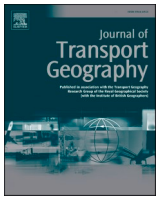
Journal of Transport Geography 102 (2022) 103376

Contents lists available at ScienceDirect

Journal of Transport Geography

journal homepage: www.elsevier.com/locate/jtrangeo



Retail sprawl and CO_2 emissions: Retail centres in Irish cities

Conor O'Driscoll *, Frank Crowley, Justin Doran, Nóirín McCarthy

Spatial and Regional Economic Research Centre, Department of Economics, Cork University Business School, University College Cork, Cork, Ireland

ARTICLE INFO

Keywords:
Cities
Retail sprawl
CO_2 emissions
Travel mode choice

ABSTRACT

The concept of sustainable retail development implies that retail centres should serve their communities economically and socially, while not degrading local environments. However, existing literature identifies that retail centres often create negative externalities, impacting the sustainable development of both the core and peripheries of city regions. International evidence also shows that retail sprawl and transport emissions have been exacerbated by existing planning architecture, notably retail parks. This has resulted in commercial centres shifting from high streets to car-dependent, suburban retail centres, worsening congestion levels and environmental degradation.

This paper examines how location-effects influence transport-related emissions and travel mode choice when shopping in Ireland's five major administrative city regions. This paper adapts 2016 Census commuting data, and utilises retail and residential location data, to estimate hypothetical travel-related emissions within a multi modal transportation network incorporating cars, buses, cycling, and walking. This analysis is performed at the Small Area level for Ireland's five major cities and their surrounding commuter belts.

The results show that retail centres generating the most travel-related emissions tend to be found outside city cores, in the fringe areas of built-up city environments, and that these retail centres are generally only accessible to car users. This supports theories suggesting that accessibility-centred development is the best option to combat the ill effects of sprawl, and that car dependency worsens the environmental degradation associated with sprawling developments. Above all, this study highlights the excessive environmental degradation caused by car dependent retail environments and offers direction for future policymaking.

1. Introduction

Urban sprawl is a by-product of haphazard, rapidly expanding urban development (Nechyba and Walsh, 2004). Due to the heterogenous nature of urban areas, and the complicated relationships between development indicators and their environment, refining this definition further can be problematic (Ewing, 1997). However, sprawled developments are commonly characterised by low population density, low accessibility, and segregated land (OECD, 2018). Urban sprawl can also refer to areas which experience spatial expansion rates greater than that of population growth, which generally decreases population density over time, and increases emission outputs due to longer travel distances (Song and Sohn, 2007). With evidence suggesting that sprawl in all forms contributes to environmental degradation (European Environmental Agency (EEA), 2006), we focus on a particular dimension of urban sprawl, namely *retail sprawl*, and its relationship with travel-related emission outputs.

Retail sprawl refers to the urban exodus of firms in favour of cheaper and more abundant land on urban peripheries (Wassmer, 2002). It specifically relates to the consequences of businesses moving to suburbs (Frenkel and Ashkenazi, 2008; Vandenbulcke et al., 2009) and was initially characterised by strip-mall development, whereby commercial developments were usually situated parallel to roads, but it has since outgrown this characterisation due to the scale of modern retail parks (Department of Housing Planning Community and Local Government, 2012).

International literature has addressed many sprawl-related problems. Specific investigations surrounding how land-use (Oueslati et al., 2015), transport networks (Lee, 2020), government incentives (Wassmer, 2002; Carruthers and Úlfarsson, 2008), retail location (Kristoffersson et al., 2018), and regional property markets (Öner, 2017) affect urban development have been conducted worldwide. This research questions whether centrally located retail centres can reduce the environmental degradation associated with travelling for leisure.

* Corresponding author.
E-mail address: 117337281@umail.ucc.ie (C. O'Driscoll).

https://doi.org/10.1016/j.jtrangeo.2022.103376
Received 17 October 2021; Received in revised form 29 March 2022; Accepted 24 May 2022
Available online 31 May 2022

Specifically, our objective is to quantify the emission outputs generated when travelling to sprawled retail centres relative to their centrally located counterparts.

Theoretically, we extend traditional central place frameworks, which usually analyze the economic consequences of locating away from central locations, to an emissions-minimising context (Erdin and Akbas, 2019). We test these locations' environmental merits by analysing whether centrally located retail environments offer optimal locations to minimise carbon impacts (Dennis et al., 2002). Complimenting this, is the incorporation of gravity framework theories (Luo and Wang, 2003; Rasouli and Timmermans, 2013), whereby we use retail centres' physical footprints to proxy the retail environment's perceived attractiveness as a shopping destination.

Methodologically, we broaden the investigative scope of retail location modelling by gauging the environmental impacts associated with travelling to retail centres, and how this relates to retail centre locations. We incorporate variables capturing multiple travel modes, residential locations, retail centre locations, retail centre sizes, and travel network data for Ireland's administrative city-regions, examining the environmental consequences associated with sprawling retail environments and induced travel behaviours.

International literature calls to develop more holistic models of retail development. Määttä-Juntunen et al. (2011) and Ahmad and Hiyasat, (2017) explicitly call for research investigating the alleviation of the '…consequences of unplanned retail service distribution in the city on its investors and users' (Ahmad and Hiyasat, 2017, p. 36), and emphasise the need to '…pay attention to the location of workplaces and commuting, which may also strongly affect the traffic flow and shopping preference' (Määttä-Juntunen et al., 2011, p. 353). We answer these calls, and contribute to global retail policymaking, by modelling retail development in terms of minimising hypothetical emissions from a multi-modal perspective, including cars, buses, cycling, and walking. This multi-modal approach fills research gaps, as many studies tend to focus exclusively on the car (Määttä-Juntunen et al., 2011; Kristoffersson et al., 2018), occasionally investigating walking (Roig-Tierno et al., 2013; Eldeeb et al., 2021), cycling (Giorgi et al., 2017), and transit (Hay, 2005; Cheng et al., 2007; Rao and Pafka, 2021), with no study cross-comparing these modes simultaneously using the same geographical scope as here.

This analysis fits into an established body of literature addressing the environmental consequences associated with retail location (Suarez et al., 2004; Scott and He, 2012; Suárez-Vega et al., 2012). We adopt a central place and gravitational theoretical lens, primarily because of the pivotal role policymaking plays within these frameworks, but also because of their proven robustness (Dolega et al., 2021; Schläpfer et al., 2021). Geographic Information Systems (GIS) facilitates our analysis by showing how hypothetical emissions, transportation networks, residential locations, retail centre size, and retail locations are related and the hypothetical emission patterns emerging therein.

The remaining sections of this paper detail a comprehensive literature review, describe the data and methodology used throughout this analysis, illustrate the results, and discuss their implications. When concluding the analysis, we highlight this study's limitations and future research avenues whilst also investigating the policy implications of this research.

2. Literature review

2.1. Urban sprawl

The rapid industrialisation experienced across the developed world post-WW2 forever changed commuting patterns as cars became more affordable, incomes steadily rose, and the desire for suburbanisation increased (Paterson, 2000; Pooley and Turnbull, 2005). Residential decentralisation created new markets for businesses to exploit (Sultana and Weber, 2014), resulting in a commercial expansion from cities, eventually leading to widespread retail sprawl. Currently, retail sprawl is most prominent in urban peripheries, encouraging the emergence of a reliance on cars to avail of these environments (Knowles et al., 2020; Eldeeb et al., 2021). Consequently, retail sprawl can exacerbate the environmental degradation associated with car use by increasing congestion and emission outputs (Focas, 2016). Furthermore, because suburbs have been found to grow in popularity with their size (Glaeser et al., 2001), residential and commercial sprawl can be linked to the environmental consequences associated with excessive travel behaviours and unsustainable regional development patterns (Frenkel and Ashkenazi, 2008; OECD, 2018).

The economic theory of sprawl stems from central place theories, which state that changes in population, income, transport technology, and land values are fundamental determinants of urban structure (Evans, 1983). In equilibrium, these models generally decrease population density through uniform peripheral expansion around a Central Business District (CBD), but maintain a monocentric nature (Evans, 1983; Oueslati et al., 2015). We strengthen our theoretical approach by incorporating gravity theories which argue that accounting for a location's perceived attractiveness can determine developmental forms (Kristoffersson et al., 2018; Erdin and Akbas, 2019; Schläpfer et al., 2021). This is typically done by arguing that an entity's attractiveness increases with its size, irrespective of distance from urban cores (Glaeser et al., 2001; Kristoffersson et al., 2018). Combining these concepts allows for a scenario whereby an entity's attractiveness exceeds that of CBDs once it reaches a certain size/status, creating potentially uncontrolled sprawl (Nechyba and Walsh, 2004).

Adapting these theories to the suburban and car booms of the mid-twentieth century illuminates sprawl as a by-product of traditionally monocentric regions becoming polycentric commercial and residential fabrics, catalysing excessive car use and exacerbating travel-related emissions as a consequence (Focas, 2016; Holz-Rau and Scheiner, 2019). Overall, this highlights the results of haste attempts to meet the demand of rapidly emerging markets chasing the 'American Dream', as the provision of alternative transport infrastructure was not prioritised in expanding peripheries (Knowles et al., 2020). This underscores the role policymaking plays in catalysing developmental patterns, as governments generally facilitated this surge (Razin, 1998; Pendall, 1999).

Increased car usage in the twentieth century was met with increased road construction as road space demand began to outpace supply (Pooley and Turnbull, 2005). The resulting congestion problem which emerged in population centres was initially believed to be the fault of transit, ultimately strengthening car-friendly policymaking and weaking alternative transport provision, despite the real problem being greater car volumes due to increased commuting from hinterland to core areas (Pooley and Turnbull, 2005). This intertwined sprawl and car dependency, which has exacerbated transport-related emissions by creating car-exclusive regions (Vandenbulcke et al., 2009).

