Sustainable Energy Authority of Ireland

National Energy Research, Development & Demonstration Funding Programme

FINAL REPORT TEMPLATE

SECTION 1: PROJECT DETAILS – FOR PUBLICATION

Project Title	DRIFT-HDV: DecaRbonisation Irish HDV FleeT	
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Total Project Duration (months)	15	
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Project Summary (max 500 words)

Road freight transportation is a key enabler of economic activity in Ireland, but the industry is mostly dependent on fossil fuels for its energy source, which presents a challenge in realising a low-carbon future. The viable decarbonisation options for net-zero emission by 2050 (NZE2050) need to go beyond the 'low hanging fruits' of improving efficiency in diesel trucks or modal shift. Full decarbonisation requires a shift to new technologies and energy carriers. The technologies to cultivate include electric vehicles, electric roads/e-highways, hydrogen or fuel cell trucks and power-to-liquid options along with renewable liquid fuels in HDV sector.

This project reviewed international and European best practices and benchmarked the Irish HDV fleet against other comparator countries, followed by quantitative assessment of barriers and facilitators to adoption of the viable future technologies for decarbonisation of freight in Ireland. The study employed both a microscopic approach focusing on individual vehicle emissions and a energy systems optimisation approach focusing on various categories (and their inter dependence) of the Irish freight HDV fleet emissions. Vehicle Energy Consumption calculation Tool (VECTO) was used to simulate emissions from individual vehicles. The emissions and fuel consumption of conventional fuel vehicles were simulated and savings with various alternative fuel vehicles were estimated. Irish urban, regional, and freeway driving cycles were developed using real-naturalistic driving data from heavy-duty vehicles for simulating the emissions. Other required simulation related inputs such as the scalar input data, and the engine and driveline data were generated. Further, through a systems approach, the study estimated the potential economic, social, and environmental impacts of adoption of various future technologies in medium-term (2030) and long-term (2050) using projected freight volumes in different growth and policy scenarios. Using the TIMES-IRELAND model, the study compared HDV decarbonisation technologies and evaluated their combinations to achieve NZE2050 in Ireland. The study recommends various short and long-term policies as well as provides guidelines to achieve the decarbonisation goals in the freight transport sector.

NB – Both Section 1 and Section 2 of this Final Report will be made publicly available in a Final Technical Report uploaded online to the National Energy Research Database.

In the following Section, please provide a clear overview of your project, including details of the key findings, outcomes and recommendations. The section headings below are provided as a guide, please update or add to these as best suits your project.

By submitting this project report to SEAI, you confirm you are happy for Section 1 and Section 2 of this report to be made publicly available. If you wish to request edits to this section in advance of publication, please contact SEAI at EnergyResearch@seai.ie.

SECTION 2: FINAL TECHNICAL REPORT – FOR PUBLICATION (max 10 pages)

2.1 Executive Summary

Global climate concerns have led to agreements on reducing greenhouse gas (GHG) emissions, particularly carbon dioxide (CO2), which significantly impact human health and socio-economic conditions. The transport sector contributes nearly 25% of GHG emissions, with a 55% increase in road freight emissions from 2000 to 2022. Ireland aims to reduce carbon emissions by 51% by 2030 and fully decarbonize its transport sector by 2050, targeting a 10% reduction for heavy-duty vehicles by 2030.

The present study employed two approaches: a microscopic simulation focusing on individual vehicle emissions and an energy systems optimization approach evaluating various HDV categories and their interdependence to project future fleet scenarios for achieving net-zero emissions. Using the EC-recommended VECTO tool, we estimated energy and GHG emissions from vehicles representing nearly 50% of the Irish HDV fleet, including alternative fuel trucks such as diesel, ethanol, biodiesel, LPG, NG, and petrol. To improve estimate precision, we developed Irish HDV driving cycles using real naturalistic driving data. We explored ways to reduce these emissions through improved system efficiencies. These vehicle inputs and driving cycles can estimate energy and emissions for various use cases, comparing alternative fuels to conventional fuels in Ireland. The analysis offers policy solutions beneficial for the transition to zero-emission vehicles.

