, projected transport demand is disaggregated based on several sets of alternative-specific coefficients and price coefficients from the logit-type choice

¹⁰<https://www.seai.ie/data-and-insights/seai-statistics/conversion-factors/>

¹¹<https://www.irishrail.ie/About-Us/Company-Information/Iarnrod-Eireann-Annual-Reports>

functions reported in Table 6 and 7 in the Appendix. The coefficients are estimated based on historical activity and vehicle stock data from 2008 to 2017 applying OLS regressions.

4.3.2 Policy scenarios

One baseline and four policy scenarios are considered. A description of the scenarios is given in Table 1. The baseline assumes that policies are unchanged and historical trends of technological improvements continue. The policy scenarios consider high energy prices, increases in carbon taxes, the removal of the diesel rebate scheme, and improvements in fuel efficiency.

Energy price scenario

Increasing energy prices are assumed over the scenario duration based on projected energy prices from De Bruin (2019), which in turn is based on the EU Reference Scenario 2016 (Capros et al., 2016). Figure 3 illustrates diesel price, which grows by 23% between 2015 and 2050.

Carbon tax scenario

In Ireland, a carbon tax of €10/tonne was introduced in 2010 and increased to €20/tonne in 2014. The carbon tax scenario sets an annual increase of €5 per tonne of CO₂ from 2020 (€30/tonne) to 2030 (€80/tonne)¹². After 2030, the carbon tax remains at €80/tonne.

Diesel rebate scenario

¹²Budget 2020 increased the level of carbon tax to €26 per tonne in Ireland. The increase applied to auto fuels from October 2019 and to solid fuels from May 2020.

A diesel rebate scheme came into effect in 2013 in Ireland. It repays some of the mineral oil tax paid by a qualifying road transport operator (mainly for heavy duty vehicles). The diesel rebate rates are between €0.000-0.075 per litre¹³. In the diesel rebate scenario, the diesel rebate (€/litre) is removed from 2020.

Fuel efficiency scenario

The European CO₂ emission performance standard for new light commercial vehicles and a newly-introduced standard for new heavy commercial vehicles aim to reduce fleet-wide average emissions of new light commercial vehicles by 31% by 2030 compared to 2021, and new heavy commercial vehicles by 30% by 2030 compared to 2005, respectively (EC, 2019b,a). This emission standard implies average annual improvement rates of 4.0% and 1.4% for new LGVs and HGVs. In the fuel efficiency scenario, the rates are set as 3.0% and 0.9% for new LGVs and HGVs between 2015 and 2050. These rates in the scenario are assumed to be lower than the rates implied by the emission standard to reflect underlying barriers in adopting new fuel-efficient and alternative vehicle technologies¹⁴.

These policy scenarios lead to changes of GDP and fuel prices based on CGE modelling of markets (De Bruin, 2019). The resulting GDP and fuel prices are the inputs to the freight transport model to capture the impacts of the macroeconomic system on transport activities. Differences in projected GDP among scenarios are relatively small, but diesel prices vary substantially across scenarios, as shown in Figure 3. Removing diesel rebate

¹³The diesel rebate targets goods vehicles over 7.5 tonnes unleaded weight (HGVs). There is no repayment when diesel prices, including VAT, are at or below €1.23 per litre. The maximum amount repayable is 7.5 cent per litre when diesel prices, including VAT, are €1.54 per litre or over. (<https://www.revenue.ie/en/companies-and-charities/excise-and-licences/mineral-oil-tax/diesel-rebate-scheme/index.aspx>)

¹⁴The average annual improvement rates of fuel efficiency for new vehicles implied by the emission standard are used for sensitivity analysis and results discussion in Section 5.2

for HGVs or improving new vehicle fuel efficiency has negligible impacts on national GDP and fuel prices.

Table 1: Scenario summary

Scenarios	Policy changes	Technological changes	Type of change
Energy Prices Scenario	High international energy prices for petrol and diesel	-	Economy-wide
Carbon Tax Scenario	Carbon tax increases to 80 euro per ton by 2030	-	Economy-wide
Diesel Rebate Scenario	Diesel rebate is removed from 2020	-	Sector specific
Fuel Efficiency Scenario	-	Annual improvement of 3.0% for new LGVs and 0.9% for new HGVs	Sector specific

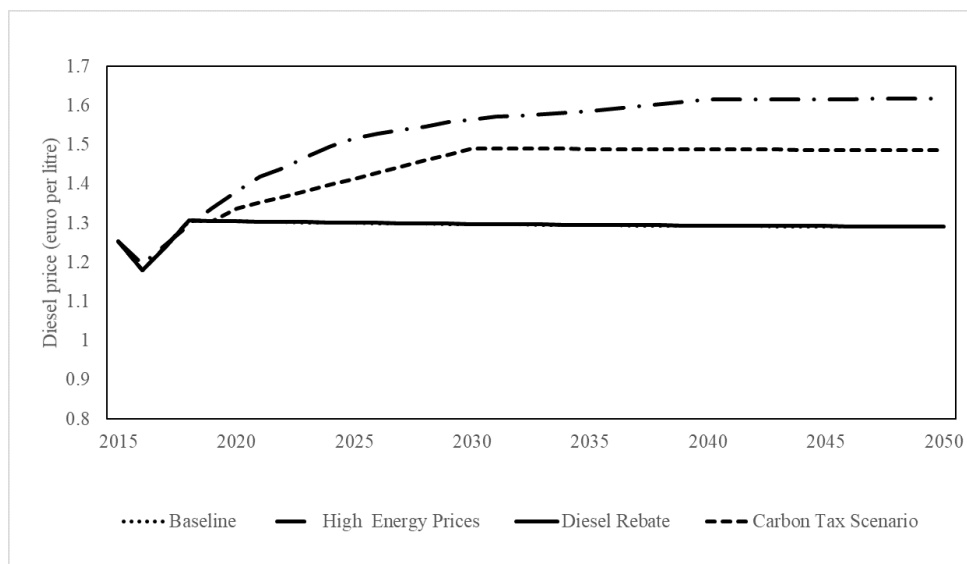


Figure 3: Diesel price from 2015 to 2050.

5 Results and discussion

This section presents and discusses the results of the various scenarios focussing on freight transport demand, energy consumption and CO₂ emissions in Ireland from 2015 to 2050.

5.1 Transport service demand

In Figure 4, total transport service demand (million *tkm*) projected from 2015 to 2050 is presented. In all scenarios, transport demand increases by approximately 100-110% (slightly above 2% annually), from 13,080 million *tkm* in 2015 to approximately 26,000-27,500 million *tkm* in 2050. Economic growth over the same period approximately doubles (210%). The removal of the diesel rebate scheme for HGVs and new vehicle fuel efficiency changes do not have substantial effects on GDP and fuel prices, and therefore, on the total transport demand. In the scenarios with higher carbon taxes and energy prices, the annual growth of demand is slower than that in the baseline.

Comparing transport demand in 2050 in the carbon tax and energy price scenarios to that in the baseline, the results show that the increases in carbon tax and energy prices lead to demand reductions of 3% and 4% respectively. A carbon tax increase and changes in energy prices have economy-wide impacts, mainly affecting fuel prices without specifically targeting sectoral performance in transportation. In the current model, the fuel price elasticity of freight transport demand is -0.18. Even with a relatively high fuel price elasticity of transport demand, such as -0.3 (de Jong et al., 2010; Dunkerley et al., 2014; Dimitropoulos et al., 2018), associated demand reductions would be 5% and 8% in 2050. Such fuel price related demand reductions (in the order of 3-8%) are relatively small compared to the total growth of transport demand, which is driven mainly by GDP. Fuel costs only account for 20-30% of operating costs for road haulage companies (Hooper and Murray, 2018; Sharpe, 2017) and therefore, limited influences of fuel price related policies on transport service price and demand are expected.