2.2. Sprawl and negative externalities

Suburbanisation, congestion alleviation, and compact developments have seldom been able to realise their theoretical potential because globally inefficient policymaking enables negative externalities, like travel-related emissions, to emerge unaddressed (Paterson, 2000). Congestion, and subsequent environmental degradation, in cities increases because of the attraction of central places and from accessibility issues (Holz-Rau and Scheiner, 2019). City dwellers tend to have excess accessibility opportunities while suburbanites tend to lack similar opportunities, exposing imbalances which generally stem from inadequate alternative transport provision (Holz-Rau and Scheiner, 2019). Given that technology and car use evolve in unison, it is unsurprising that technology has proven inept at balancing the externalities associated with excessive travel behaviours, further demonstrating the importance of effective policymaking (Paterson, 2000; Määttä-Juntunen et al., 2011).

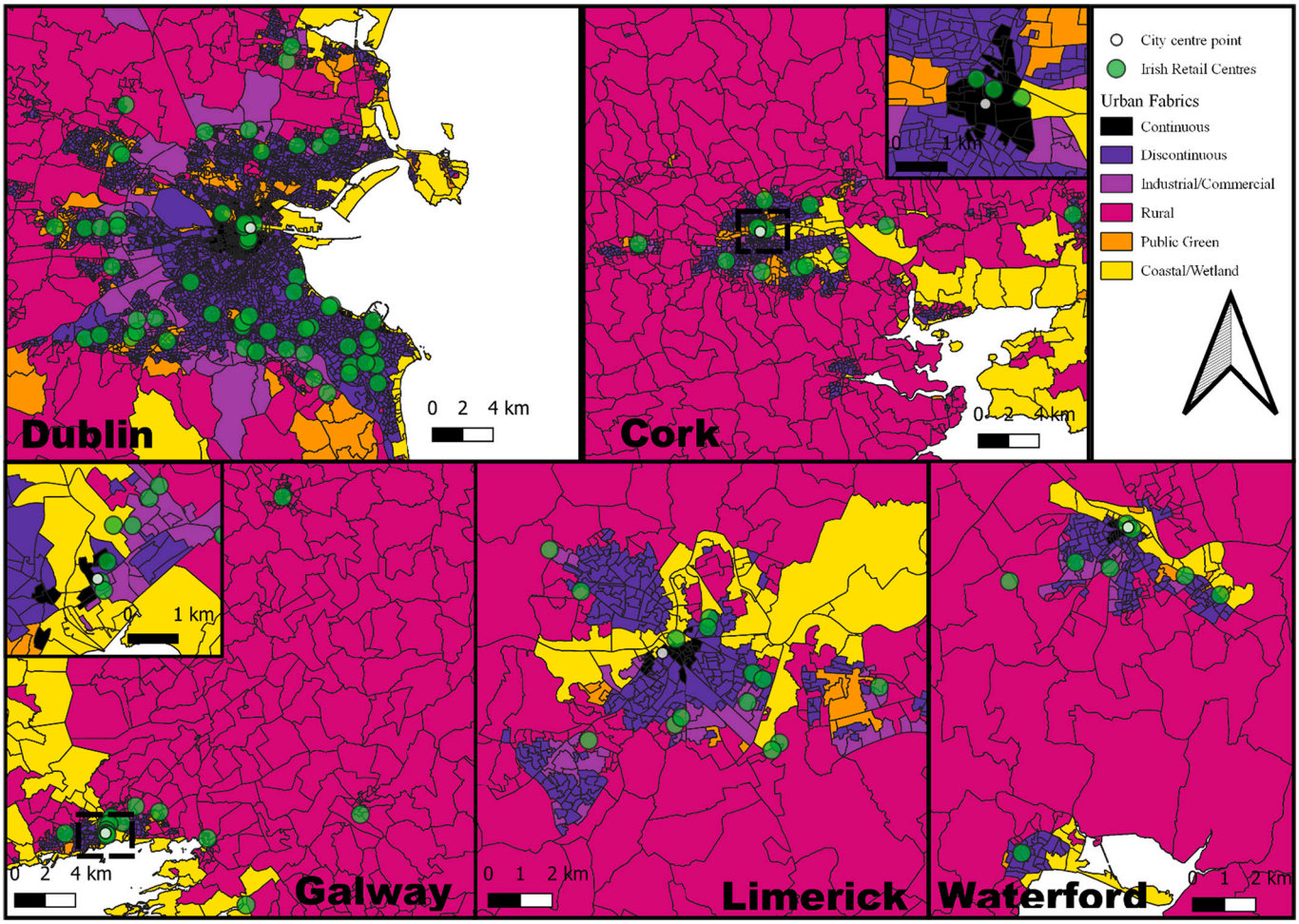


Fig. 1. Irish retail centres in Irish cities and their surrounding built environment.

Table 1
Transport Mode Share (%) by Journey Purpose and Duration as per *The National Travel Survey* (2016).

Journey Purpose	Private Car	Public Transport	Walk/Bike
Commute (to Work)	28.6	28	15.5
Shopping	22.5	19.1	25.6
Journey Duration			
15 min or less	77.4	1.6	17.8
16–30 min	71.3	7.5	16.7
31–45 min	70.8	13.8	10.9
46–60 min	67.2	16.4	12.9

The cost of public services is negatively related to density and positively related to the spatial extent of developed land, making sprawl a more expensive form of development than more compact urban forms (Carruthers and Úlfarsson, 2008; OECD, 2018). Sprawl exacerbates emission outputs through the emergence of car-dependent commuter belts and increases infrastructure costs and habitat degradation through its spatial demands (Nechyba and Walsh, 2004). These negative externalities outweigh the positives sprawl produces, as these tend to be individualistically centred, often revolving around private transport, embodying the environmental unsustainability characterising twenty-first century development (OECD, 2018). If the primary cost of sprawl can be surmised by its spatial demands, measures countering these demands should be prime options to alleviate these effects (Song and Sohn, 2007).

The promotion of accessibility can alleviate some sprawl-related problems. This is because accessibility inherently involves mixed-use land, efficient infrastructure usage, and multi modal transportation (Ewing, 1997; Vandenbulcke et al., 2009; Kono et al., 2012; Lee, 2020; Yang et al., 2020). This approach is supported by evidence showing highway driving to be more environmentally damaging than city driving (OECD, 2018; Holz-Rau and Scheiner, 2019) and the seemingly positive relationship between regional accessibility, subjective wellbeing, and sustainable development (Song and Sohn, 2007; Öner, 2017; Zhang et al., 2020). Therefore, by exposing accessibility problems and thereafter addressing them at institutional levels, the excessive environmental degradation attributable to transport-related emissions and inefficient land use can be abated.

2.3. Retail sprawl and CO_2 emissions

Retail sprawl encapsulates regional development as a spatial economic issue (Nechyba and Walsh, 2004). Given the fixed costs associated with retail park establishments, it is surprising that the embrace of retail sprawl advanced more rapidly than the understanding of it. Environmentally, these centres clearly produce externalities, something exacerbated as distances from urban cores increase as intense travel behaviours are encouraged (Erdin and Akbas, 2019; Holz-Rau and Scheiner, 2019), suggesting links between the hidden costs associated with commuter belt living (Song and Sohn, 2007). Internalising these externalities has been found to alleviate retail park establishment by disincentivizing their location far from urban centres, incentivizing the use of alternative transport, and reducing emission outputs (Feitelson and Rotem, 2004; Carruthers and Úlfarsson, 2008; OECD, 2018). Subject