In this study, we employed the TIMES-Ireland Model (TIM), a new Energy Systems Optimisation Modelling (ESOM) tool. TIM is a bottom-up, techno-economic optimization model used to analyse energy systems and evaluate decarbonization pathways. It assesses the cost and feasibility of various energy supply and demand options, providing an optimal mix of technologies for a low-carbon energy system. We considered three categories of HGVs—light, medium, and heavy—with diesel, hydrogen, and electricity supply systems, tailoring solutions to each category. The model accounts for hidden costs of zero-emission trucks, such as recharging/refuelling time, reduced cargo capacity, and reluctance to invest in immature technology. The study identifies feasible pathways to decarbonize the road freight sector, evaluates the impact of intangible costs on ZEV adoption across different weight categories, and analyses the effect of zero-emission trucks on the energy system, focusing on electricity and hydrogen supply and associated costs. Policy guidelines specific to Ireland are provided as a result of this analysis.

2.2 Introduction to Project

As a member of the EU, the Republic of Ireland is committed to reducing its carbon emissions by 51% by 2030 and aims to fully decarbonise its transport sector by 2050, as outlined in the Climate Action Plan 2023 (CAP23) (GoI, 2023). However, the targets for HDVs are slightly different. CAP23 recognises the lack of immediate alternatives to achieve higher emissions reductions immediately from the sector and has set a target for a 10% reduction by 2030 for HDVs. Despite being only 9% of the total vehicles and accounting for only 17% of vehicle miles, freight trucks are responsible for 39% of road vehicle GHG emissions and a larger share of other air pollutants. The freight transportation sector is expected to lead the transport sector's emissions by 2030 since the shift away from conventional fuel Heavy-Duty Vehicles (HDVs) faces technological hurdles. This is because zero-emission alternatives like Battery Electric Vehicles (BEVs) and hydrogen Fuel Cell Vehicles (FCVs) are critical yet challenging to adopt broadly due to technology and infrastructure immaturity. The slow adoption of these technologies, with fewer than 2000 sold in the EU in 2022, reflects these challenges. In line with this, the EU's emission reduction strategy involves gradual steps towards sector-wide decarbonization, highlighting the need for transition technologies and strategies to achieve zero-emission freight transport.

In the current study, we use both the simulation approach to estimate individual vehicle emissions savings with alternative vehicles and the energy systems optimisation approach to estimate the total number of different vehicles in different future scenarios and their potential to reduce emissions. The simulation approach helps to control and monitor GHG emissions from the freight sector through an accurate estimation of GHG emissions from the national HDV fleet. European Commission recommended Vehicle Energy Consumption calculation TOol (VECTO) (European Commission, 2019) was used for the simulation. The simulation also involves generation of input data that represent specific vehicle types. In the Energy Systems Optimisation Modelling (ESOM) model, TIMES-Ireland Model (TIM) is used (Figure 1)

