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Examining the long-term reduction in commuting emissions from working from home

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ABSTRACT

To develop effective climate strategies, it is necessary to model the long-term impacts of combined policy measures. This study examines how an increase in working-from-home (WFH) practices, coupled with higher private car fleet penetration of electric vehicles (EVs), could change commuting patterns and associated emissions. Simulations for the Dublin Region show that if half of white-collar workers were WFH and EVs made up one-third of the fleet as forecasted for 2030, emissions from travel activities could be reduced by up to 35% for carbon dioxide (CO₂) and 25% for particulate matter (PM). However, transitioning from a moderate to a high WFH scenario may not deliver significant benefits in terms of travel length, modal shift, and emissions reduction. In addition, a decrease in commuter trips can lead to an increase in other trips. This suggests that there is a need for additional measures to discourage car usage when commuter trips decline.

1. Introduction

The global climate is changing due to increased greenhouse gas emissions from human activities, including transportation, which disrupt the biosphere. To limit and reverse rising temperatures, emission reduction targets are set at national and transnational levels. Achieving climate change mitigation goals requires the transformation of the mobility system, where many journeys could be avoided without lowering living standards (Creutzig et al., 2022). The COVID-19 pandemic and the digitalisation of work routines demonstrate that remote work¹ can reduce commuting trips¹ (Hook et al., 2020). The impact of telecommuting on travel behaviour and emissions depends on the scale of adoption and a combination of multiple factors.

COVID-19 regulations prompted more teleworking, leading to a rise in European employees working from home (WFH). In Germany, over half qualify for at least partial remote work (Marz and Şen, 2022). Ireland has the highest rate in the European Union (EU),

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¹ Remote work, also known as telework or telecommuting, refers to performing work activities from a location outside of the traditional workplace environment, typically from home (Eldér, 2020; Jain et al., 2022; Melo and de Abreu e Silva, 2017).

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with 32 % WFH in 2021, up from 25 % in 2019 (Eurostat, 2022). 98 % of those who worked remotely in November 2021 chose to work from home (CSO, 2022). Ireland supports remote work with good infrastructure and favourable legislation (Stefaniec et al., 2022). The National Remote Work Strategy mandates one-fifth of public sector employees to work remotely, invests in remote working hubs and accelerates the provision of high-speed broadband across the country (Bisello and Profous, 2022; DETE, 2021) while the Work Life Balance Bill entitles employees to request remote working arrangements from their employer (Dáil Éireann, 2022). The practice is also viewed as a remedy for Ireland's high GHG emissions from the transport sector, where private cars account for 73.7 % of all trips, with work trips making up 23.6 % (DoT, 2021).

Reducing the number of car journeys not only helps achieve climate targets but also improves air quality which has a positive impact on public health. The compounds of transport emissions that contribute to climate change include long-lived GHGs, such as carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O), and short-lived compounds that indirectly contribute to global warming by affecting the ozone layer, such as sulphur dioxide (SO₂), nitrogen oxides (NO_x), carbon monoxide (CO), non-methane volatile organic compounds (NMVOCs), black carbon (BC), and organic carbon (OC); (Aminzadegan et al., 2022)). The short-lived compounds listed above are the primary air pollutants that affect human health (EEA, 2019). Particulate matter mainly consists of BC and OC and its particles are classified into PM_{2.5} and PM₁₀.

The main contribution of this research is that it combines the different policy paradigms within the avoid-shift-improve framework of sustainable transport. The results demonstrate how one must be mindful of potential knock on impacts in other sectors when introducing sustainable transport policy. This study explores the impact of an increased share of private electric vehicles (EVs) on the transport emissions produced by various levels of employees WFH. This work is important because it sheds light on the impact of combined policy measures on GHG emissions targets and air quality, allowing for more accurate simulations of likely future conditions. Such a research design enables higher precision in estimating the environmental benefits of WFH, which has been subject to a heated debate in the literature.

2. Literature review: Working from home, work travel and emissions

The COVID-19 pandemic has led to significant changes in daily routines, accelerating shifts towards telecommuting and online shopping, affecting both urban and rural communities (Nelson and Caulfield, 2022) and having implications for strategic transport modelling (Hensher et al., 2021). These disruptions can be seen as a window of opportunity for sustainable mobility, breaking habitual travel behaviours (Schmidt et al., 2021). The rapid policy change during the pandemic demonstrates the feasibility of achieving changes, providing insights into how this change can be facilitated or obstructed (Marsden and Docherty, 2021).

The shift to WFH necessitates revisions in transport models and policies (Beck and Hensher, 2020; Hensher et al., 2021). Post-pandemic travel behaviour appears to differ from pre-pandemic patterns, with a sustained increase in WFH potentially reducing peak commuting but not offsetting the mode shift from public transport to car driving (Currie et al., 2021). Walking to work or the absence of a commute due to WFH is associated with increased job and leisure time satisfaction, suggesting that shorter and walkable commutes can improve subjective well-being (Clark et al., 2020). While it is too early to claim a new stable pattern of commuting activity, ongoing monitoring of adjustments in travel activity and WFH is essential for informing future transport and land use policies (Beck et al., 2020). There is also evidence that WFH is viewed favourably by both employees and employers, representing a significant potential contribution to the management of transport networks, especially in larger metropolitan areas (Beck and Hensher, 2021; Stefaniec et al., 2022).

After the COVID-19 pandemic introduced flexible work arrangements, researchers began to intensively explore the impact of telecommuting on work travel patterns, congestion, and emissions. Two review studies summarise the research conducted before widespread experience with teleworking and notice that differences in scope, methodological approach, and assumptions make it challenging to compare the results of various studies on this topic and estimate the strength of the impact of telecommuting on energy use and emissions (Hook et al., 2020; O'Brien and Yazdani Aliabadi, 2020). It was concluded that because of the complex nature of this problem, the data available pre-pandemic and the methods used were inadequate to determine whether WFH reduces or increases emissions and to what extent (O'Brien and Yazdani Aliabadi, 2020). Having experience with an increased volume of teleworkers allowed scholars to approach the problem once more. However, again inconclusive findings are being presented in the literature, and similarly, due to the variety of research designs, it is problematic to reconcile the discrepancies. Below we report the common methods and assumptions used to estimate work travel volume and emissions, looking for patterns that emerge from the analysis of post-pandemic studies and their comparison to the earlier literature (see Appendix A).