In the carbon tax and energy price scenarios, the carbon tax rate (€/tonne) and fuel price (€/litre) increase during the period between 2015 and 2030, and are relatively stable after 2030. These increases lead to lower annual growth rates of transport demand for 2015-2030 compared to 2030-2050. The average annual growth rates of transport demand are 1.91% for 2015-2030 and 2.14% for 2030-2050 in the carbon tax scenario, and 1.85% for 2015-2030 and 2.11% for 2030-2050 in the energy price scenario. However, in the baseline, such rates for both periods are around 2.10%.

Notably, overall freight transport demand is mainly associated with economic activity (measured by GDP). Although the decoupling of transport demand and economic activity is contentious in the empirical research, decoupling can be achieved by factors, such as logistics optimization and improvements in supply chain management (Alises et al., 2014; Alises and Vassallo, 2015). Therefore, overall transport demand may be overestimated if the model is not responsive to aggressive decoupling. Transport demand projections by other studies estimate a growth in Europe of surface or land transport demand of 86% from 2015 to 2050 or 82% from 2010 to 2050 (ITF, 2017; Ambel et al., 2017). For the UK, Brand et al. (2012) project an increase of domestic freight transport by 73% by 2050. Compared to these estimates, our estimated transport demand in Ireland is somewhat higher (approximately 100-110%).

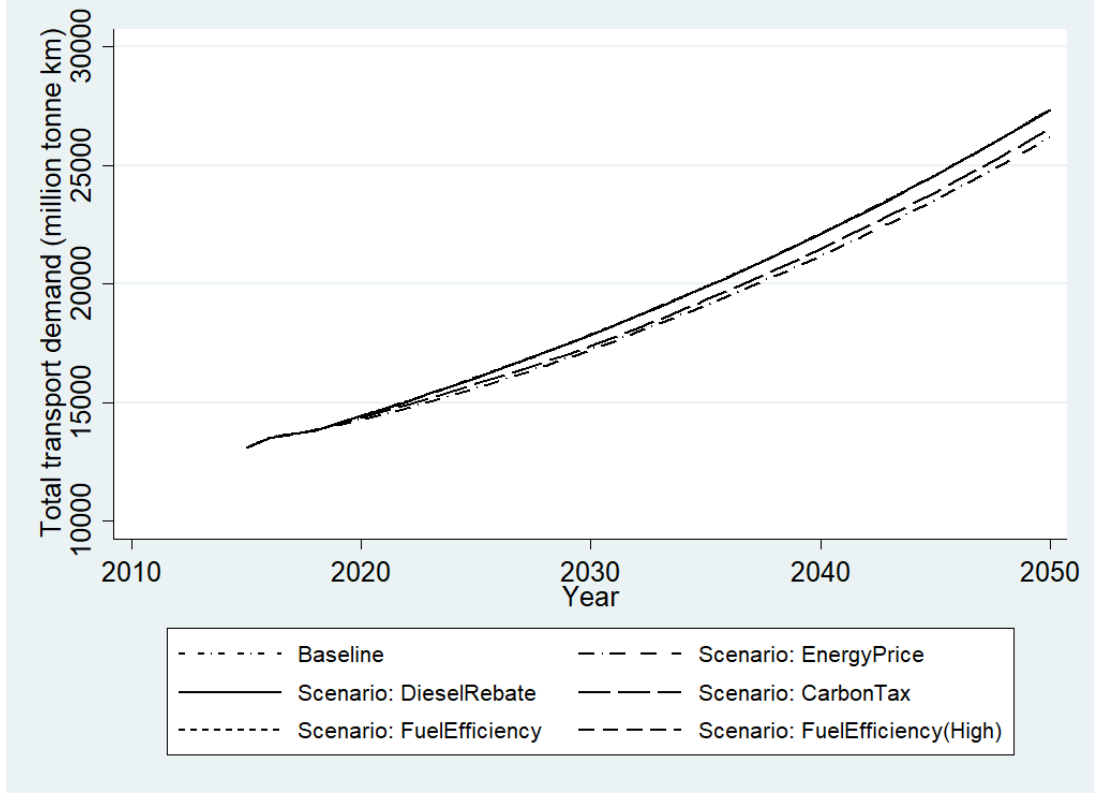


Figure 4: Total transport service demand projected from 2015 to 2050.

Figure 5 presents the breakdown of total transport demand by transport mode. Among all land freight transport modes, HGVs account for the bulk of the tonne kilometres in freight transport (93% - 94%), followed by LGVs (5% - 6%) and rail (less than 1%). In the baseline from 2015 to 2050, the shares of HGVs and rail in the total demand decrease by 0.5% and 0.1%, respectively, while the share of LGVs increases by 0.6%. This is because that with higher rates of fuel efficiency improvements, LGVs have a larger reduction in transport prices than HGVs. In the other scenarios, changes in demand shares follow similar trends to those in the baseline. However, the scales of changes vary across scenarios. When the diesel rebate is removed (impacting mainly HGVs), HGVs show slightly higher reductions in demand share from 2015 to 2050 (0.6%), compared to the baseline. Removing the diesel rebate increases fuel costs of HGVs and therefore, discourages HGV activities. However,

the impact of the diesel rebate on total energy consumption by HGVs and LGVs is rather small since the rebate rates is less than 2.5% of diesel prices ¹⁵.

The reduction of HGV demand share from 2015 to 2050 is higher in the scenarios of carbon tax and energy price than in the baseline. This is because HGVs are more sensitive to changes in fuel prices than LGVs due to their higher fuel consumption per kilometre. As fuel costs of HGVs are significantly reduced in the fuel efficiency scenario, where HGVs fuel efficiency is improved by 0.9% annually, HGVs have the lowest reduction (0.4%) in demand share in this scenario. In addition, no specific policies are implemented to support a transport freight demand shift to rail in all scenarios. The demand of rail freight, as a lower emission transport mode, is almost constant between 2015 and 2050.

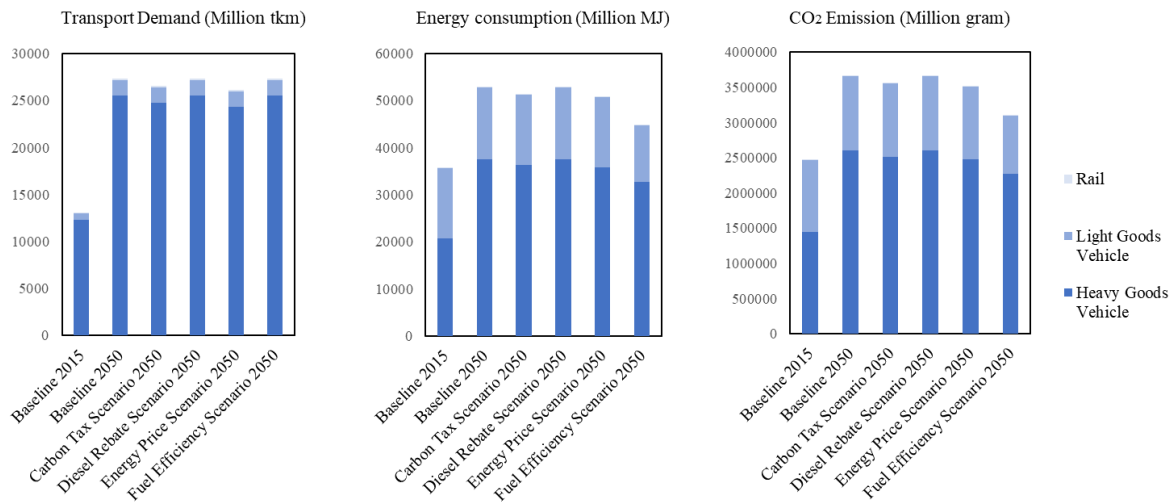


Figure 5: Transport service demand by modes.