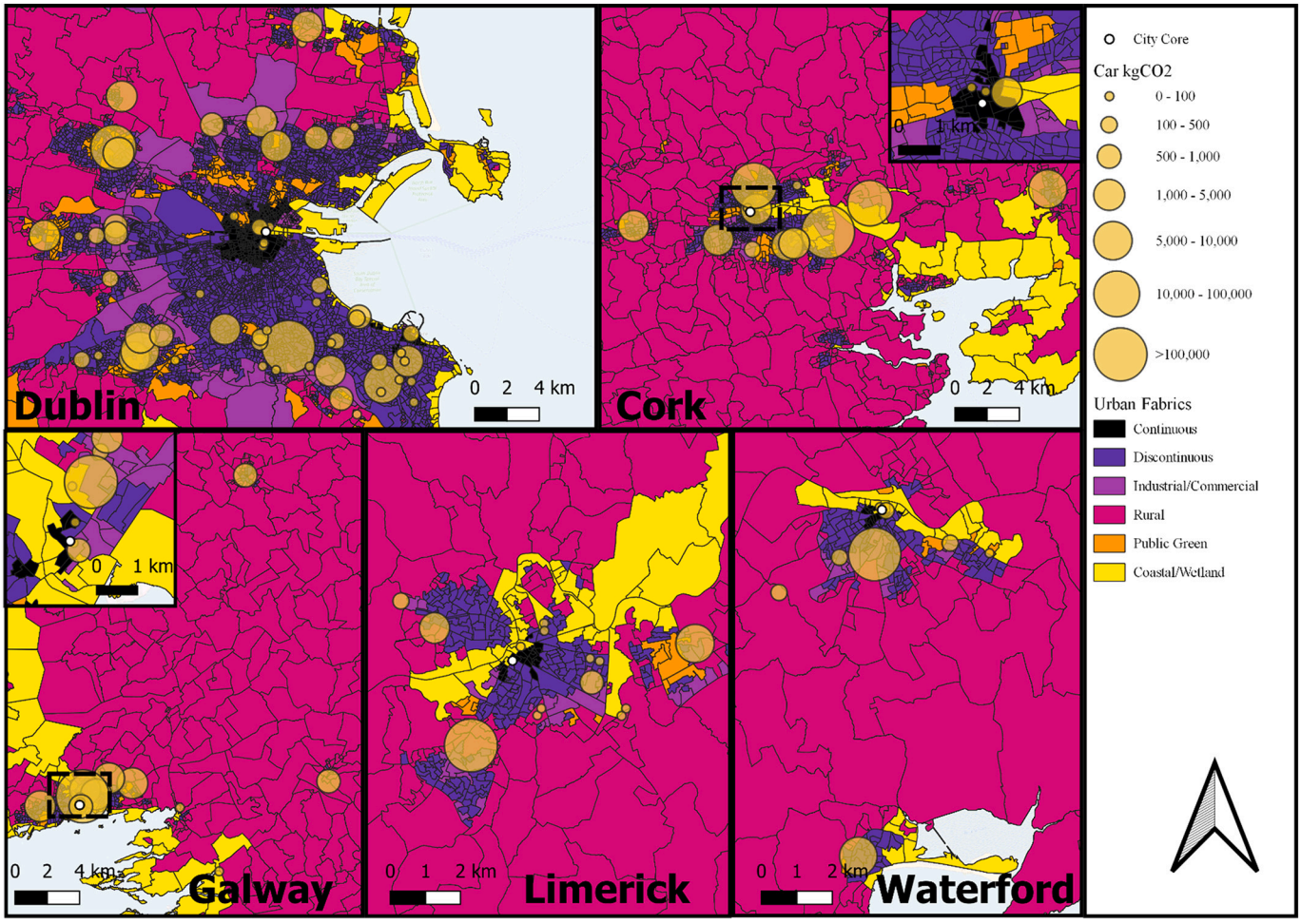


Fig. 2. The hypothetical travel-related emissions attributable to travelling to retail centres by car.

to policy coordination, this internalisation is said to cause shifts in demand by promoting accessibility, subsequently reducing travel-related emissions (Feitelson and Rotem, 2004; Carruthers and Úlfarsson, 2008).

Historically, retail location analysts have adopted multiple theoretical lens' (Clarkson et al., 1996; Suarez et al., 2004; Suárez-Vega et al., 2012). While individually, many of these theories have been contested as outdated (Ahmad and Hiyasat, 2017; Dolega et al., 2021), when combined, central place and gravitational models make up the most robust conceptual framework for analysing retail location from a sustainability perspective. This is primarily because they capture some of the central tenets of travel behaviour, principally, distance, and the perceived attractiveness of destinations (Clarkson et al., 1996; Dennis et al., 2002; Dolega et al., 2021). We extend central place modelling by incorporating theoretical principles embedded within gravity frameworks by assuming that perceived attraction and the time spent travelling determine destination choices. We calibrate this by weighting the size of retail environments over the time it takes to travel from each possible origin within the travel threshold, thereby identifying the retail centre each Small Area visits.

Arguably the most important advance in studying sprawl has come from adopting mapping software (GIS) to aid in understanding the phenomenon whereby retail sprawl is typically conceptualised as a problem of accessibility and incentives (Cheng et al., 2007; Määttä-Juntunen et al., 2011; Suárez-Vega et al., 2012; Roig-Tierno et al., 2013; Ahmad and Hiyasat, 2017). Global evidence sharply points to increasing retail sprawl and car dependency, which increases emissions and degrades regional environments, underscoring the need for this type of research.

Most surveyed literature recognises private cars to be the preferred transport mode for shoppers, rendering most studies effectively unimodal in scope (Määttä-Juntunen et al., 2011; Mohamad et al., 2015; Ahmad and Hiyasat, 2017). However, existing evidence indicates that transit or active modes can serve as primary modes when shopping depending on built environment considerations (Susilo et al., 2013; National Transport Authority, [NTA], 2014), justifying a multi-modal approach which investigates the environmental impact attributable to travelling for leisure. Strategies mapping optimal routes have been incorporated in studies concerned with city accessibility (Vandenbulcke et al., 2009), consumer behaviour (Kristoffersson et al., 2018), commute lengths (Giorgi et al., 2017), and travel-related emissions (Määttä-Juntunen et al., 2011). We expound these models by incorporating a multimodal transport system and a proxy for retail attractiveness (retail centre size) into the emissions minimising retail location literature.

3. Data and methods

3.1. Study area

Our analysis focuses on Ireland's five administrative city regions: Dublin, Cork, Limerick, Galway, and Waterford. Retail centres were selected according to administrative county boundaries, enabling a comprehensive contextualization of each region's retail environment. Boundaries for our model are based on travel times to these retail centres for each specific mode. This regulates population statistics, while also capturing commuter belts for cities and out-of-town commercial hubs, whose catchment may extend beyond political boundaries.

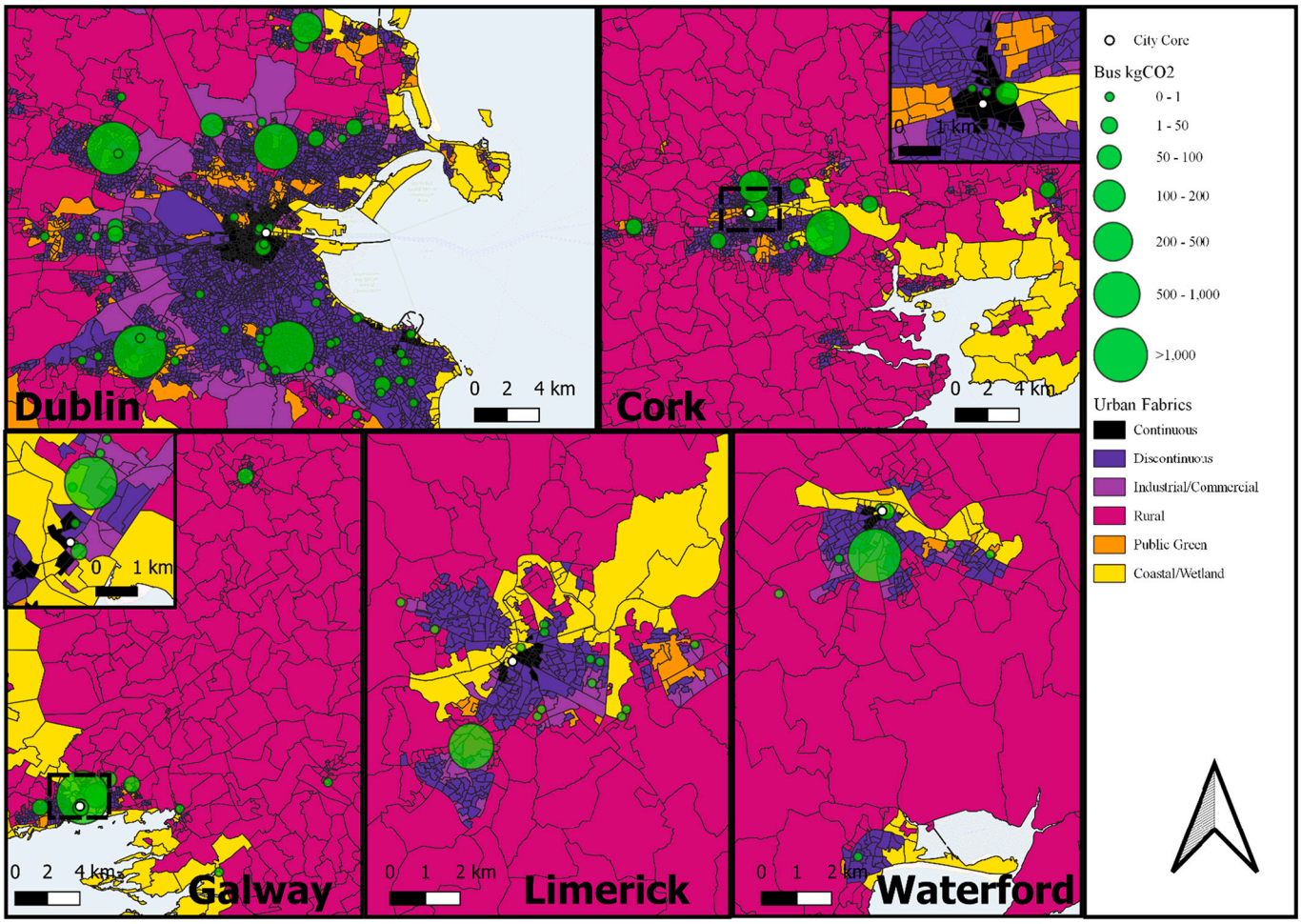


Fig. 3. The hypothetical travel-related emissions attributable to travelling to retail centres by bus.

Existing literature cites anywhere between 10 km and 100 km as an appropriate travel boundary for this type of study when travelling by car/transit (Hay, 2005; Cheng et al., 2007; Määttä-Juntunen et al., 2011). The National Travel Survey (Central Statistics Office [CSO], 2016) refines this by demonstrating one-hour trips to capture 73% of all one-way shopping related journeys, with 45.7% of these being completed in thirty-minutes, further suggesting that trips typically diminish in quantity and frequency as travel time increases, indicating one-hour is the maximum travel time accountable for 'regular' journeys (Central Statistics Office [CSO], 2016). Furthermore, active travel literature cites 10-min as an appropriate one-way travel threshold for walkers/cyclists, showing strong distance decay effects to emerge thereafter (Millward et al., 2013; Spinney and Millward, 2013; Gunn et al., 2017).

3.2. Retail centres and city cores

Our definition for retail centres builds on the work of Pitt and Musa (2009) and Dolega et al. (2021), who distinguish between increasingly convergent supermarket and retail centre characteristics, highlighting how there is no one-size-catch-all definition. Accordingly, retail centres here refer to planned developments comprising of either a singular building, or an agglomeration, of no particular size, surrounded by, or surrounding, a car park, which serves multiple consumer purposes (Dennis et al., 2002). Retail centre environments should also accommodate socialising through the availability of amenities, like open seating areas (Pitt and Musa, 2009; Dolega et al., 2021).