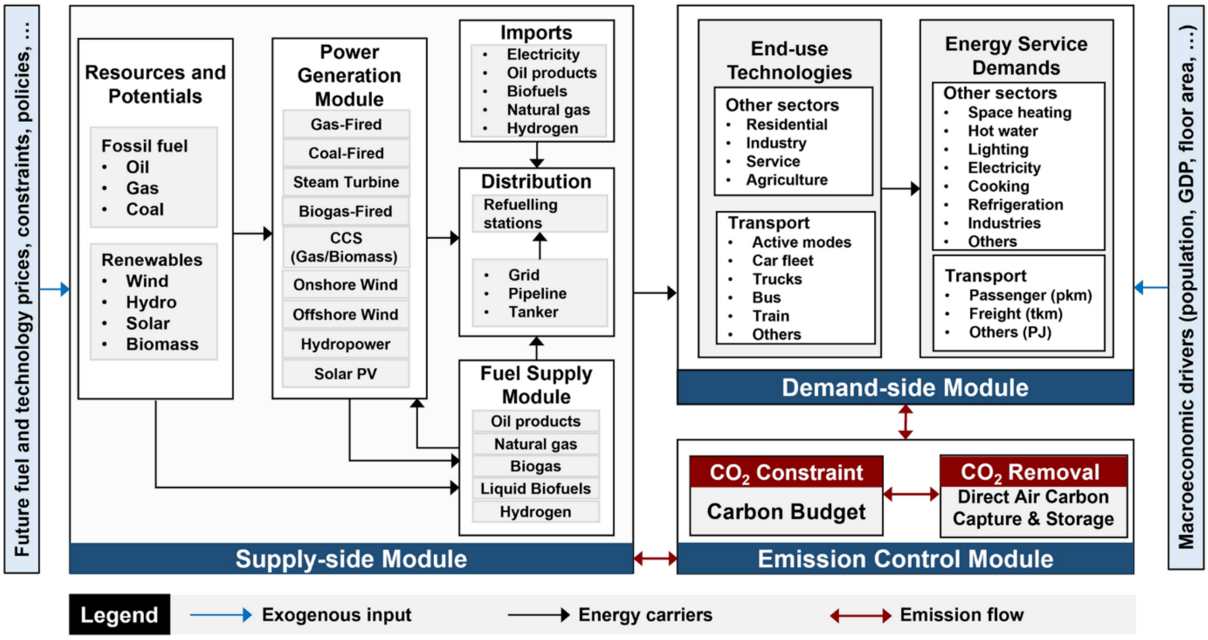


Figure 1 Simplified structure of energy system in TIM.

2.3 Project Objectives

The key objectives of this study are to:

- To identify the suitable decarbonisation option for Irish HDV fleet considering international experts' opinion.
- To investigate the potential of existing and projected HDV electrification technologies for Irish HDV fleet.
- To investigate the potential of different alternative fuels for decarbonising the Irish HDV fleet.
- Establish a baseline profile of HDV sector in Ireland. Compare Ireland's HDV sector profile with other countries to gauge potential effectiveness/suitability of measures.
- To develop Irish HDV driving cycles for various use cases, urban, regional, and freeway.
- Assess the impact of intangible costs on the adoption of ZEVs in various weight categories.

- Analyse the effect of zero-emission trucks on the energy system, with a focus on electricity and hydrogen supply, and associated costs.

2.4 Summary of Key Findings/Outcomes

Network-wide Analysis of Alternative Fuel Solutions for Freight

Energy Systems Optimisation Models (ESOMs) can be used to understand the complex interactions and capture dynamics across the entire energy system. ESOMs are widely used to inform national-level decision making. These technology-rich, bottom-up models use linear programming to minimise the cost of energy provision by optimising technology capacity and utilisation. The present study employs a whole-systems ESOM modelling approach, TIMES-Ireland, that considers inter-sectoral dynamics, intangible costs (vehicle purchasing decisions, including availability, reliability, quality, social desirability, and popularity among operators and drivers), and the carbon budget. The optimal solution is the minimisation of the total costs of the entire energy system discounted to a base year. The model is run on three different scenarios, one reference and two mitigation scenarios. In the reference scenario, it is assumed that a business-as-usual situation where current trends in energy consumption and technology performance continue without any measures to address climate change. In the first mitigation scenario, Net-Zero (NZ) Scenario, the model produces energy system pathways for energy supply and demand in Ireland that align with a predetermined carbon budget target. In the second mitigation scenario, which is Net zero + Intangible costs (NZI), in addition to the carbon budget, intangible costs are also considered. Also, a sensitivity analysis is performed to understand the effects of intangible costs through a variation of ±30% in the factors considered.