Overall, freight transport demand shifts between the transport modes from 2015 to 2050 are relatively small. This is mainly due to following three reasons:

i) The foreseen interventions in most of the scenarios are moderate, especially for the

¹⁵In 2015, the historical average rebate rates are between 0.000 and 0.022 €/per litre. <https://www.revenue.ie/en/companies-and-charities/excise-and-licences/mineral-oil-tax/diesel-rebate-scheme/diesel-rebate-rates.aspx>

period of 2030-2050. Each policy intervention is applied alone and independent in the scenarios to identify its own impacts on transport demand. The integrated and long-term effects, such as policy-induced improvements in technologies and supply chain management, are not included.

ii) Currently options for shifting to other freight vehicles technologies (e.g. natural gas, electric trucks and hydrogen trucks) are limited (Sharpe, 2017; Kluschke et al., 2019)¹⁶. Additionally, Ireland has a limited capacity and usage of rail for freight transport.

iii) Freight transport activities are less amenable to shifts to low emission modes/vehicles, compared to passenger transport. This is because freight transport is more heterogenous concerning modes/vehicle types (load capacity and weight), types of goods delivered by industries (for instance, courier services for LGVs and carrying fuel and minerals for HGVs), and decision makers of transport activities (suppliers, transporters, and consumers).

5.2 Energy consumption

Figure 6 shows that total energy consumption increases between 2015 and 2050 across the scenarios. The baseline has the highest overall growth rate of total energy consumption (48.2%), followed by the diesel rebate scenario (48.4%), carbon tax scenario (44.0%), energy price scenario (42.4%), and fuel efficiency scenario (25.5%). The growth rate of energy consumption is around half of the growth rate of transport demand, which reflects an improvement in average fuel efficiency (MJ/tkm) in the freight transport. Notably, energy consumption in the fuel efficiency scenario may be higher, in the short or mid term,

¹⁶In Europe, five manufacturers account for nearly 100% of the market, where for cars the top 7 car manufacturers capture < 50% (Ambel et al., 2017).

than energy consumption in the carbon tax and energy price scenarios. This is due to a lag in greening the vehicle stock by introducing new fuel-efficient technologies gradually in the fuel efficiency scenarios.

In the high fuel efficiency scenario (dash line in Figure 6), the improvements of fuel efficiencies in new LGVs and HGVs are higher than those in other scenarios, which lead to a much smaller growth of energy consumption by 4.7% from 2015 to 2050. The projections show fuel efficiency/CO₂ improvements of new vehicles can be very effective towards the decarbonization of transport sector. Although there has been a stagnation in fuel efficiency since 2000 (ICCT, 2016), there is still potential to increase vehicle efficiency with existing fuel-saving technologies for diesel/gasoline vehicles. Three vehicle segments - panel van, rigid box truck, and tractor-trailer, have maximum cost-effective technical reduction potentials of 30%-40% (Norris and Escher, 2017). However, full fuel efficiency improvements of a whole goods vehicle fleet indicated by the new vehicle emission standards can be ambitious considering uncertainties in policy compliance and technical barriers, especially for alternative vehicle technologies. Four types of barriers are identified as uncertain return on investment, high capital cost restraints, split incentives between vehicle owner and operator, and lack of technology availability (Sharpe, 2017).

Comparing energy consumption in the scenarios in 2050 to 2015, the results show that an increase of carbon tax, higher international energy prices and significant energy efficiency improvements of new vehicles lead to energy consumption reductions of 3%, 4% and 10%. As discussed in Section 5.1, with a higher elasticity of demand to fuel price, increases in carbon tax and energy prices leads to around 5% and 8% reduction in energy consumption. However, the removal of diesel rebate (for HGVs) leads to a slight increase of energy

consumption of 0.2%, as transport demand slightly shifts to LGVs which have higher energy consumption per *tkm* than HGVs.

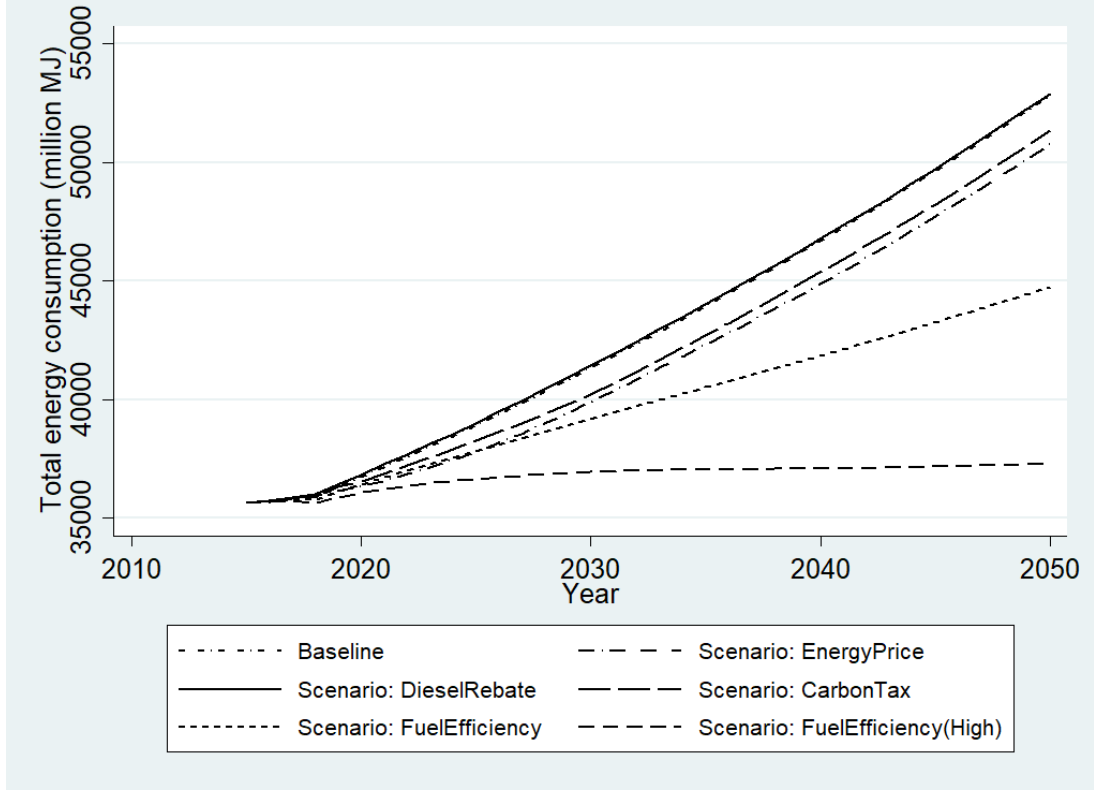


Figure 6: Total energy consumption from 2015 to 2050.