Additionally, if an overarching centre shares a title with its anchor store, and/or this anchor store constitutes >50% of the centre's total square footage, these centres are generally excluded from the analysis based on this indicating centres primarily dedicated to local supermarkets (Pitt and Musa, 2009). With this framework in place, OpenStreetMap (OSM) is used to identify commercial/business units within these regions. If OSM's algorithm fails to highlight units as commercial/business entities, they are not considered, ensuring methodological consistency throughout the analysis.

City cores refer to historical city centres prior to the emergence of car technologies, something which usually revolves around a singular Central Business District (CBD) (Knowles et al., 2020). This historical centre is generally defined as the main (shopping) street. Here however, further specificity is gauged by plotting the centroid of continuous urban fabrics within city areas (Copernicus Land Monitoring Service, 2021). In this case, the emergence of discontinuous urban fabrics constituted the boundaries of core areas, enabling the contextualisation of spatial boundaries. Fig. 1 below illustrates this by mapping existing retail centres according to their regional urban fabric, with cores represented by the darkest coloured cluster in each region.

3.3. Data

Utilizing Irish Census (Central Statistics Office [CSO], 2016)) and OpenStreetMap data, we construct an Origin-Destination (OD) Matrix comprised of residential locations (origins) and retail locations (destinations). An OD-Matrix calculates network routes from *each* origin to *every* destination, compiling a dataset containing every minimum-cost route taken along the network(s) expressed in terms of travel time. To

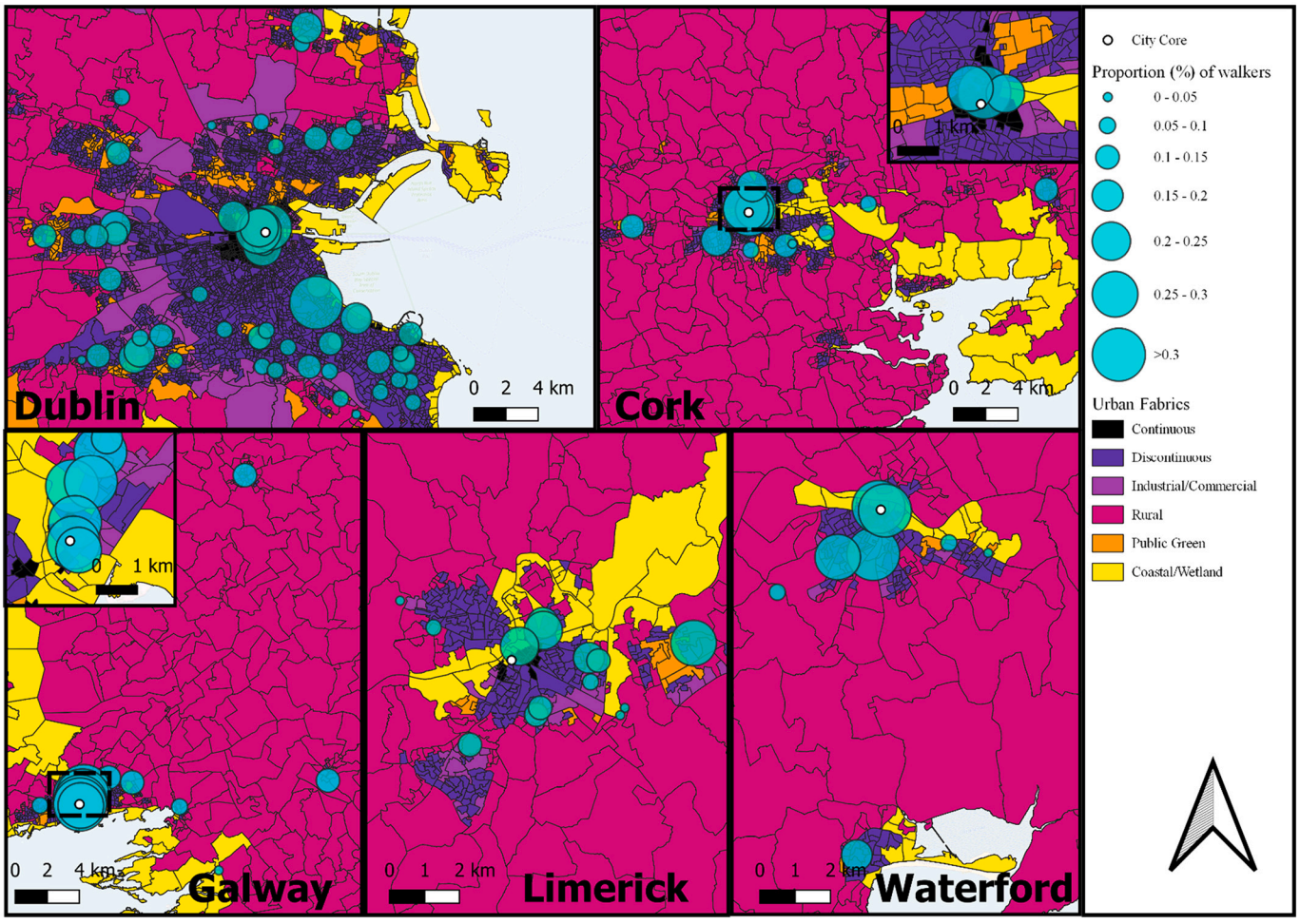


Fig. 4. The proportion of people per surrounding Small Area (i.e., within a 10-min walk) who commute to work by walking.

prevent overestimating accessibility, bus stops are used as origins when analysing bus travel.

Small Areas (SA), the smallest spatial units within the Irish Census, are the spatial unit of analysis used. The centroids of each SA are used as departure points for all trips (except for the bus analysis), a commonality in existing literature (Määttä-Juntunen et al., 2011). The network layer utilised is the national road network with speed limits manually inputted as per Road Safety Authority standards and road types (Road Safety Authority [RSA], 2021). This network is filtered to incorporate bus routes, and a new combination of footpaths, cycle lanes, and any walkable surfaces, make up the network for walkers and cyclists. The overarching scenario is that when travelling by motorised transport, people will go to their largest, nearest retail centre, but when travelling by active modes, they will go to their nearest centre, scenarios implicit in existing evidence (Song and Sohn, 2007; Wilson et al., 2013).

3.4. Model specifications

We adopt three assumptions to balance the constraints present within our datasets. Firstly, we assume that the travel mode utilised when commuting is also the mode used when shopping. This assumption stems from global mode-choice literature, which highlights substantial amounts of study populations to be unimodal in nature (Susilo et al., 2013; Ton et al., 2020). That is, people will generally exhibit habitual behaviour whereby they travel for work and leisure using the same mode, usually their commute mode (Ton et al., 2019; Jeong et al., 2022). While specific statistics on retail centre visits by mode at national level are unavailable, the National Travel Survey (Central Statistics Office [CSO], 2016) documents mode choice by broad journey purpose and by journey duration separately for unweighted samples (Central Statistics Office [CSO], 2016). Table 1 below details these statistics. Table 1 shows that across the modes investigated here, the relative share used for commuting and shopping varies by <10.1%, showing reasonable consistency and robustness in our assumptions. Secondly, we assume people's shopping trips start and end at the home, a similar approach to that of Gim (2018). Finally, we assume that any catchment pulls beyond the chosen travel threshold for any mode will have a negligible effect in attracting regular customers, something supported by existing evidence (Mohamad et al., 2015; Central Statistics Office [CSO], 2016).

This study is broken into four separate analyses examining hypothetical patterns of car use, bus use, cycling, and walking to retail centres. For motorised transport, catchment zones were capped at 60-min one-way trips. To prevent overestimating accessibility, only populations living within a 10-min walk from bus stops are used when travelling by bus (Millward et al., 2013). Similarly, the walking and cycling travel time to any existing retail centre is capped at 10-min per one-way trip, in line with active travel literature (Millward et al., 2013; Roig-Tierno et al., 2013; Spinney and Millward, 2013; Gunn et al., 2017; Ton et al., 2019). The insights provided here prove robust with travel-time changes to 15- and 20-min active travel trip lengths. The results of which are available in this manuscript's Supplementary Material.