2.1. Methods for estimating commuting emissions

Modelling is increasingly utilised in post-pandemic literature to analyse the impact of telecommuting on travel patterns. This simulation approach uses census and survey data to create models that can explore scenarios at various spatial and temporal scales, ranging from city to region or country level. The quality of a simulation is limited by the accuracy of the underlying models and sub-models (O'Brien and Yazdani Aliabadi, 2020). Several scholars have employed the modelling technique to assess the impact of telecommuting and the effects of reduced work-related travel on atmospheric pollution by manipulating the proportion of telecommuters within the working population of a city or metropolitan area. Classifying modelling approaches, it is evident that a variety of techniques were employed, including activity-based simulation (Shabanpour et al., 2018; Tenailleau et al., 2021; Wang et al., 2021), macroeconomic models (Zhang and Zhang, 2021), and virtual city models (Marz and Şen, 2022). Assumptions are made about anticipated shares of remote working ranging from 0 to 50 % (Marz and Şen, 2022; Santos and Azhari, 2022; Shabanpour et al., 2018;

Tenaillieu et al., 2021; Zhang and Zhang, 2021), and even 59 % (Wang et al., 2021), or 4 days a week (Navaratnam et al., 2022). Typically, studies assume a share of 20–50 % of working remotely, mostly at home, and these assumptions play a crucial role in shaping the results.

A variety of emissions estimation methods were used to assess the impact of telecommuting on climate change (greenhouse gases) and human health (air pollutants). Most studies calculated emissions based on vehicle fleet characteristics employing emission factors for a broad range of vehicles, fuel consumption and vehicle-km travelled (Marz and Şen, 2022; Zhang and Zhang, 2021). In contrast, studies analysing traffic congestion (Shabanpour et al., 2018; Wang et al., 2021) applied the motor vehicle emission simulator (MOVES), which allows for spatial analysis of emissions at each segment of the road network. The MOVES model is characterised by high precision in estimating emissions and utilises detailed data on vehicle types, travel patterns, fuel usage, meteorological conditions, emission regulations, geographical information and temporal variations. While some studies only estimate CO₂ emission levels (Marz and Şen, 2022; Zhang and Zhang, 2021), others analyse aggregated GHG and PM_{2.5} emissions (Shabanpour et al., 2018; Wang et al., 2021), or consider up to twenty compounds (Tenaillieu et al., 2021).

Using different methods, the literature attempts to estimate changes in transport and building emissions resulting from teleworking. Researchers employ simple emission estimation models that incorporate generic emission factors, such as mode-specific for transportation and fuel-specific for building heating and cooling, to compute GHG emissions from the transport, commercial, and residential sectors (Navaratnam et al., 2022; Santos and Azhari, 2022). Surveys and travel diaries were also used to assess the effect of teleworking on travel demand and emissions (O'Brien and Yazdani Aliabadi, 2020). Other studies examine the impact based on factual emission concentration during COVID-19 (Eregowda et al., 2021; Mehlig et al., 2021) and pre-COVID periods (Cerqueira et al., 2020).

2.2. Does telework reduce or increase emissions?

Despite the potential of telecommuting, different assessments of emissions yield conflicting results, with some studies suggesting it reduces energy use and emissions while others raise concerns about increased non-work trips and residential emissions (Marz and Şen, 2022; Santos and Azhari, 2022). More optimistic views come from pre-COVID studies highlighting emission reductions from shorter commutes and lower office energy use (O'Brien and Yazdani Aliabadi, 2020; Hook et al., 2020), while critical perspectives consider the balance between emission reductions and increased energy demand in buildings (Hook et al., 2020; Navaratnam et al., 2022; O'Brien and Yazdani Aliabadi, 2020; Santos and Azhari, 2022). Post-COVID research generally indicates modest emissions savings from telecommuting, with diminishing long-term benefits (Marz and Şen, 2022; Santos and Azhari, 2022). However, the emissions savings from reduced transportation still offset the increased energy use in buildings (Navaratnam et al., 2022). The methodological approach and assumptions play a crucial role in differentiating the results.

The “rebound effects” that offset the initial emissions reduction from telecommuting trips are associated with increased non-work energy consumption (Horner et al., 2016) and refer primarily to longer commutes, more non-work travel, a potential shift towards more car use, and increased residential energy consumption (Hook et al., 2020). In line with Marchetti’s constant (van Wee and Witlox, 2021), employees who spend less time commuting may choose to relocate further from the city centre and workplace, seeking a more attractive environment and larger living space (Cerqueira et al., 2020; Stefaniec et al., 2022). Residing in suburban areas may increase the probability of local trips being made by car (Cerqueira et al., 2020). With a car more readily available at home, it might be also used by other household members for various purposes (Kim et al., 2015). With reduced commuting costs, households may decide to drive more and use fuel-intensive vehicles or might allocate their budget to other activities that generate an additional carbon footprint (Marz and Şen, 2022) and make more non-work trips (Budnitz et al., 2020). While some research suggests that only a small portion of these non-work trips are made by car, with a higher proportion of teleworkers using active modes and public transport (Caldarola and Sorrell, 2022), other studies indicate that telecommuters use more polluting modes for non-work travel (de Abreu e Silva and Melo, 2018; Reiffer et al., 2023). Overall, households’ decisions can lead to longer commuting trips and higher transport emissions, as well as increased building emissions due to heating or cooling larger homes used as workplaces. Residential heating and cooling systems may be less efficient than those in workplaces or remote hubs, resulting in additional carbon emissions (Bisello and Profous, 2022; Caulfield and Charly, 2022). These mechanisms can reduce the environmental benefits of teleworking by counterbalancing the emissions savings from fewer commuting trips, although the literature remains inconclusive regarding the magnitude of these rebound effects.

2.3. Does the adoption of electric vehicles affect telecommuting emissions?

The potential for emissions reduction from increased WFH is a subject of debate, and conflicting findings due to methodological differences make it challenging to reach definitive conclusions. However, there is limited focus on balancing the diminishing effect of telecommuting through policy interventions that can secure its environmental benefits. One area of interest is the role of vehicle technology improvement, such as electrification, which remains an outstanding research question in the context of increased teleworking practice (O'Brien and Yazdani Aliabadi, 2020). Marz and Şen (2022) suggest that combining telecommuting with additional environmental policies can maximize the benefits of reduced travel. Incorporating likely future conditions in simulation scenarios is crucial to ensure that future energy and emission profiles are accurately represented thus facilitating the development of tailored policy approaches. While isolating factors can help identify the direct impact of single interventions, understanding how different measures interact with each other is even more valuable. Some studies have attempted this, such as Wang et al. (2021), by investigating the moderating effect of social distancing on telecommuting emissions and by analysing various lifestyles and policy interventions in isolation (Zhang and Zhang (2021)).