The scenario comparison and growth rates of energy consumption between 2015 and 2050 by transport mode are presented in Figure 5 and Table 3. Overall, HGVs have higher growth rates of energy consumption than LGVs. In the baseline, the energy consumption of HGV increases by 81% from 20,791 million *MJ* in 2015 to 37,541 million *MJ* in 2050, while that of LGVs increases by 3% from 14,836 million *MJ* in 2015 to 15,241 million *MJ* in 2050. The scenarios follow similar growth trends as the baseline. Only the scenario of higher fuel efficiency improvement for new vehicles exhibits a different trend, where the growth of HGV energy consumption is lower at 58%, while the energy consumption of LGVs decreases by 20%.

In the freight transport model, fuel efficiency improvements have two types of effects on total energy consumption.

- i) “direct effects”: fuel efficiency improvements reduce fuel consumption per kilometre directly, and lower total energy consumption, as shown in Equation 18.
- ii) “indirect effects”: fuel efficiency improvements reduce transport generalized prices in Equation 13, and therefore, lead to higher transport demand and higher energy consumption in the choice functions in Equation 3, 6 and 9. The indirect effects are associated to shifts of transport demand between transport modes and technologies. This refers to rebound effects caused by fuel efficiency improvements (Khazzoom, 1980).

In the fuel efficiency scenario, the annual improvement rates of fuel efficiency for new LGVs and HGVs (3% and 0.9%) are much higher than baseline (2% and 0.4%). The results in Table 2 show that energy consumption for HGVs and LGVs in the fuel efficiency scenario in 2015 and two scenarios for 2050. The scenario labelled 2050 includes both direct and indirect effects. The scenario labelled 2050* is assumed to have no changes in relative transport service prices, which lead to fixed demand shares of transport modes over years. Under the scenario, indirect effects are excluded¹⁷. In the absence of indirect effects (demand shifts between transport modes and technologies) transport demand for each mode has the same growth rate of 109% from 2015 to 2050* (109% is the growth rate of overall transport demand from 2015 to 2050). Applying average energy efficiency, MJ/tkm , energy consumption in 2050* are obtained in Table 2.

Net effects (direct and indirect effects) of fuel efficiency improvements on energy con-

¹⁷In the calculation, the overall freight transport demand is assumed to be affected by GDP and fuel prices. Rebound effects of overall demand induced by improved vehicle fuel efficiency are not considered.

sumption are calculated as the differences between energy consumption in 2015 and 2050. Direct effects are calculated as the differences between energy consumption in 2015 and 2050*. Indirect effects are the differences between net effects and direct effects. The indirect effects are smaller, compared to the direct effects. As LGVs become more fuel efficient, energy consumption decreases. However, greater fuel efficiency improvements of LGVs leads to a relatively larger reduction in transport service prices ($\text{€}/tkm$) than HGVs, which results in demand shifts from HGVs to LGVs and increases LGVs' energy consumption to some degree.

Table 2: Direct and indirect effects of fuel efficiency improvements

	Transport demand			Energy consumption			Average energy efficiency		Net effects on energy consumption	Direct effects on energy consumption	Indirect effects on energy consumption
	(Million tkm)			(Million MJ)			MJ/tkm		(Million MJ)	(Million MJ)	(Million MJ)
	2015	2050	2050*	2015	2050	2050*	2015	2050	2050	2050	2050
HGV	12,277	25,556	25,674	20,791	32,769	32,920	1.69	1.28	11,978	12,129	-151
LGV	707	1,635	1,478	14,836	11,938	10,793	20.99	7.30	-2,897	-4,043	1,146
Rail	96	162	202	25	42	52	0.26	0.26	17	27	10
Total	13,080	27,353	27,353	35,652	44,750	43,765					

Table 3 also presents the annual growth rates of vehicle stock, transport demand and energy consumption for HGVs and LGVs. The vehicle stock grows by around 1.9-2.3% annually, together with annual growth of 2.0-2.5% in total transport demand, which is stronger in LGVs than in HGVs. Compared with the growth of transport demand, energy consumption has lower annual growth rates for HGVs and LGVs, as newer and more efficient vehicles enter the stock. In all, in spite of the fuel efficiency improvements, total energy consumption for HGVs increases with total transport demand driven by the growth of GDP, while the total energy consumption of LGVs decreases.

Table 3: Growth rates of energy and relevant variables from 2015 to 2050 for HGVs and LGVs.

Scenario	Type	Energy consumption (million MJ)		Overall growth rate (%)	Annual growth rate (%)		
		2015	2050		Vehicles	Transport demand	Energy consumption
Baseline	HGV	20,791	37,541	80.56	2.00	2.11	1.70
	LGV	14,836	15,241	2.73	2.26	2.45	0.08
CarbonTax	HGV	20,791	36,279	74.49	1.89	2.02	1.60
	LGV	14,836	15,001	1.11	2.22	2.40	0.03
DieselRebate	HGV	20,791	37,564	80.67	2.00	2.11	1.70
	LGV	14,836	15,289	3.05	2.27	2.46	0.09
EnergyPrice	HGV	20,791	35,731	71.86	1.85	1.98	1.56
	LGV	14,836	14,982	0.99	2.22	2.40	0.03
FuelEfficiency	HGV	20,791	32,769	57.61	1.98	2.12	1.31
	LGV	14,836	11,938	-19.53	2.24	2.43	-0.62

5.3 CO₂ Emissions

Figure 7 shows that baseline CO₂ emissions from freight transport increase by 48.2% between 2015 and 2050 (from 2.5 million to 3.7 million tonnes), followed by 48.4% in the diesel rebate scenario, 44.0% in the carbon tax scenario, 42.4% in the energy price scenario and 25.5% in the fuel efficiency scenario. The CO₂ emissions in the fuel efficiency scenario is about 10% less than that in the baseline in 2050. The emission reduction could be 20% if full potential of new vehicle fuel efficiency improvements can be realized in the (high) fuel efficiency scenario, as shown by the dash line in Figure 7.

In all scenarios a fixed blending rate (6% in volume) of biofuel (biodiesel and bioethanol) into diesel and gasoline is assumed when calculating CO₂ emissions. The blending of biofuel brings an additional reduction in CO₂ emissions of 5.5% for diesel and 3.9% for gasoline. The blending rate is expected to increase in the future, but there are tech-

nical ceilings regarding the amount of biofuel that can be blended given current engine technologies.

The transport sector accounted for 9% of Irish GHG emissions in 1999, while in 2015, the share increased to 20% (DCCAE, 2017). The 2020 EU non-ETS target is a 20% reduction, compared to 2005. This target increases to a 30% reduction by 2030 and a 80% reduction by 2050 DCCAE (2013, 2019). The EU White Paper on Transport also sets a 60% reduction target of transport GHG emission in 2050 compared to 1990 (EC, 2011). Overall emission reduction (or renewable) targets have been set for the whole transport sector. Most political attention has been paid to passenger transport, such as private cars. Without strong policy instruments in the freight transport sector, few technological and commercially matured alternative vehicle technologies will be available to replace the conventional goods vehicles, especially for HGVs (Kluschke et al., 2019). Given the strong growth of total CO₂ emissions over time in the scenarios, it will be a challenge for freight transport to make positive contributions to the sectoral emission reductions targets.