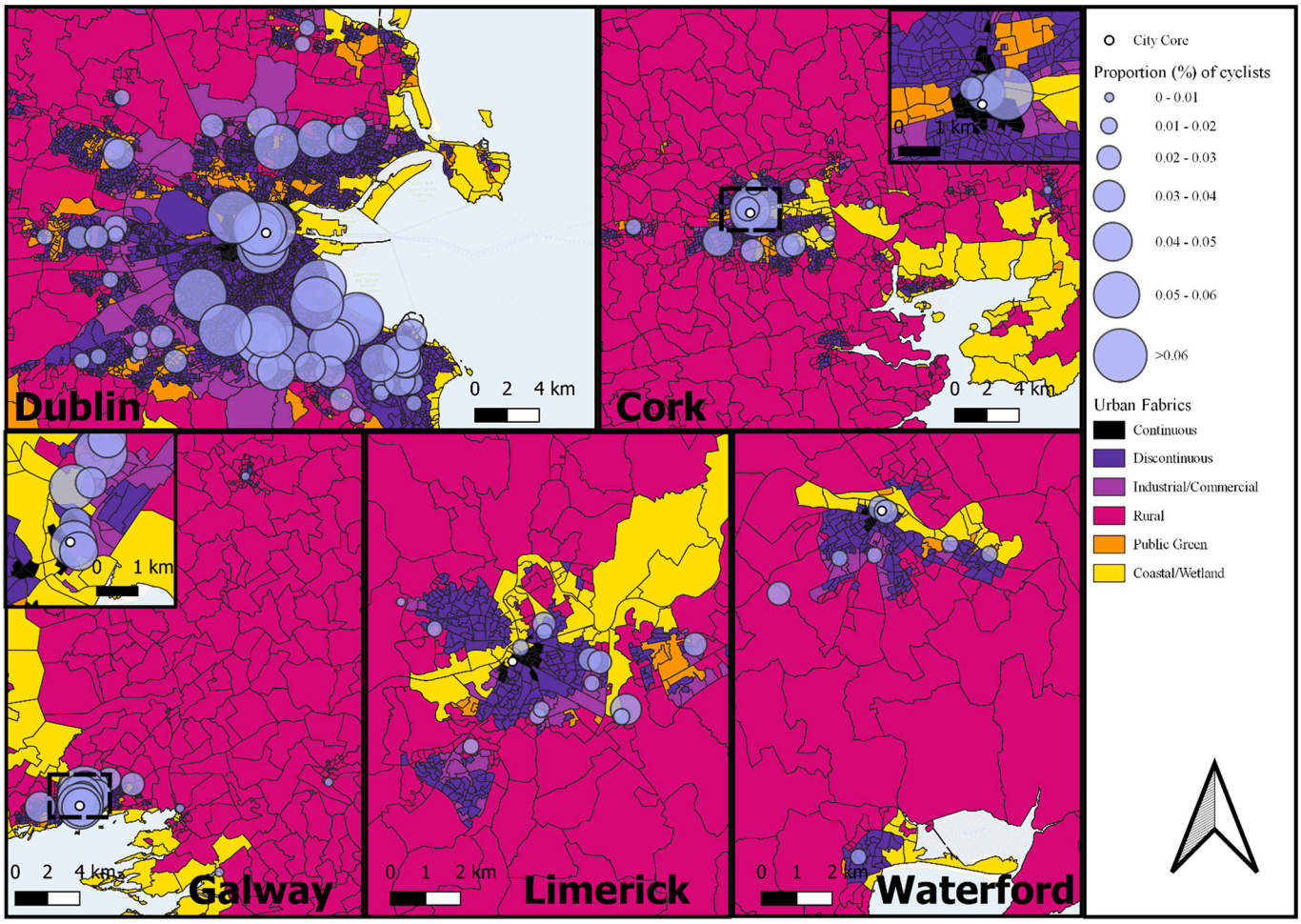


Fig. 5. The proportion of people per surrounding Small Area (i.e., within a 10-min cycle) who commute to work by cycling.

Emission figures are based on indicators produced by Walsh et al. (2008)[1] (and replicated in Crowley et al. (2021)), who calculate emission factors for multiple modes based on kilograms of CO_2 released per kilometre travelled. Emission estimates for each specific retail centre can be calculated by accumulating the number of potential trips within the OD-Matrix. This uses the proportion of the population who commute by each mode per Small Area and the travel-time necessary to get from each Small Area to their chosen retail centre. Firstly, the destination of these hypothetical trips is based on travel time alone. Thereafter, this destination is chosen by weighting retail centre size with travel time, proxying retail attractiveness. The size variable used in this analysis is collected by manually measuring the relevant building areas in Google Maps ($size_m$).

When a weight proxying attractiveness is not included, the implicit assumption is that people only consider travel time when travelling for shopping. Arguably, when $size_m$ is included, the study's theoretical underpinning is strengthened because choosing shopping destination is more nuanced than travel time alone (Öner, 2017). Retail centre attractiveness, at its foundation, tends to be a function of service diversity, site investment, and consumer perspectives, variables generally correlated with size (Mohamad et al., 2015; Öner, 2017; Kristoffersson et al., 2018), meaning in this analysis, a region's largest retail centre is usually its most attractive, subject to travel-times.

Our mode-specific emission estimates (computed in terms of kgCO2 released per minute travelled), are multiplied by the time each origin takes to reach its preferred destination. Thereafter, this value is multiplied by the proportion of people per origin (Small Area) who commute to work via each mode under study. This final value is accumulated across all Small Areas and matched to each destination, creating our hypothetical emissions estimate for each retail centre, highlighting the hypothetical travel-related emissions attributable to each retail centre as a function of the amount of eligible people (i.e., people living within the travel thresholds) who will hypothetically use these modes to travel. So, while the primary goal here is to quantify hypothetical emission outputs, we can also gauge the relative hypothetical accessibility of each retail centre for each mode, as greater emission outputs indicate greater numbers of trips.

Analysing the use of active modes (walking and cycling) when shopping focuses on incorporating active, low-carbon transport modes into a typically motorised modelling framework. Specifically, we pivot from estimating emissions to quantifying mode usage, complimenting the previous analyses by highlighting the infrastructural characteristics surrounding retail centres.[2] This analysis excluded retail centre size as a determining variable for active modes, concluding that travel time alone provided adequate estimates for the destination of active shoppers.

[1] Alternative emission variables can vary considerably. The consequence of inaccurate emissions variables in-and-of-itself is non-consequential in this analysis due to the variables only changing the absolute values of the hypothetical estimates, not their relative value.

[2] Given our focus on transport policy, we provide greater contributions by focusing on using these modes to measure travel behaviour. This is because the emissions attributable to these activities stem from metabolic activity.

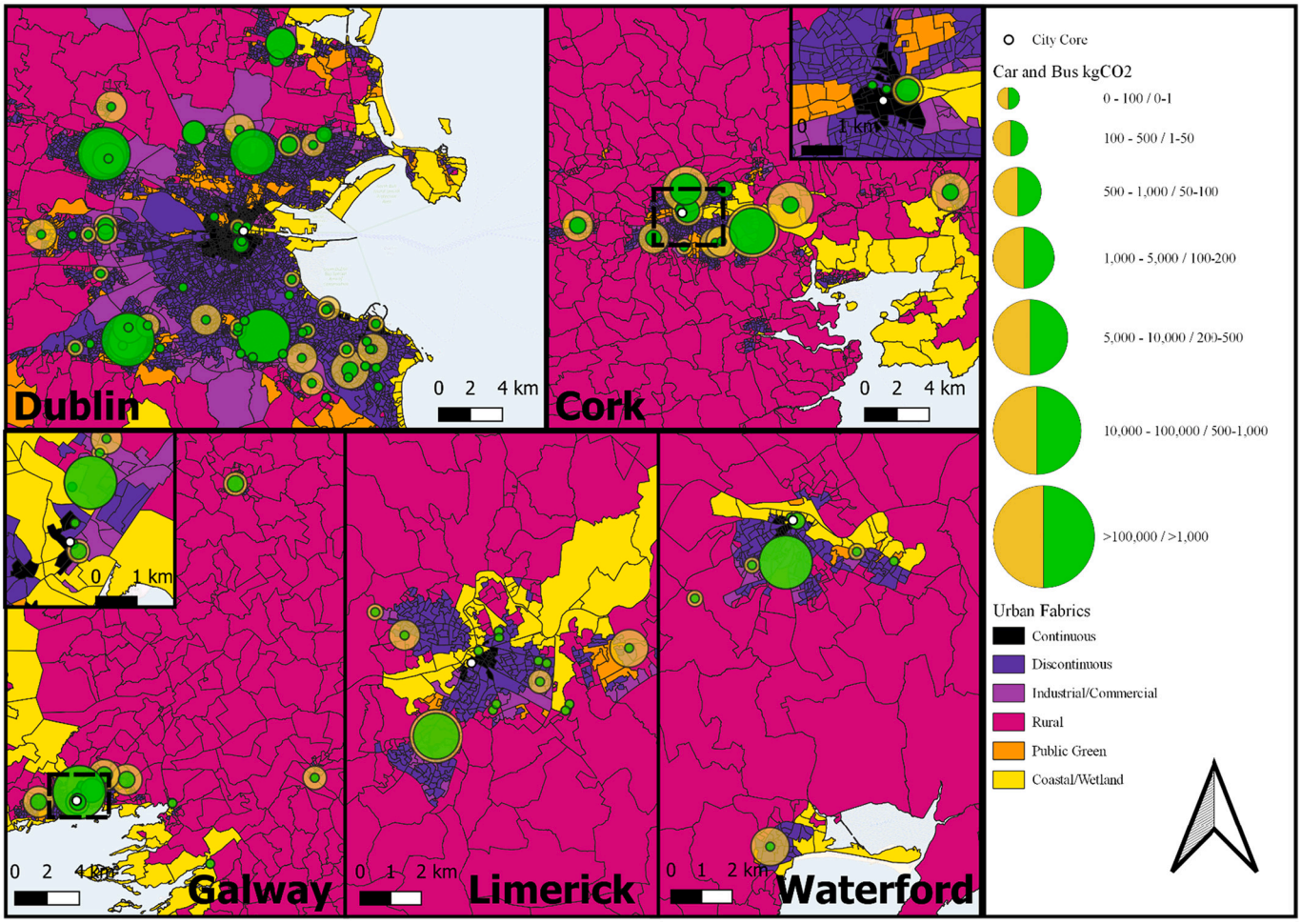


Fig. 6. The hypothetical travel-related emissions attributable to car use relative to those attributable to bus use.

Given the diminishing effect each additional minute has on the likelihood of regularly travelling actively (Gunn et al., 2017; Rao and Pafka, 2021), an effect whose strength increases once travel-times go beyond 10 and 15-min one-way thresholds (Spinney and Millward, 2013; Gunn et al., 2017), this decision is in line with existing literature.

4. Results and discussion

In the subsequent series of Figures,[3] retail centres are presented as circular points within the context of their regional urban fabric. The size of each circular point increases and decreases in size in unison with emission outputs or modal usage, as estimated by the model. This manuscript's supplementary material offers a numerical presentation of these results whereby travel-related emissions are presented relative to the distance retail centres are from their nearest city core.

4.1. Shopping by car

Initially, we assumed that people only consider travel time when shopping by car. These results generally proved inconclusive, as some regions showed peripheral retail centres to generate the most hypothetical travel-related emissions, while some showed central retail centres to generate the most hypothetical emissions, and some showed no distinguishable pattern.