This research investigates how the increased presence of private EVs in the fleet affects commuting travel emissions in scenarios

with a higher share of WFH. Considering the progress (Falchetta and Noussan, 2021) and governmental targets related to vehicle electrification (Wu and Kontou, 2022), studying the role of EVs is particularly relevant. Both electrification and WFH are measures aimed at achieving climate targets in Ireland (GoI, 2023) and elsewhere (DHPLG, 2021). The study uses the Regional Modelling System by the National Transport Authority (NTA) of Ireland to simulate changes in travel behaviour in the Eastern Region under different WFH scenarios and an increased EV uptake based on 2030 forecasts. GHG emissions and air pollutants are estimated using the COPERT's parameters. The regional approach, with a long-term timeframe, provides valuable insights for policymaking (O'Brien and Yazdani Aliabadi, 2020) and adds to the current literature on telecommuting emissions.

3. Methods

3.1. Regional modelling system

This study utilises the NTA's Regional Modelling System (RMS), which is described in Appendix B.² The RMS is a set of region specific strategic transport models for five regions of Ireland (Fig. 1). This paper focuses upon the Eastern Region, which is dominated by the Greater Dublin Area, and the surrounding hinterland. The RMS is based on a traditional four stage transport model, with Trip Generation taking place at national level, while Mode and Destination Choice and Route Assignment are modelled at the regional level. Trip making within the ERM is dictated by trip rates estimated via a negative binomial regression from the National Household Travel Survey (NTA, 2018). The trip rates, which are inputs to the model, are set at the outset and do not vary during the modelling process. To test scenarios that involve different trip rates, it is necessary to update the appropriate input files in the dBase database prior to initiating the model runs. These updates are specifically applied at the Trip Generation stage, which is the first stage of the model. The remaining three stages – Trip Distribution, Mode Choice, and Route Assignment – respond to these changes, reflecting the impact of the altered trip rates from the Trip Generation stage (Appendix B). This approach allows for the examination of different scenarios by varying the initial trip rates and observing the subsequent effects throughout all stages of the model.

3.2. Scenario design

3.2.1. Commuting demand scenarios

This case study utilises a pre-Covid year (2019) as the reference scenario as it has stable and known trip rates, as well as a known transport network. The two future WFH scenarios have been developed, necessitating adjustments to the trip rates in order to model the reduced number of trips resulting from higher levels of WFH. The two scenarios with increased levels of WFH should be viewed as stable counter-factual 2019 scenarios rather than transition periods. For example, a 2019 where WFH is a well-established fact of life rather than an emerging phenomenon. It is important because four-stage models typically operate under the assumption of a stable cost environment, where it is presumed that trip makers are well-informed about the relative costs of their available travel options. Hence, consistent and established working arrangements provide a more reliable framework for assessing travel behaviours.

The travel demand scenarios are defined by the levels of commuting that occur within white-collar workers, with respect to the reference scenario. These represent 25 % and 50 % reductions in trips made within this segment (Table 1). The work trip rates are applied to an average weekday, indicating that 25 % or 50 % of white-collar employees, depending on the scenario, will not commute on that day. Statistics show that 32 % of Irish employees worked remotely at least part-time in 2021 (Eurostat, 2022), and a survey conducted in the same year revealed that 77.9 % of white-collar workers prefer some form of WFH (Stefaniec et al., 2022). Literature typically assumes 20–50 % WFH rates (see section 2.1). Therefore, considering Ireland's highest WFH rates in Europe and the preference for part-time rather than full-time WFH arrangements, the rates of 25 % and 50 % WFH assumed in this study are deemed reasonable.

The trip rates were altered in the first stage of the model, that is the Trip Generation stage. For each model zone,² trip rates estimated from survey data (Stefaniec et al., 2022) are applied to various socio-economic segments. For example, within the white-collar commute segment, a full-time female between 45 and 60 will attend work at a different rate than a part-time male aged 15–19. Trip rates are used to calculate the number of trips from a zone, by applying the respective trip rates to the number of individuals within a zone that fall into a given category. This can be described by:

$$T_i = \sum_{k=1}^K TR_k * N_{ki} \quad (1)$$

where:

T_i = number of trips leaving zone i .

TR_k = trip rate for socio-economic group k .

N_{ki} = number of individuals of type k with zone i .

Therefore, taking rural female full-time employed workers between 45 and 59, a trip rate of 0.736 or 73.6 trips per 100 people of this type on an average week day, is used in the reference model. For the 75 % scenario is 0.552 or 55.2 trips per 100 people, and for the 50 % scenario, the trip rate is 0.368 or 36.8 trips per 100 people.

² The model uses Central Statistics Office (CSO) Census Small Area Population Statistics (SAPS) for this calculation (CSO, 2016).



Fig. 1. Coverage area of Ireland’s regions, including the Eastern Region Model (ERM) (NTA, 2021a).

Table 1

Commuting demand scenario definitions.

Scenario	Description
Baseline	The 2019 standard run of the Eastern Regional Model (ERM)
Moderate WFH	The 2019 run of the ERM with the white-collar commuting trip rate reduced to 75 % of reference scenario
High WFH	The 2019 run of the ERM with the white-collar commuting trip rate reduced to 50 % of reference scenario

This is repeated across the different segments and summed together to create the total demand arising from each zone for the respective scenarios.

While it is acknowledged that second-order effects such as increased trip-making for non-work purposes may occur as a result of increased WFH (de Abreu e Silva and Melo, 2018), only trip rates for commuter trips were altered due to the lack of precise forecasts for these second-order effects within an Irish context and elsewhere.