Apart from fuel efficiency improvements, adoption of alternative vehicles (e.g. electric vehicle and hydrogen/fuel cell vehicles) can also contribute to freight transport decarbonization. The combination of using battery electric vehicle technologies, e-highways, hydrogen or fuel cell trucks could offer a complementary pathway to zero-emission freight transport in 2050 (Ambel et al., 2017). DTTAS (2019) presents an indicative forecast of alternative fuelled vehicles. In 2030 projected vehicle numbers include 23,000 electric light duty vehicles, 5 electric heavy duty vehicles, 4,500 CNG (compressed natural gas) light duty vehicles and 150 CNG heavy duty vehicles. A simplified calculation is undertaken here to show the potential of emission reductions from shifting to alternative vehicles

(electric and CNG vehicles). The projected new vehicles are assumed to replace LGVs and HGVs that operate in 2030. A uniform average annual distance travelled per vehicle, 21,519 km ¹⁸, is used here, although alternative vehicles may have lower distances travelled than conventional vehicles. If diesel trucks, electric trucks and CNG trucks are assumed to have CO₂ emission rates of 434 g/km , 0 g/km and 363 g/km ¹⁹, total CO₂ emissions can be reduced by 221,954 tonnes, which is around 8% of overall freight transport emissions in 2030 (baseline). The simplified estimation with a “what-if” scenario shows an addition reduction of 8% can be achieved by shifting to alternative vehicles up to 2030. However, the freight transport model does not directly capture the penetration of new alternative vehicle and fuel technologies. First, lack of historical data on new alternative vehicles sales in Ireland is an obstacle to empirically estimate parameters in the choice functions. Secondly, many of the alternative vehicle technologies are not commercially available in Ireland. There are uncertainties in the future technical developments of vehicles capacity, fuel efficiency and costs, which makes it hard to predict transport service prices. Nevertheless, the coefficients and parameters can be set arbitrarily based on expert opinions and technological characteristics, which is out of the scope of this paper.

¹⁸<https://statbank.cso.ie/px/pxeirestat/Statire/SelectVarVal/Define.asp?maintable=THA10&PLanguage=0>

¹⁹https://www.gasnetworks.ie/business/natural-gas-in-transport/celtic-linen-case-study/CNG_Case_Study.pdf

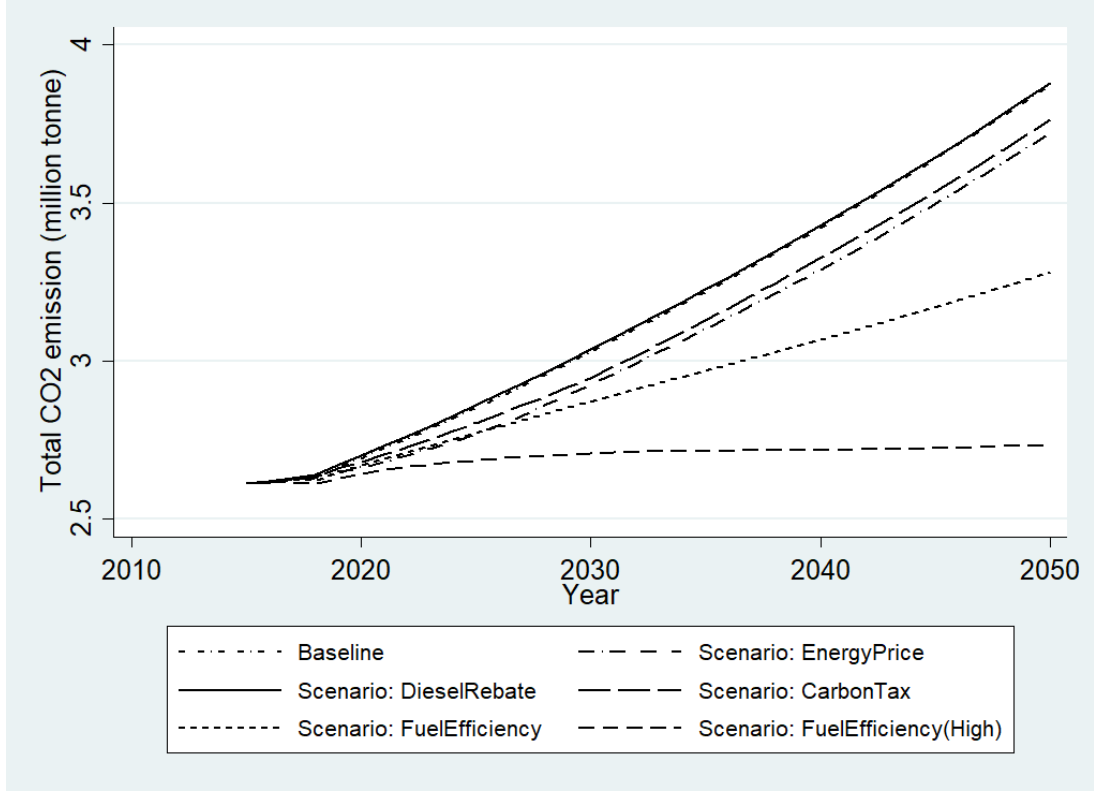


Figure 7: Total CO₂ emission projected from 2015 to 2050.

5.4 Policy implications

In this section we discuss the potential policy implications of the results presented in this paper.

First, increases in carbon tax and international energy prices are able to reduce the total freight transport demand (tkm) but on a modest scale. Pricing policies, such as carbon taxes or fuel taxes, have an influence on fuel prices and operating costs of freight transport activities, and therefore, affect transport demand. The modest impacts of pricing policies (or modest demand elasticities to fuel prices) indicate the lack of substitutes between transport modes and vehicle technologies in the freight transport sector. LGVs and HGVs have great differences in their industrial purpose of freight activities and cannot easily

be substituted for each other. Additionally, Ireland lacks low emission substitutes of transport mode (e.g., rail and waterway) for freight activities.

Second, unlike economy-wide policies (e.g., carbon tax), the removal of the diesel rebate for HGVs barely impacts economic activity, fuel prices and transport demand. The removal of the diesel rebate increases the operating costs of diesel HGVs. Diesel goods vehicles dominates current goods vehicle market, in particular for HGVs. The removal of the diesel rebate is expected to shift energy consumption from diesel to non-diesel fuels and from HGVs to other transport modes (e.g., LGVs and rail). Without more options in alternative vehicle technologies (e.g., electric truck) and low emission modes (e.g., rail), and supply chain optimization, freight energy consumption shifts from diesel to gasoline and from HGVs to LGVs in our results. This shift does not significantly affect total energy consumption and emissions in the freight transport sector.

Third, sectoral policies to improve vehicle fuel efficiency have the potential to significantly reduce energy consumption and emissions from freight transport in the long run to meet climate targets. Improvements in fuel efficiency of new vehicles directly reduce energy consumption without putting restrictions on transport demand (or economic activities), in spite of small rebound effect caused by lower transport prices ($\text{€}/tkm$). However, fuel efficiency or CO₂ emission performance standards face uncertainties in policy compliances due to potential technical barriers. Improvements due to new vehicle fuel efficiency will have several years to be realised due to the lag in updating the vehicle stock. Pricing policies, such as a carbon tax have a more immediate effect. Given the urgency for both early and substantial emissions reduction in the Paris Agreement²⁰, multiple policy

²⁰<https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement>

instruments should be considered.