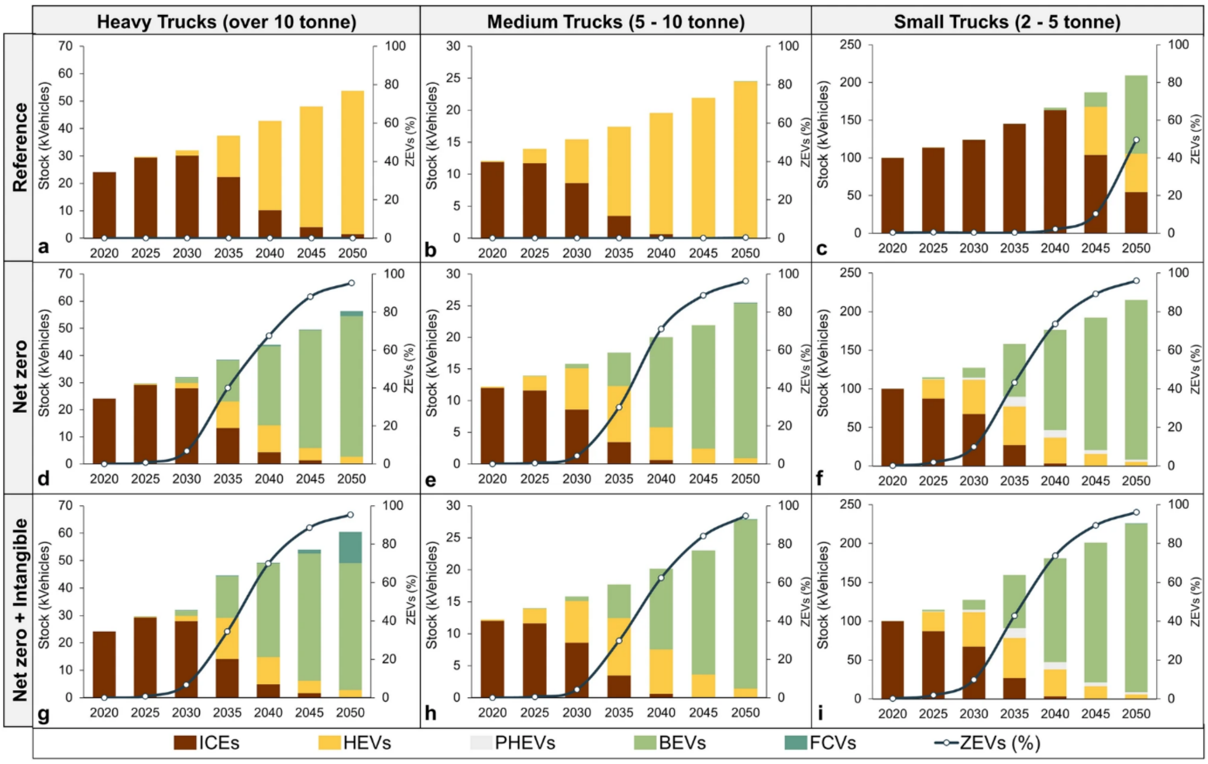


Figure 2 Fleet mix in different scenarios and for different weight categories.

Figure 2 outlines fleet composition changes for light (2–5 tonnes), medium (5–10 tonnes), and heavy (over 10 tonnes) trucks over the next three decades. Figures 2a and 2b indicate that Hybrid Electric Vehicles (HEVs) will replace internal combustion engines (ICEs) in heavy and medium trucks due to cost-efficiency and high upfront costs of advanced technologies. Zero-Emission Vehicle (ZEV) adoption remains low. Figure 2c highlights a shift to Battery Electric Vehicles (BEVs) for light trucks by 2050, spurred by advancements in battery technology making them feasible for this category. In the Net Zero (NZ) scenario, which imposes carbon budget constraints, there is a significant shift in market dynamics towards electrified freight transportation across all truck sizes. As shown in Figures 2d, 2e, and 2f, Battery Electric Vehicles (BEVs) will emerge as the dominant technology, claiming over 95% market share in all weight categories. Hybrid Electric Vehicles (HEVs) serve as a practical interim option, while Plug-in Hybrid Electric Vehicles (PHEVs) play a key role in transitioning light trucks towards a low-carbon future. In the latter stages, Fuel Cell Vehicles (FCVs) make a modest appearance, particularly in the heavy truck segment.

In the NZ + Intangibles (NZI) scenario depicted in Figures 2g, 2h, and 2i, transition trends are similar to the NZ scenario until 2040-2045. For heavy trucks, the trend favors electrification before showing a significant shift (20% market share) towards FCVs due to BEVs' cargo capacity limitations, higher recharge times, and reduced hydrogen and vehicle costs for FCVs. Light trucks follow the NZ scenario, as intangible costs impact them less due to quicker commercialization and improvement of battery technologies, minimizing BEVs' limitations for this segment. In the Reference scenario, truck numbers rise gradually until 2030, increasing sharply beyond 2035 as inefficient ICEs are replaced. In the NZ and NZI scenarios, truck counts mirror the Reference until 2030, then rapidly increase post-2035 due to the adoption of zero-emission trucks and their need to offset limitations like lower cargo capacity and longer charging times.