Nevertheless, in a four-stage transport modelling system, altering work trip rates at the Trip Generation stage can indirectly affect non-work trips, although the direct impact is on work trips. At the Trip Distribution stage, changes in work trip rates can alter the

distribution pattern of trips across the network. A decrease in work trips changes the overall travel demand pattern, affecting congestion levels and travel times, which in turn can influence the attractiveness or feasibility of certain routes or destinations for non-work trips. Furthermore, changes in work trip rates might shift the overall demand for certain modes, potentially affecting their availability, frequency, or congestion levels. This change can indirectly influence the assignment of mode choices for non-work trips in the Mode Choice stage. Due to the inclusion of feedback loops in the modelling, changes in one stage can lead to adjustments in previous stages (NTA, 2021a). Therefore, a change in work trip rates will also lead to iterative adjustments in trip generation for both work and non-work trips, as the model seeks to balance and reflect realistic travel patterns. Consequently, despite only manipulating work trip rates in the initial stage, this alteration also influenced the number, mode, routes, and destinations of non-work trips, as evidenced by the subsequent model results.

3.2.2. Fleet composition scenarios

This study uses two car fleets (Table 2): the standard fleet representing the Irish car fleet in 2019, and a fleet with increased EV uptake based on a 2030 forecast. The forecast, developed by the NTA and Department of Transport (NTA&DoT, 2023), projects that by 2029, all new private car purchases will be electric, with a composition of 80 % battery EVs and 20 % plug-in hybrid EVs. Historical analysis of fleet growth indicates that approximately 183,000 private cars are added annually, resulting in a 6.4 % increase in the fleet from 2019 to 2030. It is estimated that by 2030, there will be 960,000 EVs on Irish roads, which would account for about 30 % of the total fleet share in that year. This fleet composition should not be treated as a definitive forecast and rather represents a plausible future during a transition to EVs.

The both fleets include electric, diesel, and petrol cars and represent probable fuel mix profiles. While there are further underlying sub-groupings aligned with Euro classes, these do not change within the various fuel types for these tests, so are not discussed further. In addition, to potentially obtain more favourable emission outcomes, one approach could be to assign shorter trips within the model to EVs. However, in our specific regional case, there is a lack of empirical evidence backing this method, and such an adjustment could be viewed as tailoring the model to produce a more desirable result. Moreover, advancements in vehicle technology are expected to increase battery capacity and range by 2030, potentially making this issue less relevant. Assigning EVs to trips originating from zones with higher adoption rates would also pose challenges due to the difficulty in forecasting the spatial distribution of future EV purchases.

The respective commuting demand scenarios and fleet profiles were combined to create six distinct test scenarios:

- 1) Baseline commuting – Standard fleet (reference scenario)
- 2) Baseline commuting – EV uptake fleet
- 3) Moderate WFH level – Standard fleet
- 4) Moderate WFH level – EV uptake fleet
- 5) High WFH level – Standard fleet
- 6) High WFH level – EV uptake fleet

3.3. Emissions estimation

Emissions from transport vehicles were estimated using COPERT 5 emission factors (NTA, 2021b). The COPERT emission factors, which cover both exhaust and non-exhaust emissions, are available for a wide range of vehicle categories (EMISIA, 2023). In this study, we consider the following emission compounds from both, exhaust and non-exhaust, sources: CO₂, CH₄, CO, NO_x, HC, PM₁₀ and PM_{2.5}. COPERT facilitates emission estimation from transport vehicles. This method has been employed to assess emissions for the existing fleet composition, and similarly, COPERT emission factors have been utilised to calculate projected emissions for the car fleet in 2030. Emissions from goods vehicles and public transport vehicles are not included but available for 2019 based on fuel consumption and COPERT emission factors, respectively, and can be estimated for 2030 using projected emission reductions, as detailed by NTA&DoT (2023).

The abovementioned estimation method does not take into account CO₂ emissions from the grid for the electricity used to power EVs. These emissions were estimated using electricity mix of the grid, vehicle kilometres travelled (VKT), and the energy consumption of EVs. The CO₂ emission intensity of power generation was 325 gCO₂/kWh in 2019 (EPA, 2021), and is projected to be 104.17 gCO₂/kWh in 2030 based on the assumption of an 80 % share of renewables (GoI, 2023). The VKT by EVs was estimated in reference to the share of EVs in the fleet. The average energy consumption of an EV was assumed to be 0.166 kWh/km (EEA, 2022).

3.4. Limitations

Although our estimates of future work practices, vehicle fleet composition, and the pace of EV adoption were informed by current

Table 2
Private car fleet composition scenarios.

Scenario	Electric car	Petrol car	Diesel car
Standard (2019 Fleet)	1.60 %	41.20 %	57.21 %
EV uptake (2030 Fleet)	33.38 %	25.49 %	41.13 %

trends, historical data, and literature, there is inherent uncertainty in predicting the future. To avoid giving an impression of false precision, we chose reductions of one-half and one-quarter in the number of commuting white-collar workers, based on insights from previous research. Converting the flexibility of WFH arrangements into an average weekday with a defined proportion of non-commuters presents a challenge in accurately determining the exact shares of telecommuting. Similarly, while we had an inventory of the national fleet for 2019, the 2030 fleet composition was only estimated. The transition to EV technology, crucial for decarbonisation targets, tends to have overoptimistic projections compared to actual adoption rates (Domarchi and Cherchi, 2023).

The emission estimates in this study exclude public transport and freight emissions. This exclusion aligns with the study's objective to solely isolate the impact of WFH arrangements and EV uptake on emissions. While public transport trips are modelled, freight trips are primarily considered as a background factor in traffic assignment. The study does not account for any potential reduction in public transport services that might result from fewer trips.

Due to the absence of precise estimates on the impact of reduced work trips on non-work trips, the rates of trips for other purposes were not modified at the model's input stage. Instead, the model was allowed to reorganise these trips based on the assignments within its four-stage framework. This approach was partly due to the lack of indications of trip induction in the Irish context and the inconclusive evidence regarding a rebound in non-work travel (Caldarola and Sorrell, 2022; Eildér, 2020). While changes in non-work trips occurred throughout the modelling process and are reflected in the results, these should be interpreted cautiously. The model was not designed to specifically address the unique travel behaviours of WFH employees for activities like leisure, shopping, and other trips.