As shown by the additional calibration and sensitivities analysis in Sections 5.1, 5.2 and 5.3, there are many other factors affecting freight transport demand and energy consumption. These factors, such as supply chain management, renewable energy and alternative vehicle technologies all have a role to play in reducing energy consumption and emissions from freight transport but are not considered within this analysis. The most obvious policy conclusion from this analysis is that policies focussed on incentivizing shifts by increasing costs of emissions to freight transporters will only be effective if transporters have alternative low carbon transport modes and/or technologies.

6 Conclusion

To achieve a low emission future for freight transport, policy instruments (e.g., fuel related taxation and emission standards) are being discussed in the political arena as well as in academic research for the purposes of improving energy efficiency, shifting to low emission modes, and managing supply chains and logistics. To provide a useful analytical tool to investigate the implications of policies and pathways to low carbon freight transport, this paper develops a freight transport model for projecting transport demand, energy consumption and associated emissions. This necessarily involves policy scenarios, which do not intend to make precise and comprehensive projections of future outcomes, but rather are used to compare the effectiveness of policies on freight transport and explore possible options with limited resources in the face of future uncertainties.

In this model, overall transport demand is driven by economic activity (GDP) and fuel

prices (including carbon tax). Transport demand is attributed to different transport modes and vehicle technologies using discrete choice functions based on historical profiles of activities, vehicle characteristics (fuel types, unladen weight bands and age) and vehicle costs. Correspondingly, energy consumption and emissions are calculated using a bottom-up approach. Such a model contributes to the existing literature by providing advanced technological details in freight transport modelling, responses of transport demand to market and cost changes, and behavioural responses in the representation of competition between transport technologies. The model provides insights to policymakers attempting to influence freight transport patterns and achieve substantial emissions reductions from the sector.

This paper presents results by applying the model to Ireland with scenarios running from 2015 to 2050. The results show a strong growth of land freight transport demand in Ireland resulting from economic growth (GDP), despite increased carbon taxes, fuel price fluctuations and other factors discussed in this paper. The modelling results tend to favor policies improving new vehicle energy efficiency. Such policies, for example, the European CO₂ emission performance standards on light and heavy-duty vehicles, have the potential to effectively slow down the growth of energy consumption from 2015 to 2050, but policy compliance and technical barriers need to be considered to fully understand the policy implications. Additionally, the improvement of new vehicle fuel efficiency may not lead to lower transport energy consumption than increases in carbon taxes/fuel prices in the short/mid term due to a lag in updating the vehicle stock with new technologies.

Given the goals of the Paris Agreement and the limited impacts of policies to decrease emissions, as seen in this study, multiple policy instruments should be considered. Fur-

thermore, the timing of various policies needs in depth consideration. For example, it is observed that LGVs in the fuel efficiency scenario are more likely to have a reduction in energy consumption and emissions in later years. Promoting low/zero emission alternative vehicles and renewable energy can bring substantial reductions in final CO₂ emissions. In all, for a low carbon future for freight transport, integrated efforts are needed to develop a comprehensive policy agenda (mandated standards, such as fuel efficiency standards, and price mechanism, such as carbon taxes) and promote low or zero emission vehicles technologies, especially for heavy goods vehicles.

The results from the freight transport model differ from what is usually anticipated in passenger models which is the focus of the bulk of existing studies on decarbonisation of transport. Freight transport demand is less elastic to policy-induced price signals, and CO₂ emissions are less likely to be reduced adequately to meet climate targets. By its nature, freight movements are more heterogeneous with respect to industrial purposes, decision making agents, and vehicle loads/capacities. The uniqueness of freight transport should be considered when developing policy initiatives to facilitate a transition to a low-carbon freight transport sector.

Apart from the full integration of alternative technologies in the modelling framework, future research calls for applications of the freight transport model to countries with significant demand share of rail freight, aviation and shipping to provide insight in freight transport mode shifting. Moreover, further demand-related interactions between transport sector in the transport model and other economic sectors in a macroeconomic model, such as feedback from transport model to a general equilibrium model, enable an evaluation of economy-wide impacts of transport policies and vehicle fleet changes.

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References

- ACEA (2016). Acea tax guide 2016. Available at: <https://www.acea.be/news/article/acea-tax-guide-2016-released>.
- Alam, M. S., Hyde, B., Duffy, P., and McNabola, A. (2017). Assessment of pathways to reduce co2 emissions from passenger car fleets: Case study in ireland. *Applied Energy*, 189:283–300.
- Alises, A. and Vassallo, J. M. (2015). Comparison of road freight transport trends in europe. coupling and decoupling factors from an input–output structural decomposition analysis. *Transportation Research Part A: Policy and Practice*, 82:141–157.
- Alises, A., Vassallo, J. M., and Guzmán, A. F. (2014). Road freight transport decoupling: A comparative analysis between the united kingdom and spain. *Transport Policy*, 32:186–193.
- Ambel, C. C., Earl, T., Kenny, S., Cornelis, S., and Sihvonen, J. (2017). Roadmap to climate-friendly land freight and buses in europe. Available at: <https://www.transportenvironment.org/publications/roadmap-climate-friendly-land-freight-and-buses-europe>.
- Brand, C., Tran, M., and Anable, J. (2012). The uk transport carbon model: An integrated life cycle approach to explore low carbon futures. *Energy Policy*, 41:107–124.
- Capros, P., De Vita, A., Tasios, N., Siskos, P., Kannavou, M., Petropoulos, A., Evangelopoulou, S., Zampara, M., Papadopoulos, D., Nakos, C., et al. (2016). Eu reference

- scenario 2016-energy, transport and ghg emissions trends to 2050. Available at: http://pure.iiasa.ac.at/id/eprint/13656/1/REF2016_report_FINAL-web.pdf.
- Carrara, S. and Longden, T. (2017). Freight futures: The potential impact of road freight on climate policy. *Transportation Research Part D: Transport and Environment*, 55:359–372.
- Daly, H. E. and Gallachóir, B. P. Ó. (2011). Modelling future private car energy demand in ireland. *Energy Policy*, 39(12):7815–7824.
- DCCAE (2013). National policy position on climate action and low carbon development. Available at: <https://www.dccae.gov.ie/en-ie/climate-action/publications/Pages/National-Policy-Position.aspx>.
- DCCAE (2017). National mitigation plan 2017. Available at: <https://www.dccae.gov.ie/en-ie/climate-action/publications/Pages/National-Mitigation-Plan.aspx>.
- DCCAE (2019). Climate action plan 2019. Available at: <https://www.gov.ie/en/publication/ccb2e0-the-climate-action-plan-2019/>.
- De Bruin, Kelly C, Y. A. M. (2019). The effects of an incremental increase in the irish carbon tax towards 2030. Available at: <https://www.esri.ie/system/files/publications/WP619.pdf>.
- de Jong, G., Schroten, A., van Essen, H., Otten, M., and Bucci, P. (2010). The price sensitivity of road freight transport: A review of elasticities. *Applied transport economics, a management and policy perspective*, De Boeck, Antwerp.