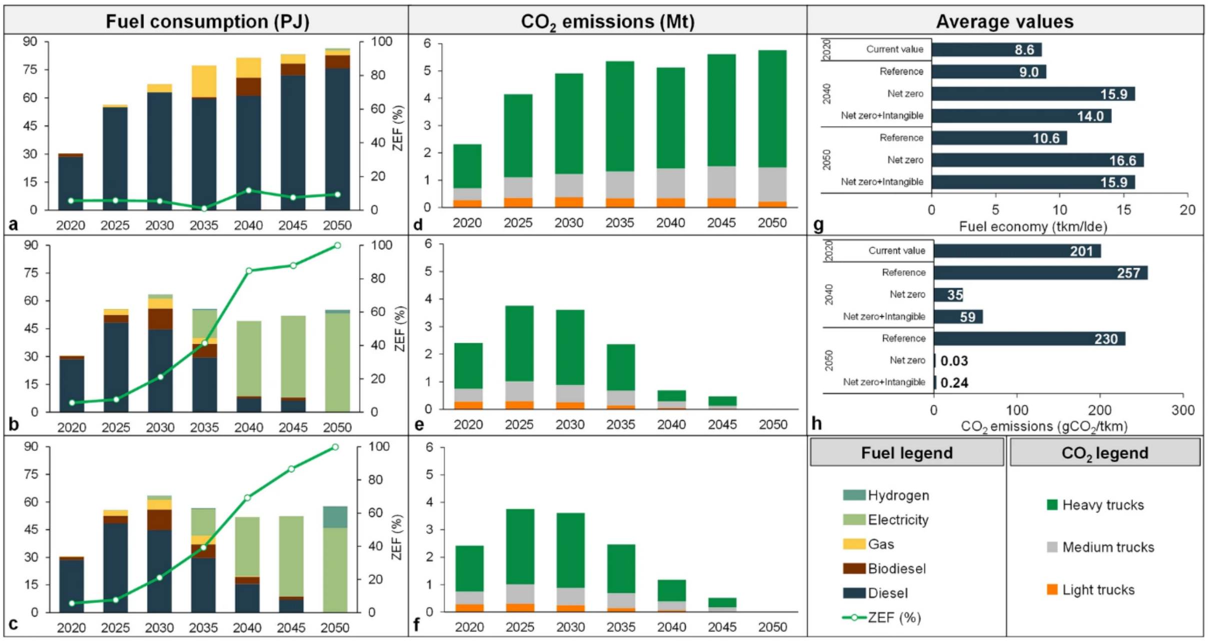


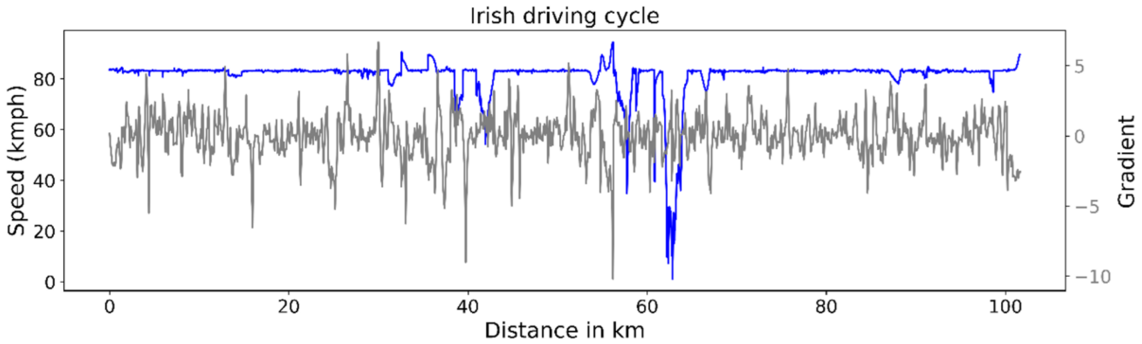
Figure 3 Fuel consumption and CO2 emissions in freight sector (Fuel consumption in (a) Reference scenario, (b) NZ scenario, (c) NZI scenario; CO2 emissions in (d) Reference scenario, (e) NZ scenario, (f) NZI scenario; (g) Average fuel economy (h) Average CO2 emissions

Figure 3 shows fuel consumption and related CO2 emissions from freight transport (light, medium, and heavy-duty trucks) across different scenarios. In the reference scenario, diesel fuel will dominate for conventional ICE and HEVs, with biofuels and natural gas having moderate consumption in the mid to long term. Zero-emission vehicle (ZEV) fuels such as electricity, hydrogen, and biodiesel remain below a 12% share, increasing significantly by 2050, thus reducing total fuel consumption and CO2 emissions from the sector.