This study was also constrained by the limitations of the modelling system and its assumptions, such as pre-set generalised costs and calibration accuracy. The modeller's primary focus was on adjusting WFH rates, making the findings reliant on the model's performance, which has been validated through its use in Irish policymaking and ongoing updates. It should also be noted that while the regional model offers comprehensive network coverage, it excludes very quiet roads, particularly in rural areas. Additionally, turning and junction delays in these rural areas are not accounted for in the buffer network due to computational limitations. Although the model is extensive, it does not encompass all travel demand in the region as it does not capture taxi trips and tourists' movements during their stay. However, by presenting scenarios in comparison to a reference scenario, it is possible to overcome these limitations, especially when discussing the relative impact of the interventions assessed.

4. Results

4.1. Commuting demand scenario analysis

Table 3 presents the main transport statistics of interest from the respective model scenarios. Several findings may be drawn regarding commuter trips and their mode shares. Specifically, for the moderate and high WFH scenarios, the total number of commuter trips decreased to 82.3 % and 64.9 % of the reference scenario, respectively. Notably, "commuter" refers to both white and blue collar commuters, explaining why the percentages of 75 % and 50 % do not correspond to the total number of trips.

Table 3
Output statistics for commuting demand scenarios.

	Scenario		
	Baseline	Moderate WFH	High WFH
Total commuter trips	1,520,161	1,251,464	986,304
As percentage of reference	N/A	82.3 %	64.9 %
<i>Commuter trips</i>			
Car	1,039,897	869,069	700,966
Public transport	232,441	176,186	128,668
Walk	165,350	141,385	109,042
Cycle	82,473	64,824	47,628
<i>Commuter trips as percentage of reference</i>			
Car	N/A	83.6 %	67.4 %
Public transport	N/A	75.8 %	55.4 %
Walk	N/A	85.5 %	65.9 %
Cycle	N/A	78.6 %	57.7 %
<i>Mode share commuter trips</i>			
Car	68.4 %	69.4 %	71.1 %
Public transport	15.3 %	14.1 %	13.0 %
Walk	10.9 %	11.3 %	11.1 %
Cycle	5.4 %	5.2 %	4.8 %
<i>Mode share all trips</i>			
Car	60.7 %	60.4 %	60.5 %
Public transport	12.9 %	12.5 %	12.2 %
Walk	23.0 %	23.8 %	24.3 %
Cycle	3.4 %	3.3 %	3.1 %
Total vehicle kilometres	44,635,770	36,094,469	33,790,046
As percentage of reference	N/A	81 %	76 %

All modes of transportation saw a decrease in the number of commuter trips. As the car mode had the highest share of total trips, it experienced the greatest reduction in the number of trips. However, in terms of percentages, a high proportion of car trips was retained, accounting for 83.6 % and 67.4 % of the reference scenario, depending on the WFH scenario. The greatest percentage reduction for both scenarios was observed for public transport trips, which decreased to 75.8 % and 55.4 % of the reference scenario, respectively, suggesting that this mode of transport is most affected by the increasing number of employees WFH. This may be due to a preference for other modes when traffic volumes decrease or because public transport commuters are among those who choose to WFH more often, however, further research is required to verify this.

The mode share of commuter trips and all trips for each scenario were compared. The car share of commuter trips increased by 1.0 and 1.7 percentage points as white-collar workers' WFH share increased, while public transport mode share decreased by 1.2 and 1.1 percentage points. Walk share slightly increased by 0.4 percentage points in the moderate WFH scenario, but otherwise active travel share decreased between 0.2 and 0.4 points. Across all trip types, car mode share remained stable at around 60.4 % to 60.7 %. Public transport mode share which was 12.9 % in the reference scenario declined by 0.4 percentage points in moderate and 0.7 in the high WFH scenario. While walk mode share which was 23.0 % in the reference scenario increased by 0.8 and 1.3 percentage points, cycling mode share which was 3.4 % in the reference scenario decreased by 0.1 and 0.3 points across the scenarios.

The above indicates that while the shifts in commuting behaviour do affect the overall trip dynamics, the overall changes remain relatively minor. The trends show an increase in car mode share for commuter trips, with a decline in public transport and active modes. This shift is largely due to the model's use of generalised cost and mode-specific preferences in determining travel choices. With

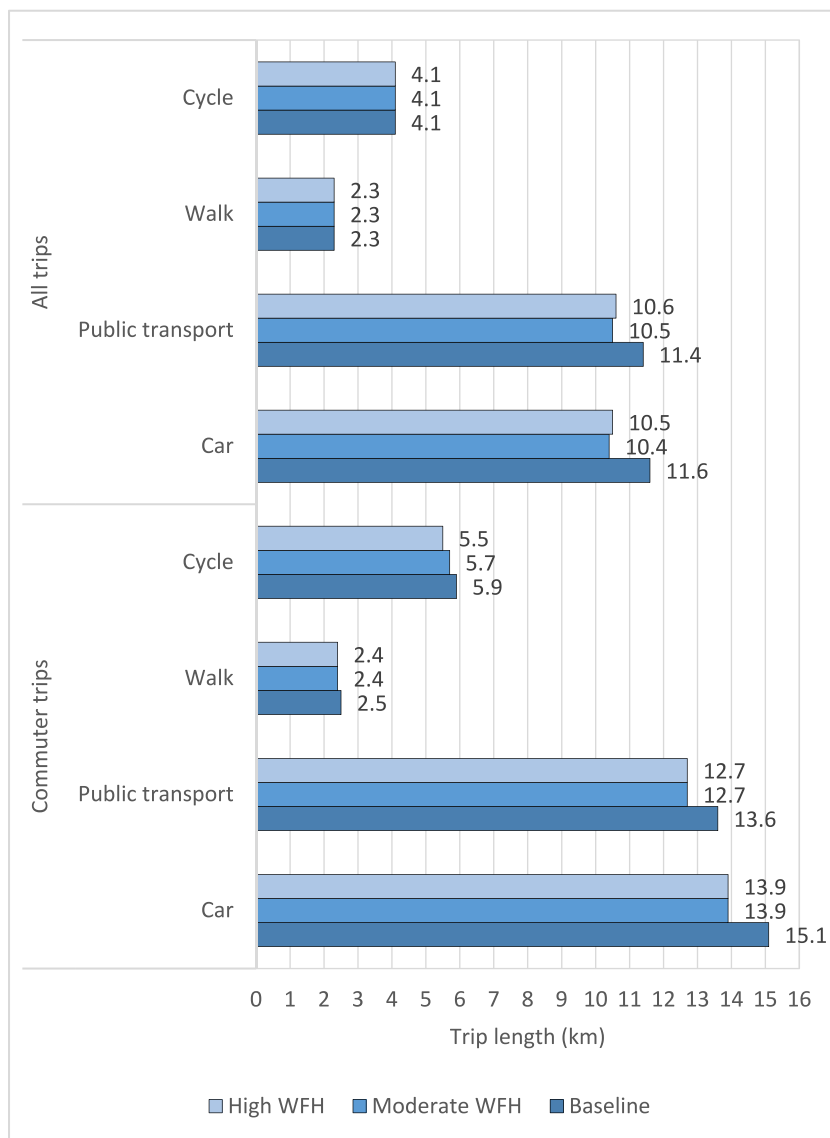


Fig. 2. Average trip length (km).