Thereafter, $size_m$ was introduced. In Cork, Dublin, and Limerick, peripheral retail centres generate the most hypothetical emissions, whereas those generating the least emissions cluster in-and-around city cores,[4] supporting existing literature (Määttä-Juntunen et al., 2011; Dolega et al., 2016). Galway and Waterford offer exceptions to this, highlighting central locations as generating the most emissions. Because most of these retail centres are located in-and-around city cores to begin with, this result is unsurprising.

Nationwide, the specific retail centres generating the least and most hypothetical emissions generally change upon introducing $size_m$. Specifically, $size_m$ holds the largest, high-profile retail centres accountable for >85% of all hypothetical travel-related emissions generated by cars. These retail centres are generally found outside city cores, as existing literature predicts (Hay, 2005; Dolega et al., 2016). Because $size_m$ acts as an attractiveness weight, and because the final estimates indicate relative accessibility levels for each mode, these emissions further illustrate regional transport hierarchies by indicating the amount of people utilizing specific modes per retail centre. Fig. 2 below illustrates these

[3] Many colour schemes can be used to represent urban fabrics. These gradients could affect colour-blind readers, potentially hampering the interpretation of colour encoded information (Geissbuehler and Lasser, 2013). O'Driscoll et al. (2022), implement a pastille, magma colour hue in the Irish case to ensure maps are accessible to colour blind readers. We implement a similar colour scheme as O'Driscoll et al. (2022), in this paper.

[4] Nuances arise whereby some retail centres generating minimal emissions are in suburban areas. This appears to happen because of competition-effects whereby bigger (i.e., more attractive) retail centres are within proximity, and absorb other centres' theoretical customer bases.

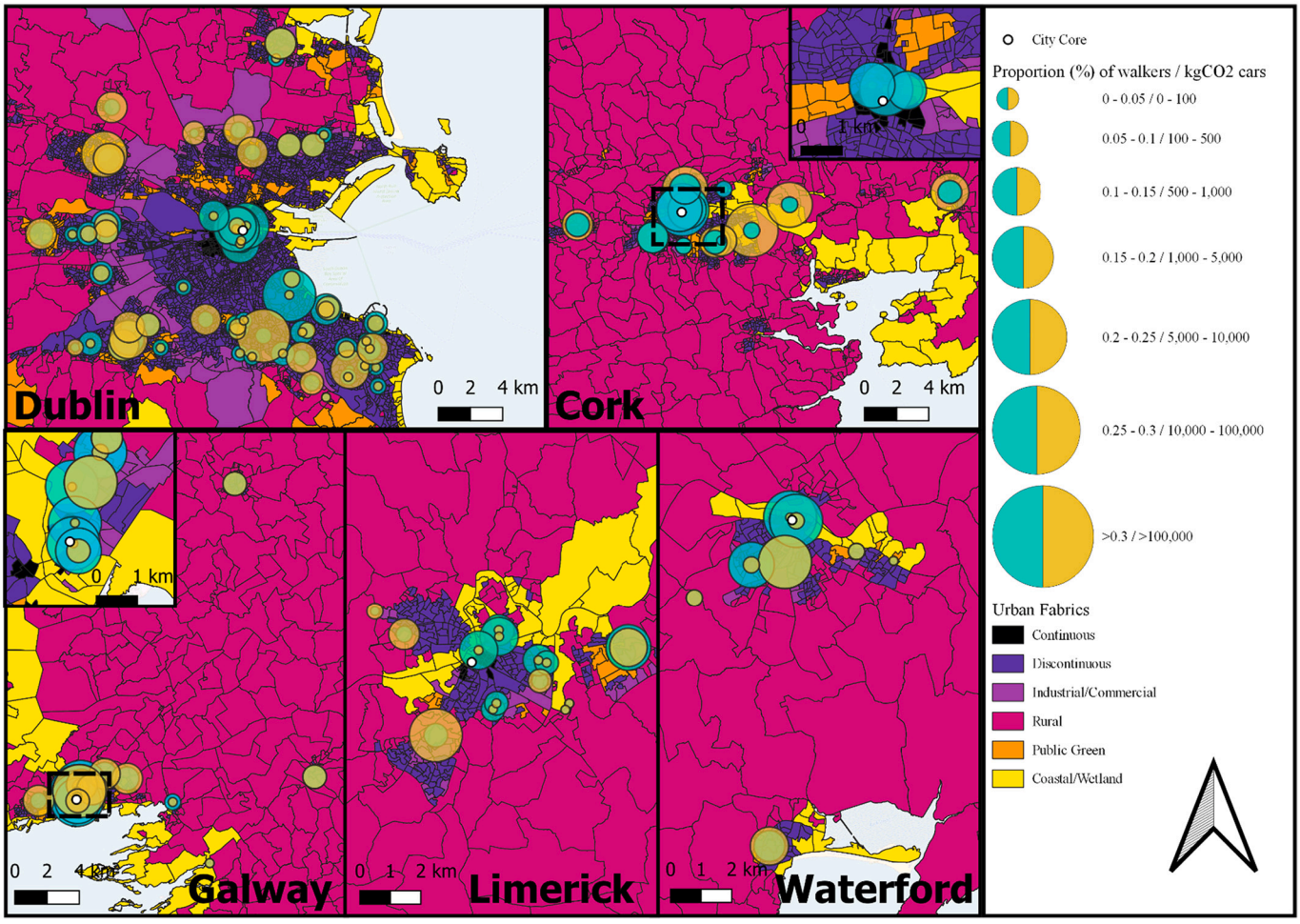


Fig. 7. The hypothetical travel-related emissions attributable to car use compared with the proportion of people per surrounding Small Area who commute to work by walking.

results by presenting every retail centre weighted by the hypothetical $kgCO_2$ output produced by cars.

4.2. Shopping by bus

Like above, we initially assume people only consider travel time when shopping by bus. Again, consistent patterns fail to emerge in these results. Some regions have random spatial distributions of travel-related emissions, while others display patterns showing these emissions are most prevalent outside city cores.

$Size_m$ provides clarity. Like before, in Cork, Dublin, and Limerick, travel-related emissions are more prevalent in fringe areas than inside city cores. Again, Galway and Waterford offer unsurprising exceptions to this because most of these retail centres are centrally located. Unlike before, the specific retail centres generating the most hypothetical emissions generally stayed the same. However, a more pronounced skewing of the results is observed, resulting in one-or-two retail centres contributing >95% of regional hypothetical travel-related emissions for buses. This illustrates discrepancies in retail attractiveness because of transport mode changes. Most of these discrepancies occur outside city cores, exposing how fringe retail centres tend to offer poor public transport links and subsequently experience relatively low visits from bus users, as gauged by minimal hypothetical emissions (Wilson et al., 2013; Cats and Birch, 2021). Fig. 3 below illustrates these results by presenting every retail centre according to the hypothetical $kgCO_2$ output produced by buses.

4.3. Shopping actively

As noted in *3.4*, $size_m$ was excluded when analysing active travel, meaning people only consider travel time when visiting retail centres using these modes. These analyses investigate the car dependency implied in Fig. 2, while also gauging which retail centres have infrastructural capabilities to reduce travel-related emissions by accommodating active modes.

When analysing walking to these retail centres, a nationwide pattern emerges whereby centrally located retail environments generally facilitate active modes more frequently than peripheral environments, showing central locations to offer better sustainable transport infrastructure than their suburban counterparts, something gauged by higher amounts of walking commuters in the vicinity. Fig. 4 below illustrates these results by presenting every retail centre according to the proportion of its surrounding population that commute by walking.

Cycling behaviour is more nuanced. In Galway, our results imply that centrally located retail centres are not utilised by cyclists, but heavily utilised by walkers. In Limerick, there is no discernible pattern with cyclists, but central locations are relatively more accommodating to walkers than peripheral locations. In Dublin, there is a clear North-South divide in cycling uptake, potentially highlighting investment inequalities. In Waterford and Cork however, walking and cycling illustrate that city cores are active mode friendly, and fringe locations are not.

Where patterns do emerge, we see that locations typically characterised by multi-modal transport, experience more sustainable transport

usage (Wilson et al., 2013; Gunn et al., 2017; Eldeeb et al., 2021). Fig. 5 below illustrates these results by presenting every retail centre according to the proportion of the surrounding population who commute by bike.

4.4. Cross-modal comparisons

When comparing motorised modes, there are clear spatial disparities in their usage. Specifically, retail centres moderately accessible to car users, become inaccessible to bus users. Because this analysis holds everything constant, except the mode used, these discrepancies are unjustified at their scale, assuming a truly multi-modal transport network. This observation is supported given the tendency of these disparities to be greatest in areas typically served sub-optimally by transit – peripheral areas (Wilson et al., 2013; Mohamad et al., 2015; Cats and Birch, 2021), exposing a unimodal nature to Ireland's transport infrastructure.

Additionally, these results imply that for car users, the most attractive retail centres are in fringe areas, *potentially* pulling people out of cities to avail of larger suburban retail environments, or *potentially* disincentivizing people from shopping in cities when travelling by car, a finding implicit in Mohamad et al. (2015). Fig. 6 below illustrates these results by presenting every retail centre according to the hypothetical $kgCO_2$ output produced by buses and cars.

When comparing active modes, shopping destination discrepancies are noticeably not as drastic between modal changes, something attributable to the fact leisure cyclists and walkers often share the same infrastructure and have similar accessibility requirements (Gan et al., 2021), hence we imply the accounts of walkers and cyclists are generally the same.

We see car dependency increase with distances from city cores, as the retail centres generating the most travel-related emissions by car, tend to exhibit the least active mode usage, meaning car use tends to dominate, inflating emissions. This highlights how peripheral retail centres generally offer inadequate infrastructure to facilitate shifts from excessive car usage, underlining car dependency as contributing to excessive travel-related emissions. Fig. 7 below illustrates these results by presenting every retail centre according to the proportion of the surrounding population who commute by walking and according to the hypothetical $kgCO_2$ output produced by car.

