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Developing two-dimensional indicators of transport demand and supply to promote sustainable transportation equity

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ABSTRACT

Inadequate supply of transport infrastructure is often seen as a barrier to a sustainable future for cities globally. Such barriers often perpetuate significant inequalities in who can and who cannot benefit from sustainable transport opportunities, and as a result there is momentum for transformative urban planning to promote sustainable transportation equity. This study introduces a new set of two-dimensional indicators, merging elements of supply and demand, to identify barriers and imbalances in sustainable transport equity. The accessibility indicators, which are generated for bus, rail, and cycle infrastructure, consider the proximity of administrative areas to good quality transport infrastructure, as well as mode-specific demand, to clearly identify areas where the supply of infrastructure is inadequate to support local populations. We present a policy case study for Liverpool City Region, which demonstrates how these indicators can be used in an analytical framework to support transformative urban planning in long-term. In particular, the indicators reveal policy priority areas where demand for sustainable transport is greater than supply, as well as neighbourhoods where multiple transport inequalities are intersecting spatially, highlighting the need for specific types of infrastructure investment to promote sustainable transport equity (e.g. more frequent services, additional cycle paths). Our framework lays the foundations for improved decision-making in urban systems, through development of mode-specific sustainable transport indicators at small area levels, which harmonise elements of supply and demand for the first time.

1. Introduction

Fostering a more equitable and sustainable society remains a significant challenge for urban systems. Goals 10 - reduced inequalities - and 11 - sustainable cities and communities - of the Sustainable Development Goals put into perspective how important these issues are, and highlight the magnitude of social, environmental, and health-related challenges being confronted by places globally (Lowe et al., 2022). Whilst it is vital to consider how all aspects of society can become more sustainable and equitable, these considerations are particularly relevant in the transportation realm (Bills & Walker, 2017). From a sustainability perspective, the transport sector contributes a significant proportion of total UK CO2 emissions (26%), especially when examining differences between private motorised vehicles and public transportation options (Department for Transport, 2023). From an equity perspective, the sector also represents an area of significant inequality, with transport accessibility, equity and justice research highlighting significant differences in who can and cannot benefit from sustainable transport opportunities (Calafiore et al., 2022; Graells-Garrido et al., 2021; Southern, 2023), and the benefits of improved access for positive social and economic outcomes (Frank et al., 2021; Lendel et al., 2020). Therefore, making improvements to the transportation sector can actively support net zero carbon goals, through encouraging use of more sustainable transport options, and practising urban social sustainability (Capasso Da Silva et al., 2019).

In seeking to improve uptake of sustainable transportation opportunities, a popular approach has been to quantify the accessibility of residents to good quality and sustainable transport infrastructure (e.g., bus stops), and identify inequalities in who can and cannot benefit from these. For example, many studies have calculated the shortest possible walking distances and durations to the nearest transport infrastructure (e.g. Frank et al., 2021; Mulley et al., 2018), whilst also recognising the importance of infrastructure quality (Ballantyne & Singleton, 2024; Calafiore et al., 2022), or in a more general sense, the '*supply*' of sustainable transport opportunities. However, limited efforts have been made to directly account for the actual use of different transport options

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(Graells-Garrido et al., 2021), linking to the idea that increased accessibility may not necessarily translate into the usage of local infrastructure. Additionally, engagement or willingness of local populations with sustainable transport is often linked to different levels of population density (Saghapour et al., 2016), or assumed to be the same across population subgroups (Peungnumsai et al., 2020), with limited efforts to instead link this to observed travel behaviours.

As such, there is a research gap in simultaneously accounting for both the transport *supply* (i.e. accessibility and infrastructure) and *demand* (population usage) components, and hence suitable composite indicators that integrate these elements. This paper aims to devise a novel two-dimensional representation of transport accessibility that harmonises *supply* and *demand,* evaluating the accessibility of residents in urban and metropolitan regions to sustainable transport opportunities. We extend previous research by building a two-dimensional (*supply* and *demand*) indicator at a small-area level that accounts for a) the quality and proximity of sustainable transport infrastructure and b) the engagement of local population. We argue that our indicator provides a more realistic representation of transport accessibility and, in turn, identifies the populations and places who would benefit most from network improvements.