fewer commuting trips, changes in travel time, monetary costs, and convenience, significantly influence mode selection. For example, less traffic shortens car travel times, making driving more attractive, especially when cars are readily available. In contrast, the inflexibility of bus schedules means they do not benefit from reduced traffic, prompting a shift from public transport to cars. Additionally, the rise in walk mode share for all trips suggests that lower traffic levels enhance walkability, reinforcing walking's popularity driven by its flexibility. This trend may also be linked to a shift in trip-chaining behaviours of employees WFH; where individuals previously relied on cars for combined work and non-work purposes, they may now opt to walk, especially if the destinations are within walking distance. Previous studies (Caldarola and Sorrell, 2022; Cerqueira et al., 2020) also show a trend towards using active modes and public transport for non-work travel among teleworkers.

The total car kilometres across all purpose trips decreased in both WFH scenarios, with a larger decrease from the reference scenario to the moderate WFH scenario (8,541,301 km reduction) than from the moderate to the high WFH scenario (2,304,423 km reduction). It is worth noting that while a moderate WFH leads to a similar percentage reduction in commuter trips and total vehicle kilometres, a high WFH would be associated with a reduction of trips to 64.9 % of the reference, but vehicle kilometres only to 76 % of the reference. This could indicate that a high volume of WFH is likely to result in longer commuter trips. However, the output statistics on average commuter trip length in kilometres suggest the opposite. The average length of the commuter trips remains constant at 13.9 km for both the moderate and high WFH scenarios (Fig. 2). Therefore, the shift from the moderate WFH to the high WFH scenario does not affect the length of commuter trips. Consequently, the increased volume of kilometres travelled should be rather interpreted as an increase in the number or length of car trips for other purposes.

4.2. Emissions results

Table 4 presents the results of different commuting demand and fleet composition scenarios for various emission compounds, including greenhouse gases (CO₂, CH₄) and air pollutants (CO, NO_x, HC, PM₁₀, PM_{2.5}). The reference scenario refers to the baseline commuting demand and standard fleet. The EV uptake scenario represents a car fleet with 33.38 % battery EVs. Overall, the findings demonstrate that the combined implementation of the two measures could result in significant reductions in emissions. Specifically, the most optimistic scenario predicts up to a 35 % reduction in CO₂ emissions, a nearly 25 % in PM emissions, and a one-third to one-half reduction in other compounds.

A moderate WFH reduces emissions by 14.34 % to 20.85 %, while a high WFH only leads to a marginal additional reduction of 3.03 to 5.07 percentage points for standard fleet scenarios, which represents 21.13 % to 24.32 % extra reduction. Similarly, partially electrified private car fleet emissions vary only slightly between the two WFH scenarios, ranging from 2.11 to 3.39 percentage points. Increasing WFH rate beyond 25 % as a standalone measure for reducing commuting emissions does not seem justified. This finding suggests that there is the need to implement supporting policy measures to discourage car usage when traffic volumes decrease. These policies would need to consider monetary incentives and disincentives not in isolation but rather as interconnected with broader investment and urban planning decisions (Khmara and Kronenberg, 2023).

Increasing the proportion of EVs in the private car fleet in each commuting demand scenario could provide an additional benefit of between 3.61 % and 34.63 % compared to reference scenario depending on the compounds (Table 5). It is worth noting that 33.38 % of the EV uptake fleet is battery EVs, resulting in a reduction in emissions equivalent to that percentage for CH₄ and CO, and a substantial decrease in HC, CO₂, and NO_x emissions. However, electrification has little effect on PM emissions, reducing them only between 3.78 % and 5.62 %. A significant amount of PM is produced from non-exhaust sources such as tyres, brakes, resuspension and road wear. Currently, both EVs and ICEVs generate a comparable quantity of PM (Timmers and Achten, 2016). Moreover, a slightly higher uptake of EVs by petrol than diesel car owners has been forecasted in this study and observed in other countries (Choi and Koo, 2021). Diesel vehicles emit more of these pollutants than petrol ones, resulting in a smaller reduction in PM. On the other hand, while petrol cars produce more CO₂, diesel vehicles generate more NO_x which is reflected in a slightly larger emissions reduction in CO₂ compared to NO_x (Kinsella et al., 2023). While there are substantial climate benefits from the reduction of CO₂ and CH₄, health impacts remain high

Table 4
Emission compounds from the six scenarios.

Absolute values (t)								
Commuting demand	Fleet	CO ₂	CH ₄	CO	NO _x	HC	PM ₁₀	PM _{2.5}
Baseline	Standard	17,572.40	0.20	32.19	39.31	1.64	3.36	2.14
Baseline	EV uptake	14,168.74	0.14	21.04	32.13	1.25	3.23	2.02
Moderate WFH	Standard	14,377.58	0.17	25.48	33.67	1.40	2.77	1.78
Moderate WFH	EV uptake	11,784.95	0.12	16.75	27.84	1.08	2.67	1.68
High WFH	Standard	13,845.76	0.16	24.16	32.45	1.34	2.66	1.71
High WFH	EV uptake	11,415.38	0.11	15.92	26.98	1.04	2.57	1.62
As percentage reduction of reference								
Commuting demand	Fleet	CO ₂	CH ₄	CO	NO _x	HC	PM ₁₀	PM _{2.5}
Baseline	EV uptake	19.37 %	30.97 %	34.63 %	18.26 %	23.93 %	3.77 %	5.63 %
Moderate WFH	Standard	18.18 %	16.04 %	20.85 %	14.34 %	14.72 %	17.46 %	16.75 %
Moderate WFH	EV uptake	32.93 %	41.52 %	47.95 %	29.17 %	34.32 %	20.52 %	21.31 %
High WFH	Standard	21.21 %	21.11 %	24.96 %	17.44 %	18.42 %	20.67 %	19.89 %
High WFH	EV uptake	35.04 %	44.91 %	50.54 %	31.36 %	36.76 %	23.54 %	24.18 %

Table 5

Percentage reduction of emission compounds from the standard fleet scenarios with equivalent commuting demand.