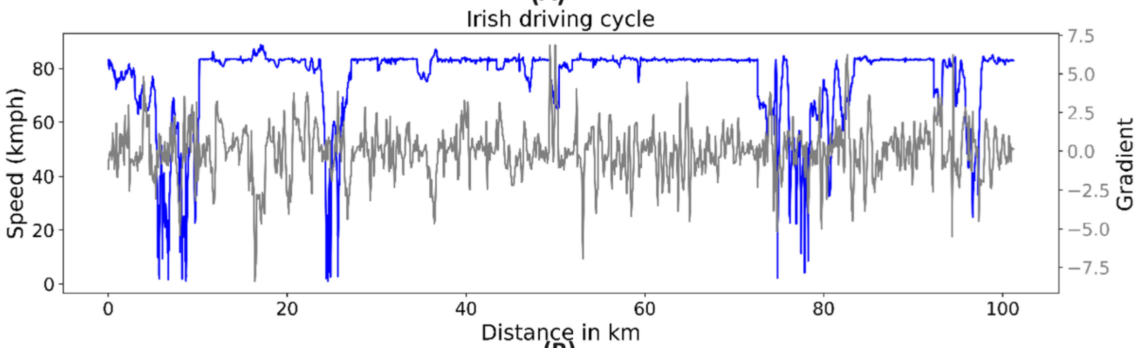
In the NZ and NZI scenarios, fuel consumption reductions of 36% and 33% respectively are achievable by 2050 compared to the reference case. A total reduction in average fuel economy in units of tonne-kilometre per litre of diesel equivalent of 23%, 93%, and 85% is achievable in the reference, NZ, and NZI scenarios compared to the base year. Figure 3 also compares emissions across different scenarios. In the reference scenario, emissions increase until 2035 and then stabilize as demand is offset by the adoption of more efficient fuels. In the alternative scenarios, decarbonization is achievable across all vehicle categories. Figure 3h shows that higher emissions reductions can be obtained by transitioning to ZEVs and implementing supply-side decarbonization strategies.
It is found that the limited cargo capacity of BEVs along with the need for further improvements in battery energy density affects their dominance in the market. Improvement in battery technology may help in promoting their wider adoption.

Energy Consumption and Emission in Microscopic Simulation

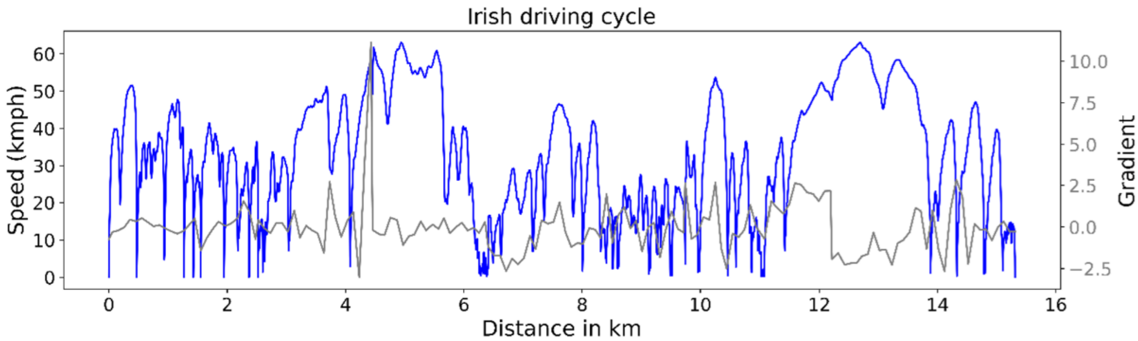
Fuel consumption and GHG emissions were obtained through a simulation conducted in VECTO (version 3.3.13.2924) in the engineering mode. VECTO is a software tool designed to monitor and certify emissions from HDVs of various categories, axle configurations, and engine specifications in the EU (European Commission, 2019). The tool uses vehicle-specific information such as scalar value inputs, drive line map data, and driving cycles to calculate the fuel consumption and CO2 emissions from Heavy-Duty Vehicles (HDVs). The predefined input data and driving cycles within VECTO may deviate from real-world conditions, leading to potential inaccuracies in emission estimations.
To address this, real-world naturalistic driving data was collected from HDVs in Ireland. An Arctic 2-axle truck from HDV group 5 was chosen for data collection, which took place over 72 days between January and March 2020 (Mane and Ghosh, 2021). During regular operations, data was recorded on all major roads throughout the island of Ireland. This comprehensive data collection captured a wide range of driving conditions and behaviors, providing a robust dataset for analysis.
The collected data was pre-processed as explained in section 3 and then divided into urban, regional, and freeway data subsets. For each of these subsets, specific Irish driving cycles were developed (Figure 4a, b, c). These driving cycles aim to more accurately reflect the unique driving conditions in Ireland compared to the standard cycles used in VECTO. For detailed information on the development of the Irish urban, regional, and freeway driving cycles, refer to Middela et al. (2024).