A specific policy case is advanced for Liverpool City Region (LCR). In 2021, Liverpool City Region Combined Authority (LCRCA) secured £710 m from the City Region Sustainable Transport Settlements (Department for Transport, 2022), to improve journey times, enable decarbonisation and provide equitable access to the transport network (Liverpool City Region Combined Authority, 2022). As a result, there is a need for evidence which can identify where changes to existing transport infrastructure could support these transitions. Recent research by Ballantyne & Singleton (2024) provides an empirical evidence base of multiple inequality for Liverpool City Region. Whilst this evidence base highlighted places across Liverpool City Region where proximity to bus stops, railway stations and cycle infrastructure was low, it failed to account for the quality of infrastructure and the characteristics of populations (i.e., *demand*) in its conceptualisation and measurement of (transport) inequality. To this end, the paper seeks to answer the following research questions:

a) How can we capture differences in sustainable transport supply at a small area level, accounting for proximity of populations and quality of infrastructure?
b) To what extent can we integrate information about the engagement of local populations into accessibility metrics (i.e., demand)?
c) How can we use a two-dimensional sustainable transport accessibility indicator to alleviate transport inequalities in Liverpool City Region?

The remainder of the paper is structured as follows: Section 2 outlines the importance of conceptualising and measuring (transport) accessibility as a two-dimensional phenomenon. Section 3 presents the conceptual framework of this work, grounded in concepts of *supply* and *demand,* before describing the methods and data used to assemble the two-dimensional indicators. Section 4 presents the final two-dimensional indicator, highlighting how it can be used to uncover transport inequalities, and target interventions to alleviate them. Finally, Section 5 discusses our key contributions and limitations, positing how the indicators can be used to support a more equitable and sustainable future for cities globally.

2. Background

2.1. Conceptualising and measuring transport accessibility

Accessibility, broadly defined as the ease with which persons can reach places and opportunities from a given location (Pereira et al., 2017), has become an increasingly important concept in urban mobility and transport research and policy (Ryan & Pereira, 2021). Whilst definitions vary, the concept of accessibility incorporates three key features as outlined by Ryan and Pereira (2021), the *potential, ease* and *extent* to which opportunities can be reached, and helps to highlight places where there are imbalances between the supply and demand of different services (Saxon et al., 2022). In a transport realm, these ideas can help to situate and define the extent to which citizens are proximal to sustainable transport options, and the extent to which urbanities represent equitable transport systems, based on different levels of spatial access. Whilst transportation 'cost' is often a key component of many measures of accessibility, in this study we are concerned with accessibility to transport-specific services or 'opportunities'.

A large body of research has contributed innovative conceptual frameworks and methodologies to measure the proximity of populations to transportation opportunities, as a metric of accessibility. Traditional approaches involve constructing isochrones around transport nodes (or residential locations) and identifying 'patches' of accessibility and inaccessibility (e.g., Southern, 2023). Whilst this method provides a powerful way to visualise patterns of accessibility, it categorises places into accessible or not accessible, when in reality accessibility is less discrete. Other studies have considered proximity to sustainable transport options as 'exposure' to different types of infrastructure. For example, Frank et al. (2021), split the population into control and treatment groups, and although this study identified interesting differences in the uptake of cycling infrastructure based on proximity, it was limited in its scalability to multiple sustainable transport options (e.g., rail, bus). The family of floating catchment area (FCA) methodologies offer a useful way to consider how proximity (i.e., *supply*) relates to *demand* for the services, but rely on specification of an arbitrary catchment (e.g., 30-min) before the accessibility measures can be calculated between locations (Saxon et al., 2022).