Commuting demand	Fleet	CO ₂	CH ₄	CO	NO _x	HC	PM ₁₀	PM _{2.5}
Baseline	EV uptake	19.37 %	30.97 %	34.63 %	18.26 %	23.92 %	3.78 %	5.62 %
Moderate WFH	EV uptake	18.03 %	30.34 %	34.24 %	17.31 %	22.96 %	3.72 %	5.51 %
High WFH	EV uptake	17.55 %	30.17 %	34.10 %	16.86 %	22.44 %	3.61 %	5.38 %

due to particularly high levels of PM after fleet electrification. This implies the need for further technological improvements to EVs to cope with these pollutants; however, from the perspectives of wellbeing and sustainability, greater benefits could be achieved by implementing strategies to limit overall car usage (Hosseini and Stefaniec, 2023).

The effectiveness of the moderate WFH and EV uptake measures in reducing emissions were compared in Fig. 3. The impact of these measures considered in isolation varied depending on the compound. The comparison suggests that a 33.38 % EV uptake and a moderate WFH scenario lead to a similar reduction in CO₂ emissions from commuter trips. However, the moderate WFH scenario results in considerably fewer PM emissions compared to the EV only scenario, which has substantially lower CH₄, CO, and HC emissions. The cumulative effect of both measures is much higher than applying each measure in isolation, as both measures are complementary. Moreover, adding up emissions savings from implementing isolated EV uptake and WFH measures results in only between 0.71 and 7.53 percentage points higher emission reduction than the scenario with combined EV uptake and moderate WFH measures. These results are promising as they suggest an almost additive effect of both measures.

5. Policy and planning implications

The presented results have several important policy and planning implications. The study found that an increase in WFH practices reduces commuting traffic volumes, but the high car mode share for commuter and all trips is maintained. This indicates a car-dependent transport system, where private cars are preferred. The simulation also exposed other symptoms of transport design favouring private car usage, such as commuter car trips being maintained while public transport trips decreased with an increase in WFH practices, and marginal uptake of walk. In these circumstances, the reduction in traffic volumes presents an opportunity to redesign the system so that the benefits do not diminish with an increasing the rate of WFH. Failing to take advantage of this opportunity is likely to offset the gains of reduced commuting trips and result in people switching to car use as traffic volumes decrease. Additional measures to deter car usage seem necessary.

As the rate of WFH increases, interventions to reduce car usage become more crucial, particularly as the benefits show diminishing returns with higher WFH rates. Embedding monetary incentives and disincentives into wider investment and urban redesign plans seems to be the optimal way (Khmara and Kronenberg, 2023). Long-term plans need to be in place, and short-term policies are required

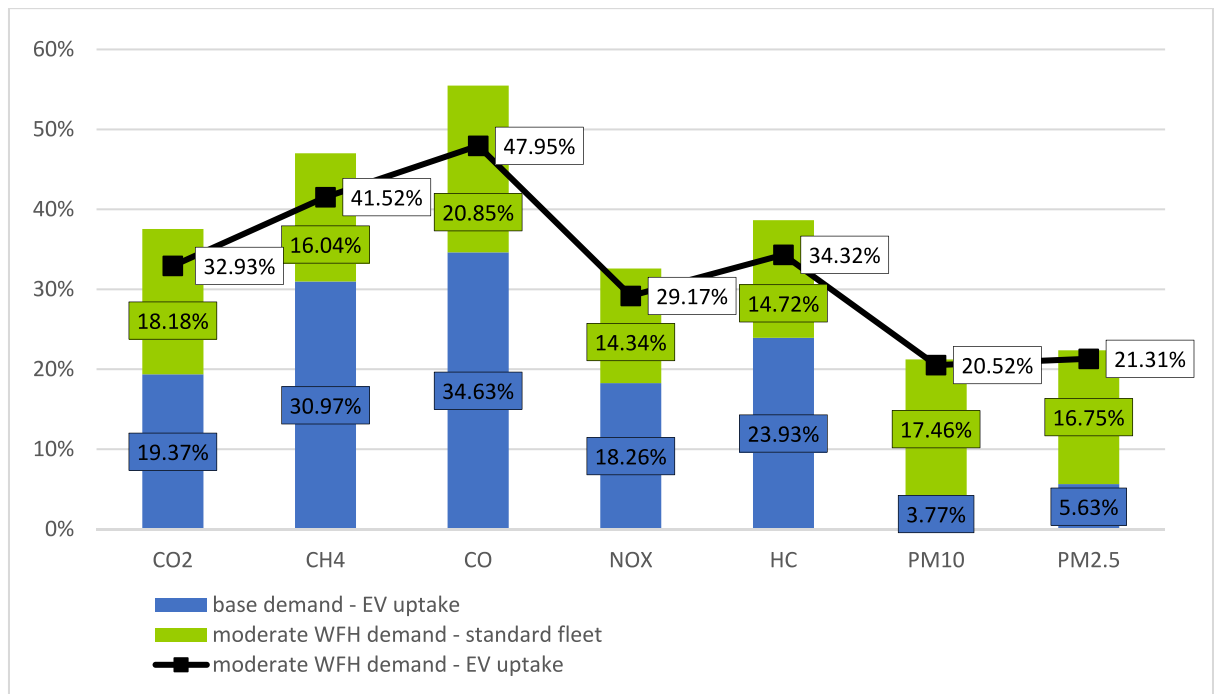


Fig. 3. Effectiveness in reducing emissions of isolated and combined EV uptake and WFH measures.

to temporarily deter private car activities. Redesign initiatives generally take longer as they involve changes to the built environment, so infrastructure improvements and policies feasible in a short timeframe would need to be implemented first to support sustainable transport solutions. These include traffic regulations favouring pedestrians and cyclists, subsidies and schemes to support private micro-vehicle uptake, facilitating the rollout of shared mobility services, and improving the frequency and convenience of public transport. Regarding infrastructure, certain street space reallocation interventions could also be undertaken at an early stage of planning, involving converting some of the current car infrastructure to prioritize walking and cycling (Hagen and Tennøy, 2021).