These results generally provide evidence on environmentally optimal retail locations by showing how compact, multimodal centred development can minimise shopping related emissions by attracting more sustainable transport users (Määttä-Juntunen et al., 2011; Wilson et al., 2013). However, the accessibility of specific retail centres to different transport modes is shown to alter trip distributions and hypothetical emission estimates considerably. Specifically, the gravity theories employed here show that retail location *alone* will not determine shopping-related travel emissions and the modes people may use to get to these centres but can provide general indications.

While in principle, travel-related emissions can be expected to increase as distances from city cores increase, in practice, we find that a retail centre's design plays an important role in determining emission levels once retail centres leave central areas. Figs. 2-7 indicate that retail centres situated outside city cores which are designed for cars will attract cars, inflating travel-related emissions, while those designed for sustainable transport will generally attract sustainable transport users, reducing emissions, no matter their relative peripherality.

5. Conclusion

Here, we highlight the environmental issues associated with peripheral retail developments, an issue typically under addressed by policymakers, often treated as an afterthought to wider sprawl problems (European Environmental Agency (EEA), 2006; Department of Housing Planning Community and Local Government, 2012; OECD, 2018). Our objectives revolve around modelling retail development in terms of emission outputs by investigating which retail centre locations tend to produce the most hypothetical travel-related emissions. Thereafter, specific comparison between central and peripheral locations is made, testing the environmental merits of central place and gravity theories. Finally, we investigate the relationship between hypothetical travel-emissions, retail locations, and transport mode.

Our principal finding is that travel-related emission problems occur when retail centres are in fringe areas. These retail environments generally witness diminishing numbers of sustainable transport users as distances from city cores increase, a problem attributed to car dependency and inadequate infrastructure, as proxied by current commuting behaviour. Furthermore, these results suggest retail centres that are most accessible by car, tend to become inaccessible when using sustainable transport modes, exposing a transport hierarchy in these fringe areas dominated by cars, reinforcing this dependency. In city cores, we find that emission problems are not as prevalent, because the proportion of trips is shared more evenly across alternative transport modes.

Considering this problem, making these retail centres less car dependent could be a first step in alleviating the troublesome emission figures produced by global transport sectors. Taking Ireland as an example, the combined (monthly) hypothetical emissions generated by cars in this analysis accounts for ~9% of the 2016, 2019, and projected 2020 monthly CO_2 output of the transport sector, whereas the same figure for buses accounts for ~0.008%, underlining the scale of these potential savings (Environmental Protection Agency [EPA], 2021, p. 6). Our results highlight the unsustainable character of retail developments in areas characterised by car dependency, corroborating the environmental merits of central place theories by arguing centrally located retail centres offer optimal conditions to minimise carbon impacts because of their infrastructural tendency to incentivise sustainable transport usage.

This evidence supports current trajectories of global policymaking which advocate for the implementation of mixed use, accessibility-driven developments to alleviate car dependency and uncoordinated sprawl, adding an otherwise absent clarity to the role retail sprawl plays in exacerbating car dependency and sprawl-induced emission outputs. Subsequently, we support calls advocating for developments which accommodate multimodal travel as the best way to pursue long-term emission reductions by incentivizing sustainable transport usage, increasing land-use efficiency, and reducing car dependency. International evidence already demonstrates a propensity for people to utilise sustainable transport if given the opportunity (Millward et al., 2013; Eldeeb et al., 2021), meaning governments should aim to optimize current infrastructure by developing compactly and efficiently before expanding peripheral boundaries, which encourages sustainable travel. Complimenting this, policymakers should aspire to make future suburban retail environments less attractive than central locations to car users. This could be done by restricting parking supply or restricting development possibilities (Feitelson and Rotem, 2004), disincentivizing locating far from urban cores and encouraging developments around multimodal transport infrastructure.

Strengthening this account are robustness tests, which adjusted network speeds, retail centre sizes, and travel times. While generally, these changes saw minor shuffling amongst the results, the overarching narrative generally remained unchanged across modes and regions.

This study is not without limitations. Principally, this analysis did not contain real shopping trip data, meaning our results rely on the assumptions presented in *3.4* holding. However, future research could incorporate congestion effects into this methodology. Additionally, one could use principal-agent based modelling and microsimulation to generate select shopping trip data. Finally, researchers should adapt this methodology when analysing commuting patterns, or when focusing on the relationship between residential locations and other places of interest.

CRediT authorship contribution statement

Conor O'Driscoll: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Resources, Validation, Visualization. **Frank Crowley:** Conceptualization, Methodology, Project administration, Supervision, Writing – review & editing. **Justin Doran:** Conceptualization, Methodology, Project administration, Supervision, Writing – review & editing. **Nóirín McCarthy:** Conceptualization, Methodology, Project administration, Supervision, Writing – review & editing.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jtrangeo.2022.103376.

References

Ahmad, A.A.E., Hiyasat, R.I., 2017. Beyond the random location of shopping malls: a GIS perspective in Amman, Jordan. J. Retail. Consum. Serv. 34, 30–37. https://doi.org/10.1016/j.jretconser.2016.09.006.

Carruthers, J.I., Úlfarsson, G.F., 2008. Does "smart growth" matter to public finance? Urban Stud. 45 (9), 1791–1823. https://doi.org/10.1177/0042098008093379.

Cats, O., Birch, N., 2021. Multi-modal network evolution in polycentric regions. J. Transp. Geogr. 96, 1–10. https://doi.org/10.1016/j.jtrangeo.2021.103159.

Central Statistics Office [CSO], 2016. National Travel Survey, 2016. Available at: https://www.cso.ie/en/releasesandpublications/ep/p-nts/nts2016/keyf/ (Accessed: 17 September 2021).

Cheng, E.W.L., Li, H., Yu, L., 2007. A GIS approach to shopping mall location selection. Build. Environ. 42 (2), 884–892. https://doi.org/10.1016/j.buildenv.2005.10.010.

Clarkson, R., Clarke-Hill, C., Robinson, T., 1996. UK supermarket location assessment. Int. J. Retail Distrib. Manag. 24 (6), 22–33.

Copernicus Land Monitoring Service, 2021. Urban Atlas 2018'.

Crowley, F., et al., 2021. The impact of labour market disruptions and transport choice on the environment during COVID-19. Transp. Policy 106, 185–195.

Dennis, C., Marsland, D., Cockett, T., 2002. Central place practice: shopping Centre attractiveness measures, hinterland boundaries and the UK retail hierarchy. J. Retail. Consum. Serv. 9, 185–199. https://doi.org/10.1016/S0969-6989(01)00021-2.

Department of Housing Planning Community and Local Government, 2012. Guidelines for Planning Authorities - Retail Planning.

Dolega, L., Pavlis, M., Singleton, A., 2016. Estimating attractiveness, hierarchy and catchment area extents for a national set of retail Centre agglomerations. J. Retail. Consum. Serv. 28, 78–90. https://doi.org/10.1016/j.jretconser.2015.08.013.

Dolega, L., et al., 2021. Beyond retail: new ways of classifying UK shopping and consumption spaces. Environ. Plan. B: Urban Anal. City Sci. 48 (1), 132–150. https://doi.org/10.1177/2399808319840666.

Eldeeb, G., Mohamed, M., Páez, A., 2021. Built for active travel? Investigating the contextual effects of the built environment on transportation mode choice. J. Transp. Geogr. 96, 1–14. https://doi.org/10.1016/j.jtrangeo.2021.103158.

Environmental Protection Agency [EPA], 2021. The Impact on 2020 Greenhouse Gas Emissions of COVID-19 Restrictions.

Erdin, C., Akbas, H.E., 2019. A comparative analysis of fuzzy TOPSIS and geographic information systems (GIS) for the location selection of shopping malls: a case study from Turkey. Sustainability 11 (3837), 1–22. https://doi.org/10.3390/su11143837.

European Environmental Agency (EEA), 2006. Urban Sprawl in Europe: The Ignored Challenge.

Evans, A.W., 1983. The determination of the Price of land. Urban Stud. 20 (2), 119–129. https://doi.org/10.1080/00420988320080271.

Ewing, R., 1997. Is Los Angeles-style sprawl desirable? J. Am. Plan. Assoc. 63 (1), 107–126.

Feitelson, E., Rotem, O., 2004. The case for taxing surface parking. Transp. Res. Part D: Transp. Environ. 9 (4), 319–333. https://doi.org/10.1016/j.trd.2004.04.002.

Focas, C., 2016. Travel behaviour and CO2 emissions in urban and exurban London and New York. Transp. Policy 46, 82–91. https://doi.org/10.1016/j.tranpol.2015.11.003.

Frenkel, A., Ashkenazi, M., 2008. Measuring urban sprawl: how can we deal with it? Environ. Plan. B: Plan.Design 35 (1), 56–79. https://doi.org/10.1068/b32155.

Gan, Z., et al., 2021. Associations between built environment, perceived walkability/bikeability and metro transfer patterns. Transp. Res. A Policy Pract. 153, 171–187. https://doi.org/10.1016/J.TRA.2021.09.007.

Geissbuehler, M., Lasser, T., 2013. How to display data by color schemes compatible with red-green color perception deficiencies. Opt. Express 21 (8), 1–13. https://doi.org/10.1364/oe.21.009862.

Gim, T.H.T., 2018. Land use, travel utility and travel behaviour: an analysis from the perspective of the positive utility of travel. Pap. Reg. Sci. 97, 169–192. https://doi.org/10.1111/pirs.12239.

Giorgi, G., et al., 2017. Active commuting: workplace health promotion for improved employee well-being and organizational behavior. Front. Psychol. 1, 1–12. https://doi.org/10.3389/fpsyg.2016.01994.