(A)



(B)



(C)

Figure 4(A) Irish freeway drive cycles; (B) Irish regional drive cycles; (C) Irish and VECTO urban drive cycles

By incorporating these tailored driving cycles, the simulation results offer a more precise estimation of fuel consumption and CO_2 emissions for HDVs operating in Ireland. This improved accuracy is crucial for developing effective policies and strategies to reduce emissions and enhance fuel efficiency in the Irish freight sector.

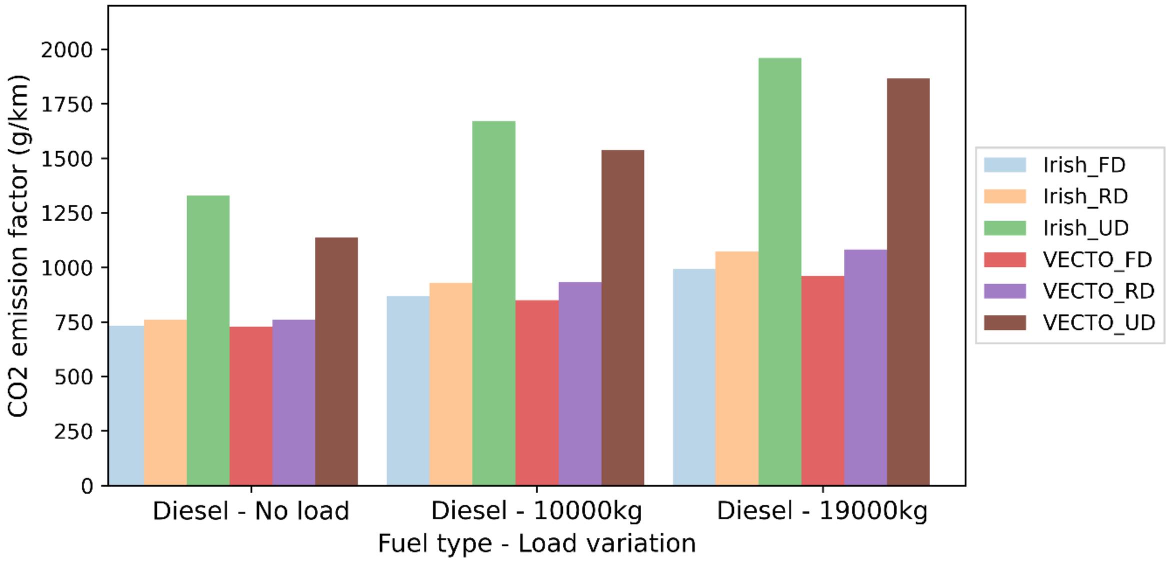


Figure 5 CO_2 emissions in g/km

CO_2 emissions results of from HDV utilising both VECTO and Irish driving cycles are shown in Figure 5. The fuel consumption patterns also closely follow the CO_2 emissions. The mean fuel consumption and emissions are higher with Irish freeway and urban driving cycles than with the VECTO driving cycles. However, they are lower in the regional case. The standard deviations also follow a similar trend. The fuel consumption and CO_2 emissions are highest in the urban case and the lowest in the freeway case. The higher fuel consumption is with the urban driving cycle, followed by the regional and freeway driving cycles. The fuel consumption observed on the field (42.94 L/100km) falls within the estimated range. The Irish driving cycles have a higher fuel consumption than the VECTO drive cycles and better replicate the observed value.