- Dimitropoulos, A., Oueslati, W., and Sintek, C. (2018). The rebound effect in road transport: A meta-analysis of empirical studies. *Energy Economics*, 75:163–179.
- DTTAS (2018). Transport trends: An overview of ireland’s transport sector 2018. Available at: <https://www.gov.ie/en/publication/e5a556-transport-trends-an-overview-of-irelands-transport-sector-2018/>.
- DTTAS (2019). National policy framework on alternative fuels infrastructure for transport in ireland: 2017 to 2030. Available at: <https://www.gov.ie/en/publication/dca438-national-policy-framework/>.
- Dunkerley, F., Rohr, C., and Daly, A. (2014). Road traffic demand elasticities: A rapid evidence assessment. Available at: https://www.rand.org/pubs/research/_reports/RR888.html.
- EC (2011). White paper on transport: Roadmap to a single european transport area: Towards a competitive and resource-efficient transport system. Available at: https://ec.europa.eu/transport/themes/strategies/2011/_white/_paper/_en.
- EC (2016). A european strategy for low-emission mobility. Available at: <https://www.eea.europa.eu/policy-documents/a-european-strategy-for-low>.
- EC (2019a). Regulation (eu) 2019/1242 of the european parliament and of the council of 20 june 2019 setting co2 emission performance standards for new heavy-duty vehicles. Available at: <https://eur-lex.europa.eu/eli/reg/2019/1242/oj>.
- EC (2019b). Regulation (eu) 2019/631 of the european parliament and of the council of 17 april 2019 setting co2 emission performance standards for new passenger cars and

- for new light commercial vehicles. Available at: <https://eur-lex.europa.eu/eli/reg/2019/631/oj>.
- EMEP/EEA (2016). air pollutant emission inventory guidebook 2016. Available at: <https://www.eea.europa.eu/publications/emep-eea-guidebook-2016>.
- Fulton, L., Cazzola, P., and Cuenot, F. (2009). Iea mobility model (momo) and its use in the etp 2008. *Energy Policy*, 37(10):3758–3768.
- Gallachóir, Ó., Brian, P., Chiodi, A., Gargiulo, M., Deane, P., Lavigne, D., and Rout, U. K. (2012). Irish times energy systems model. Available at: <https://cora.ucc.ie/handle/10468/7293>.
- Girod, B., van Vuuren, D. P., Grahn, M., Kitous, A., Kim, S. H., and Kyle, P. (2013). Climate impact of transportation a model comparison. *Climatic change*, 118(3-4):595–608.
- Hooper, A. and Murray, D. (2018). An analysis of the operational costs of trucking: 2017 update. Available at: <https://trid.trb.org/view/1552714>.
- ICCT (2016). European vehicle market statistics, 2016/2017. Available at: <https://theicct.org/publications/european-vehicle-market-statistics-20162017>.
- IEA (2016). World energy outlook 2016. Available at: <https://www.iea.org/reports/world-energy-outlook-2016>.
- IEA (2017). The future of trucks – implications for energy and the environment. Available at: <https://webstore.iea.org/the-future-of-trucks>.

- ITF (2017). Itf transport outlook 2017. Available at: <https://www.itf-oecd.org/transport-outlook-2017>.
- Khazzoom, J. D. (1980). Economic implications of mandated efficiency in standards for household appliances. *The energy journal*, 1(4).
- Kloess, M. and Müller, A. (2011). Simulating the impact of policy, energy prices and technological progress on the passenger car fleet in austria—a model based analysis 2010–2050. *Energy Policy*, 39(9):5045–5062.
- Kluschke, P., Gnann, T., Plötz, P., and Wietschel, M. (2019). Market diffusion of alternative fuels and powertrains in heavy-duty vehicles: A literature review. *Energy Reports*, 5:1010–1024.
- Kyle, P. and Kim, S. H. (2011). Long-term implications of alternative light-duty vehicle technologies for global greenhouse gas emissions and primary energy demands. *Energy Policy*, 39(5):3012–3024.
- Luderer, G., Leimbach, M., Bauer, N., Kriegler, E., Baumstark, L., Bertram, C., Giannousakis, A., Hilaire, J., Klein, D., Levesque, A., et al. (2015). Description of the remind model (version 1.6). Available at: <https://www.pik-potsdam.de/research/transformation-pathways/models/remind/>.
- McCollum, D. L., Wilson, C., Pettifor, H., Ramea, K., Krey, V., Riahi, K., Bertram, C., Lin, Z., Edelenbosch, O. Y., and Fujisawa, S. (2017). Improving the behavioral realism of global integrated assessment models: An application to consumers’ vehicle choices. *Transportation Research Part D: Transport and Environment*, 55:322–342.

- Merven, B., Stone, A., Hughes, A., and Cohen, B. (2012). Quantifying the energy needs of the transport sector for south africa: A bottom-up model. Available at: <https://open.uct.ac.za/handle/11427/16905>.
- Mishra, G. S., Kyle, P., Teter, J., Morrison, G. M., Kim, S., and Yeh, S. (2013). Transportation module of global change assessment model (gcam): model documentation. Available at: https://www.researchgate.net/publication/262933366_Transportation_Module_of_Global_Change_Assessment_Model_GCAM_Model_Documentation_-_Version_10.
- Mittal, S., Dai, H., Fujimori, S., Hanaoka, T., and Zhang, R. (2017). Key factors influencing the global passenger transport dynamics using the aim/transport model. *Transportation Research Part D: Transport and Environment*, 55:373–388.
- Mulholland, E., O’Shea, R. S., Murphy, J. D., and Gallachóir, B. P. Ó. (2016). Low carbon pathways for light goods vehicles in ireland. *Research in Transportation Economics*, 57:53–62.
- Muncrief, R. and Sharpe, B. (2015). Overview of the heavy-duty vehicle market and co2 emissions in the european union. Available at: <https://theicct.org/publications/overview-heavy-duty-vehicle-market-and-co2-emissions-european-union>.
- Norris, J. and Escher, G. (2017). Heavy duty vehicles technology potential and cost study. Available at: <https://theicct.org/publications/heavy-duty-vehicles-technology-potential-and-cost-study>.
- Schäfer, A. (2012). Introducing behavioral change in transportation into en-

- ergy/economy/environment models. Available at: <https://hvtc.edu.vn/Portals/0/files/6356909146562691961813-9450-6234.pdf>.
- Sharpe, B. (2017). Barriers to the adoption of fuel-saving technologies in the trucking sector. Available at: https://theicct.org/sites/default/files/publications/HDV-fuel-saving-tech-barriers_ICCT-briefing_07072017_vF_0.pdf.
- Van den Brink, R. M. and Van Wee, B. (2001). Why has car-fleet specific fuel consumption not shown any decrease since 1990? quantitative analysis of dutch passenger car-fleet specific fuel consumption. *Transportation Research Part D: Transport and Environment*, 6(2):75–93.
- Venturini, G., Tattini, J., Mulholland, E., and Gallachóir, B. Ó. (2019). Improvements in the representation of behavior in integrated energy and transport models. *International Journal of Sustainable Transportation*, 13(4):294–313.
- Whyte, K., Daly, H. E., and Gallachóir, B. P. Ó. (2013). Modelling hgv freight transport energy demand in ireland and the impacts of the property construction bubble. *Energy*, 50:245–251.
- Zhang, R., Fujimori, S., Dai, H., and Hanaoka, T. (2018). Contribution of the transport sector to climate change mitigation: insights from a global passenger transport model coupled with a computable general equilibrium model. *Applied energy*, 211:76–88.