The study found that a reduction in commuter trips was associated with an increase in other trips, indicating the need for countermeasures. This finding is consistent with other evidence that suggests an increase in travel by households that WFH (de Abreu e Silva and Melo, 2018). Research has shown that compact development initiatives, which increase the proximity of services such as shopping or recreation to residential areas by incorporating mixed land use functions, reduce the need for longer distance travel and encourage modal shift (Holz-Rau and Scheiner, 2019). The concept of 15 or 20-minute neighbourhoods is gaining traction in various locations, providing an opportunity to further test this approach (Calafiore et al., 2022). In addition, growing interest in walking was observed despite a slight reduction in the popularity of public transport and cycling. This could also be seen as an opportunity to reinforce pedestrian activities and their right to the space by improving walking conditions and implementing spatial and traffic regulation interventions granting more rights to walkers (Buehler et al., 2017; Egan and Philbin, 2021). The research provides an evidence that the walking behaviour is associated with neighbourhood design (Zhao and Wan, 2020).

Replacing one-third of private cars with EVs was found to generate comparable CO₂ emissions savings and greater savings in other emissions compared to a moderate WFH strategy. However, the cost-effectiveness of this measure is much lower than facilitating a workplace shift from the office to home for a quarter of white-collar employees. This is due to high expenditure of the exchequer on subsidies and tax reliefs. In addition, the low uptake of EVs at present could pose a risk to the feasibility of this transition. To reduce non-exhaust PM emissions generated by EVs, technological improvements and the imposition of car weight restrictions would need to be accelerated. In current conditions, WFH practices lead to much higher savings in PM emissions, reducing them by almost a quarter. Nevertheless, greater benefits could be reached by limiting the number of cars, including EVs, on the roads. Research suggest that this could create more liveable communities, freeing space for life-enriching activities and active travel and ultimately redesigning settlements in line with compact development principles (Nieuwenhuijsen, 2020).

Considering the climate emergency, a combination of various policies is recommended, particularly when their impacts are complementary. This is the case of combined electrification and WFH practices, which have an additive effect in reducing emissions. As multiple factors, including residential emissions, could offset these emissions savings, efforts across sectors that target other aspects of consumption and production-based emissions are necessary to achieve the required emission reductions. The literature suggests that a systemic approach to emissions reduction is considered the most effective (IPCC, 2023). Therefore, to analyse the impact of policies on emissions, it is advisable to conduct research that takes a holistic and comprehensive approach, accounting for multiple measures and factors when simulating the effects of climate strategies. More research in this direction could better inform climate actions.

6. Conclusions

This study aimed to determine the reduction in commuting activities and emissions resulting from increased WFH practices among white-collar employees combined with the adoption of EVs. The results were obtained using the ERM model developed for the Eastern Region of Ireland and the COPERT's parameters for emissions estimation. The WFH scenarios include the baseline commuting demand, a moderate WFH rate (25 %), and a high WFH rate (50 %), while the private car fleet composition scenarios contain the current fleet and an EV uptake of 33.38 %, as forecasted for 2030.

The following findings can be drawn from the analysis of results presented in this study:

- WFH practices lead to a 1–2 percentage point increase in car mode share of commuter trips, a 1 percentage point drop in public transport mode, and a negligible decrease in active travel modes. Considering all trips, the shifts in modal share were minimal, except for a slight increase in walking.
- The change from a moderate to high WFH scenario shows diminishing benefits in terms of total travel length and modal shift. Consistent with these findings, emissions reduction was substantial following a moderate level of white-collar employees WFH but only marginal with increased levels of WFH activities.
- An increase in car trips for other purposes and their length, and not longer distances of commuter trips were found to be a reason of offsetting the impact of WFH in terms of reducing total kilometres travelled. This indicates that a reduction in commuter trips is associated with an increase in other trips.
- The EV uptake and WFH measures were found to have almost cumulative effect on reducing emissions, suggesting their complementary relationship.
- Implementing the two measures could result in significant reductions of up to 35 % in CO₂ emissions, nearly 25 % in PM emissions, and a one-third to one-half reduction in other compounds (CH₄, CO, NO_x, HC) in the most optimistic scenario.
- The EV uptake generated CO₂ emissions savings comparable to the moderate WFH strategy, and higher savings of other compounds, but much lower PM emissions reduction. The health impacts of fleet electrification remain high due to high levels of PM.

This research has significant implications for sustainable transport policy and planning, particularly in light of the increasing prevalence of WFH. The findings suggest that additional measures will be needed to discourage car usage, when commuting activities decline, to prevent a loss of the benefits from reduced traffic. Providing high-quality daily and recreational services in proximity to

residential areas is important to limit motorised trips for non-work purposes. Furthermore, reducing private car usage through WFH and other policies is preferable to electrifying cars due to the greater benefits to both emissions reduction and wellbeing, and lower cost.

While this paper is one of the few to consider the impacts of WFH in conjunction with other measures, and the first to analyse the relationship between WFH and EV adoption, it does not account for all other relevant measures and factors. Therefore, it is recommended that future research adopt a systemic approach to emissions reduction in scenario analysis to develop effective climate strategies. Worth noting, that although the model encompasses public transport and freight, their emission estimates were excluded. This exclusion ensures that the study focuses solely on the impact of WFH practices and EV adoption, without the confounding influence of other emissions. Additionally, it should be considered that the alterations in non-work trips were not pre-determined but emerged during the modelling process as an indirect effect of reduced work trips. It is crucial to acknowledge that any forecasts about future EV uptake, fleet composition, and travel choices in a WFH context are inherently uncertain and hence the results are constrained by the assumptions of the model.

CRedit authorship contribution statement

Agnieszka Stefanić: Conceptualization, Data curation, Formal analysis, Project administration, Validation, Writing – original draft, Writing – review & editing. **William Brazil:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Validation, Writing – original draft, Writing – review & editing. **Warren Whitney:** Conceptualization, Data curation, Formal analysis, Methodology, Project administration, Writing – original draft, Writing – review & editing. **Wen Zhang:** Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Barry Colleary:** Conceptualization, Data curation, Formal analysis, Writing – original draft, Writing – review & editing. **Brian Caulfield:** Conceptualization, Data curation, Formal analysis, Methodology, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.trd.2024.104063>.

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