A sensitivity analysis varying payload, gradient, and idling proportion revealed that ignoring road gradient can underestimate emissions by nearly 7%, while reducing idling can cut fuel consumption by 4%. Vehicle payload significantly affects fuel consumption and emissions, indicating that fleet operators and planning agencies could optimize routes based on payload variation. Steeper roads increase emissions, suggesting the need for choosing fuel-efficient routes over shorter ones and introducing emissions tolls. Targeted driver training, professional development programs, and incentives to reduce idling are crucial for lowering fuel consumption and emissions. The analysis suggests that these effects may vary between regions, highlighting the need for region-specific sensitivity analyses when estimating emissions and fuel consumption.

2.5 Project Impact

The DRIFT-HDV project conclusions can inform policymakers and practitioners on improving the energy and cost efficiency of the Irish freight sector, with the objective of meeting and transitioning to the net-zero target.

The developed Irish driving cycles and the proposed methodology for driving cycle development can aid in simulating fuel consumption and GHG emissions. This helps in evaluating fleet-renewal or alternative fuel policies, supporting the transition phase until electric vehicles become widely available in Ireland.

Various stakeholders, including the scientific community, automotive industries, logistics companies, fleet operators, and policymakers, can leverage the findings to inform research and development, enhance operational efficiency, and shape effective policies for sustainable freight transport and decarbonization.

2.6 Recommendations

The recommendations are from two paradigms:

Network-wide

- Cargo capacity and recharging time significantly influence the adoption of zero-emission battery electric trucks (BEVs) more than purchase price, with minimal impact from hurdle rates.
- Operational expenditure incentives can be more effective for promoting the adoption of freight vehicles.
- Early action on emissions pathways and prioritizing decarbonization efforts for heavy-weight categories are crucial for efficient carbon mitigation and preventing lock-in effects, as mandated by carbon budgets.

User-specific

- The developed driving cycles tailored for Irish conditions can be valuable for planning agencies and manufacturers in emissions testing, as they can simulate fuel consumption and emissions from heavy-duty trucks.
- Ignoring road gradients can underestimate emissions by nearly 7%, and reducing idling can reduce fuel consumption by 4%. Steeper roads increase emissions, so fleet operators and planning agencies could optimize routes considering payload variation and enforce fuel-efficient routes through emissions tolls. Targeted driver training and incentivization schemes to reduce idling can also help lower fuel consumption and emissions.

2.7 Conclusions and Next Steps

The problem of reducing emission and carbon footprint of HDV sector is a challenging one. There exists several solutions but implementation of those may have significant financial & operational costs. Some of the solutions are still not market or infrastructure ready.

Future studies could estimate GHG emissions using real vehicle-specific data. With more manufacturer data for a broader range of HDV models, including hybrid electric vehicles, these studies can compare emissions on Irish roads and develop policies for fleet renewal to support net-zero targets. Additionally, incorporating daily travel behaviour for small and medium-sized trucks may reveal that drivers can manage recharging effectively, favouring battery electric vehicles (BEVs) over fuel cell vehicles (FCVs). Exploring battery swapping solutions to address prolonged recharging times and the trade-offs with widespread recharging infrastructure can also be beneficial. Cost optimization modelling in future research should address uncertainties related to upfront costs, as these significantly impact the outcomes.

The availability of vehicle models remains a significant barrier to the adoption of electric trucks, and future studies should consider the technology and manufacturing readiness of zero-emission trucks for series production. This consideration is crucial for large-scale ZEV adoption. The current study highlights the need for a Life Cycle Analysis of the HDV fleet, which could assist policymakers in developing effective policies for decarbonizing the Irish HDV fleet in both the short and long term.