Appendix

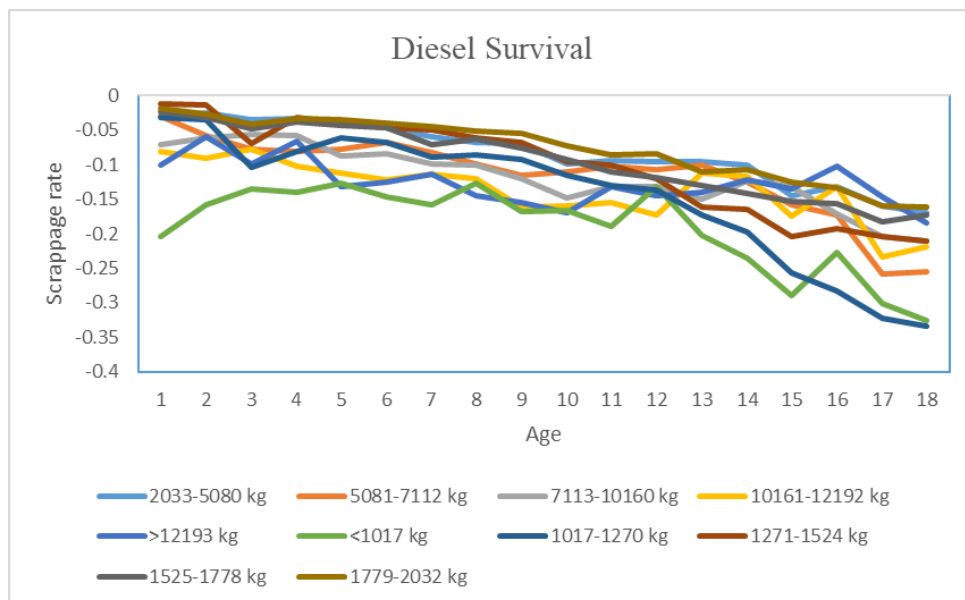


Figure 8: Scrappage rates by weight band for diesel vehicles.

Note: There are a very small number of petrol LGVs and almost no petrol HGVs exist in most of the weight bands. The scrappage rates for diesel vehicles are applied in this case.

Table 4: Variables and parameters.

Notation		Description	Units
Subscripts	t	Year	
	m	Transport mode (e.g. rail and road)	
	f	Vehicle fuel type (e.g., petrol and diesel)	
	w	Vehicle unladen weight band (e.g., H1(2033-5080 kg))	
	v	Year of registration	
	a	Age	
	M	A set of transport modes. (mM).	
	F	A set of vehicle fuel types. (fF).	
	W	A set of vehicle unladen weight bands. (wW).	
	V	A set of years of registration. (vV).	
Variables	TD	Overall transport demand of freight transport sector	tkm
	TD_{OLD}	Total transport demand of existing goods vehicles	tkm
	TD_{NEW}	Total transport demand of new goods vehicles	tkm
	VD_{OLD}	Annual vehicle distance travelled (per vehicle) for old vehicles	km
	VD_{NEW}	Annual vehicle distance travelled (per vehicle) for new vehicles	km
	GP	Generalized price	$€/tkm$
	SD	Transport demand share	%
	$TotalVehicles$	The total number of all vehicles (existing and new vehicles)	
	$OldVehicles$	The total number of old vehicles	
	$NewVehicles$	The total number of new vehicles	
	$CarPrice$	Car price vehicles	€
	$PurchaseTax$	Purchase tax (vehicle registration tax)	€
	$FuelCost$	Fuel cost	€
	$OwnershipTax$	Vehicle ownership tax	€
	FE_{OLD}	Specific fuel consumption of old goods vehicles	MJ/km
	FE_{NEW}	Specific fuel consumption of new goods vehicles	MJ/km
	ER_{OLD}	Specific emission rate of old goods vehicles	g/km
	ER_{NEW}	Specific emission rate of new goods vehicles	g/km
	TF	Overall fuel consumption of freight transport sector	MJ
	TE	Overall emission of freight transport sector	g
	GDP	Gross Domestic Product	€
	FP	Fuel Price	€
Parameters	LF	Average load factor per goods vehicle	$tonnes$
	$ScrapRate$	Average scrappage rate	%
	φ_{GDP}	GDP elasticity of transport demand	
	φ_{FP}	Fuel price elasticity of transport demand	
	α	A set of alternative-specific coefficients by mode	
	β	Price coefficient by mode	

Table 5: Load factors.

Average tonnes per vehicle		2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Weight bands	L1	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11
	L2	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11
	L3	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
	L4	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
	L5	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
	H1	1.24	1.22	0.93	0.84	0.85	0.78	0.73	0.83	0.77	0.72
	H2	3.36	2.86	2.47	2.54	2.68	2.37	2.52	2.99	3.20	3.29
	H3	5.81	5.78	5.63	5.39	5.71	5.09	4.92	5.09	5.50	5.43
	H4	11.40	11.59	10.45	9.99	10.31	9.95	10.05	9.70	9.61	9.54
	H5	11.30	11.29	11.47	11.63	11.57	11.43	11.78	11.85	11.58	11.35

Table 6: Price coefficients.

	Price coefficient	Standard error	Number of observations
β_{mode}	-1.07	0.2900	9
β_{fuel}	-5.50	0.6140	40
β_{weight}	-0.71	0.0600	1981

Table 7: Alternative-specific coefficients.

	Mode	Fuel type	Weight band	Alternative-specific coefficients
α_m	Rail			.0018
	Road			1
α_{mf}	Road	diesel		1
	Road	petrol		1.02
α_{mfw}	Road	diesel	H1	94.08
	Road	diesel	H2	9.71
	Road	diesel	H3	26.78
	Road	diesel	H4	42.96
	Road	diesel	H5	113.89
	Road	diesel	L1	1
	Road	diesel	L2	12.75
	Road	diesel	L3	26.46
	Road	diesel	L4	25.14
	Road	diesel	L5	54.65
	Road	petrol	H1	13.49
	Road	petrol	H2	0.12
	Road	petrol	H3	0.70
	Road	petrol	H4	1.30
	Road	petrol	H5	1.84
	Road	petrol	L1	1
	Road	petrol	L2	2.52
	Road	petrol	L3	2.84
	Road	petrol	L4	2.83
	Road	petrol	L5	3.16

Note: Data source: own estimation.

Table 8: Data processing.

Data processing	
Activity data	<p>For LGVs, the distance data by vehicle fuel and weight are based on the national commercial vehicle road worthiness test (CVRT). The breakdown of the distance data by year of registration is calculated by using average historical distance decay rates. The decay rates are estimated from CSO road traffic volume data by year of registration for all LGVs. The road traffic volume dataset contains overall kilometres travelled based on odometer data for Irish goods vehicles. For HGVs, the road traffic volume dataset is broken down by weight band and year of registration. The data for HGVs is divided into vehicle fuel type profiles by assuming that annual distance travelled by petrol vehicles is 25% lower than that by diesel vehicles, since there are very few petrol HGVs in the stock.</p>
Fuel efficiency data	<p>For LGVs, the fuel efficiency of new vehicles by fuel and weight from SEAI have been recorded from 2011 to 2017. Back projection to 1999 is carried out based on an average rate. For HGVs, the (weighted average) fuel efficiency data (MJ/km) by fuel, weight band and year of registration is obtained by using vehicle stock (by year, fuel, weight band and euro standard) and fuel efficiency data (by fuel, weight band and euro standard) from EMEP/EEA (2016).</p>