Glaeser, E.L., Kahn, M., Chu, C., 2001. Job Sprawl: Employment Location in U.S. Metropolitan Areas. Washington DC.

Gunn, L.D., et al., 2017. Identifying destination distances that support walking trips in local neighborhoods. J. Transp. Health 5, 133–141. https://doi.org/10.1016/j.jth.2016.08.009.

Hay, A., 2005. The transport implications of planning policy guidance on the location of superstores in England and Wales: simulations and case study. J. Transp. Geogr. 13, 13–22. https://doi.org/10.1016/j.jtrangeo.2004.07.001.

Holz-Rau, C., Scheiner, J., 2019. Land-use and transport planning – a field of complex cause-impact relationships. Thoughts on transport growth, greenhouse gas emissions and the built environment. Transp. Policy 74, 127–137. https://doi.org/10.1016/j.tranpol.2018.12.004.

Jeong, J., Lee, J., Gim, T.T., 2022. Travel mode choice as a representation of travel utility: A multilevel approach reflecting the hierarchical structure of trip, individual, and neighborhood characteristics. Pap. Reg. Sci. 1–21. https://doi.org/10.1111/pirs.12665.

Knowles, R.D., Ferbrache, F., Nikitas, A., 2020. Transport's historical, contemporary and future role in shaping urban development: re-evaluating transit oriented development. Cities 99. https://doi.org/10.1016/j.cities.2020.102607.

Kono, T., et al., 2012. Optimal regulation on building size and city boundary: an effective second-best remedy for traffic congestion externality. Reg. Sci. Urban Econ. 42, 619–630. https://doi.org/10.1016/j.regsciurbeco.2012.02.004.

Kristoffersson, I., Daly, A., Algers, S., 2018. Modelling the attraction of travel to shopping destinations in large-scale modelling. Transp. Policy 68, 52–62. https://doi.org/10.1016/j.tranpol.2018.04.013.

Lee, C., 2020. Metropolitan sprawl measurement and its impacts on commuting trips and road emissions. Transp. Res. Part D: Transp. Environ. 82, 102329 https://doi.org/10.1016/j.trd.2020.102329.

Luo, W., Wang, F., 2003. Measures of spatial accessibility to health care in a GIS environment: synthesis and a case study in the Chicago region. Environ. Plan. B: Plan.Design 30 (6), 865–884. https://doi.org/10.1068/b29120.

Määttä-Juntunen, H., et al., 2011. Using GIS tools to estimate CO2 emissions related to the accessibility of large retail stores in the Oulu region, Finland. J. Transp. Geogr. 19 (2), 346–354. https://doi.org/10.1016/j.jtrangeo.2010.03.001.

Millward, H., Spinney, J., Scott, D., 2013. Active-transport walking behavior: destinations, durations, distances. J. Transp. Geogr. 28, 101–110. https://doi.org/10.1016/j.jtrangeo.2012.11.012.

Mohamad, M.Y., Al Katheeri, F., Salam, A., 2015. A GIS application for location selection and customers' preferences for shopping malls in Al Ain City; UAE. Am. J. Geograph. Inform. Syst. 4 (2), 76–86. https://doi.org/10.5923/j.ajgis.20150402.03.

National Transport Authority, [NTA], 2014. Dublin City Centre Shopper Survey Report.

Nechyba, T.J., Walsh, R.P., 2004. Urban sprawl. J. Econ. Perspect. 18 (4), 177–200. https://doi.org/10.1257/0895330042632681.

O'Driscoll, J., et al., 2022. The spatiotemporal dimension of population change in Ireland: visualisation of growth and shrinkage in Irish electoral divisions (1986–2016). J. Maps 1–7. https://doi.org/10.1080/17445647.2022.2052766.

OECD, 2018. Rethinking Urban Sprawl, Rethinking Urban Sprawl: Moving Towards Sustainable Cities (Policy Highlights). https://doi.org/10.1787/9789264189881-en.

Öner, Ö., 2017. Retail city: the relationship between place attractiveness and accessibility to shops. Spat. Econ. Anal. 12 (1), 72–91. https://doi.org/10.1080/17421772.2017.1265663.

Oueslati, W., Alvanides, S., Garrod, G., 2015. Determinants of urban sprawl in European cities. Urban Stud. 52 (9), 1594–1614. https://doi.org/10.1177/0042098015577773.

Paterson, M., 2000. Car culture and global environmental politics. Rev. Int. Stud. 26 (2), 253–270. https://doi.org/10.1017/S0260210500002539.

Pendall, R., 1999. Do land-use controls cause sprawl? Environ. Plan. B: Plan.Design 26 (4), 555–571. https://doi.org/10.1068/b260555.

Pitt, M., Musa, Z.N., 2009. Towards defining shopping centres and their management systems. J. Retail. Leis. Prop. 8, 39–55. https://doi.org/10.1057/rlp.2008.25.

Pooley, C.G., Turnbull, J., 2005. Coping with congestion: responses to urban traffic problems in British cities c.1920–1960. J. Hist. Geogr. 31 (1), 78–93. https://doi.org/10.1016/j.jhg.2003.08.019.

Rao, F., Pafka, E., 2021. Shopping morphologies of urban transit station areas: a comparative study of central city station catchments in Toronto, San Francisco, and Melbourne. J. Transp. Geogr. 96, 1–11. https://doi.org/10.1016/j.jtrangeo.2021.103156.

Rasouli, S., Timmermans, H., 2013. Assessment of model uncertainty in destinations and travel forecasts of models of complex spatial shopping behaviour. J. Retail. Consum. Serv. 20 (2), 139–146. https://doi.org/10.1016/j.jretconser.2012.05.001.

Razin, E., 1998. Policies to control urban sprawl: planning regulations or changes in the "rules of the game"? Urban Stud. 35 (2), 321–340. https://doi.org/10.1080/0042098985005.

Road Safety Authority [RSA], 2021. Driving In Ireland, RSA.ie: Driving In Ireland. Available at: https://www.rsa.ie/en/RSA/Licensed-Drivers/Driving-in-Ireland/ (Accessed: 12 July 2021).

Roig-Tierno, N., et al., 2013. The retail site location decision process using GIS and the analytical hierarchy process. Appl. Geogr. 40, 191–198. https://doi.org/10.1016/j.apgeog.2013.03.005.

Schläpfer, M., et al., 2021. The universal visitation law of human mobility. Nature 593. https://doi.org/10.1038/s41586-021-03480-9.

Scott, D.M., He, S.Y., 2012. Modeling constrained destination choice for shopping: a GIS-based, time-geographic approach. J. Transp. Geogr. 23, 60–71. https://doi.org/10.1016/j.jtrangeo.2012.03.021.

Song, Y., Sohn, J., 2007. Valuing spatial accessibility to retailing: a case study of the single family housing market in Hillsboro, Oregon. J. Retail. Consum. Serv. 14, 279–288. https://doi.org/10.1016/j.jretconser.2006.07.002.

Spinney, J.E.L., Millward, H., 2013. Investigating travel thresholds for sports and recreation activities. Environ. Plan. B: Plan.Design 40, 474–488. https://doi.org/10.1068/b37161.

Suarez, A., et al., 2004. Accounting for heterogeneity in shopping Centre choice models. J. Retail. Consum. Serv. 11, 119–129. https://doi.org/10.1016/S0969-6989(03)00011-0.

Suárez-Vega, R., Santos-Peñate, D.R., Dorta-González, P., 2012. Location models and GIS tools for retail site location. Appl. Geogr. 35, 12–22. https://doi.org/10.1016/j.apgeog.2012.04.009.

Sultana, S., Weber, J., 2014. The nature of urban growth and the commuting transition: endless sprawl or a growth wave? Urban Stud. 51 (3), 544–576. https://doi.org/10.1177/0042098013498284.

Susilo, Y.O., Hanks, N., Ullah, M., 2013. An exploration of shoppers travel mode choice in visiting convenience stores in the UK. Transp. Plan. Technol. 36 (8), 669–684. https://doi.org/10.1080/03081060.2013.851505.

Ton, D., et al., 2019. Cycling or walking? Determinants of mode choice in the Netherlands. Transp. Res. A Policy Pract. 123, 7–23. https://doi.org/10.1016/J.TRA.2018.08.023.

Ton, D., et al., 2020. The experienced mode choice set and its determinants: commuting trips in the Netherlands. Transp. Res. A Policy Pract. 132, 744–758. https://doi.org/10.1016/j.tra.2019.12.027.

Vandenbulcke, G., Steenberghen, T., Thomas, I., 2009. Mapping accessibility in Belgium: a tool for land-use and transport planning? J. Transp. Geogr. 17, 39–53. https://doi.org/10.1016/j.jtrangeo.2008.04.008.

Walsh, C., et al., 2008. A comparison of carbon dioxide emissions associated with motorised transport modes and cycling in Ireland. Transp. Res. Part D: Transp. Environ. 13 (6), 392–399. https://doi.org/10.1016/j.trd.2008.07.002.

Wassmer, R.W., 2002. Fiscalisation of land use, urban growth boundaries and non-central retail sprawl in the western United States. Urban Stud. 39 (8), 1307–1327. https://doi.org/10.1080/00420980220142655.

Wilson, J., et al., 2013. Blame the exurbs, not the suburbs: exploring the distribution of greenhouse gas emissions within a city region. Energy Policy 62, 1329–1335. https://doi.org/10.1016/j.enpol.2013.07.012.

Yang, L., et al., 2020. Accessibility to transit, by transit, and property prices: spatially varying relationships. Transp. Res. Part D: Transp. Environ. 85, 102387 https://doi.org/10.1016/j.trd.2020.102387.

Zhang, S., van Duijn, M., van der Vlist, A.J., 2020. The external effects of inner-city shopping centers: evidence from the Netherlands. J. Reg. Sci. 60 (4), 583–611. https://doi.org/10.1111/jors.12473.