When building accessibility metrics, calculating routed walk/drive times between residential locations and destinations (e.g., transport nodes) are more typical. Traditional GIS-based approaches for such measurements have often suffered from long computation times when trying to generate routes between large pairs of origins and destinations (Pönkänen, 2022). However, owing to advancements in computational methodologies and open-source routing software, such tasks have become more feasible (Pereira, Saraiva, Herszenhut, Braga, & Conway, 2021), and as a result the literature demonstrating these computational methodologies has matured. For example, in Capasso Da Silva et al. (2019), the authors computed network distances between different transport nodes in Tempe to examine how well the 20-min city concept maps onto the reality of transportation and urban mobility in the city.

2.2. Inequality and (transport) accessibility

A typical component of accessibility research involves the use of accessibility metrics to capture spatial inequalities across urban systems, notably the impact of differential transport access on important societal assets. The literature documenting these effects is rich and well developed, spanning multiple domains such as food (Farber et al., 2014), healthcare (Green et al., 2018), mobility (Graells-Garrido et al., 2021) and social interaction (Jamme, 2024). Furthermore, much of this literature has highlighted specific groups of people who are negatively impacted by differential access. For example, Southern (2023) identified strong associations between railway station accessibility, unemployment and welfare claimants, and Calafiore et al. (2022) showed evidence of low accessibility in some of the most deprived areas of Liverpool, promoting 'forced car ownership' and resulting in higher transport costs.

These examples highlight the importance of the local context and characteristics of the population when examining social and spatial inequalities in transport accessibility, and the importance of measuring transport accessibility given its role in determining access to other important societal assets. However, whilst context and observed transport behaviours are intrinsically linked to transport accessibility (e.g., Saghapour et al., 2016), they are often not accounted for when building measures of accessibility. This links to the idea that *place-based* accessibility research typically overlooks the relationship between a person's characteristics, and their ability to engage with different types of transport (Geurs & Östh, 2016). Arguably, by under-representing the people and places who would benefit most from this, and treating all local contexts as having equal transport engagement, researchers may suppress the effectiveness of strategies that seek to reduce these inequalities. However, there is significant analytical scope and need to incorporate measures which balance proximity and the quality of infrastructure (i.e., *supply*) with the overall engagement or use of different transport modes by different population subgroups - i.e. *demand* (Higgs et al., 2019; Tanguay et al., 2010), based on observed travel behaviours.

2.3. The policy case study - Liverpool City region

The Metropolitan Mayor of Liverpool City Region, Steve Rotheram, has set out priority for a 'fairer, stronger, cleaner, connected and vibrant city region' (Liverpool City Region Combined Authority, 2021). In April 2022, LCRCA secured £710 m as part of the City Region Sustainable Transport Settlements (CRSTS hereafter), to focus on enhancing the transport network, through improvements to journey times, enabling decarbonisation and providing equitable access for all (Liverpool City Region Combined Authority, 2022). At the same time, LCRCA's 'Five Year Climate Action Plan' highlights the need for a reduction in car trips by 48–72% each year to reach net zero by 2040 (Liverpool City Region Combined Authority, 2023), an aspiration which is dependent on access to reliable sustainable transportation alternatives.

Research thus far has highlighted the presence of significant transport inequalities throughout Liverpool City Region, which could be seen as barriers to some of these equity and sustainability targets. Calafiore et al. (2022) identified that whilst bus stops were accessible for all within a 10-min walk, only 14% of people could access train stations, with further attention needed to account for the performance and reliability of these services. Furthermore, Southern (2023) identified relatively low train usage across the city (< 10%), with particularly low usage of sustainable transport modes in specific parts of the city (e.g., Everton), where accessibility is lowest. In terms of active travel, and specifically cycling, Dunning et al. (2021) showed that in Liverpool City Region, usage of active travel was highly related to socio-demographic outcomes, creating pockets of active travel disadvantage in the most deprived parts of the city. As a result, there is a need to better understand the current state of multi-modal transport inequality at the regional level, through provision of an empirical evidence base which highlights where improvements are most needed.

Given that composite accessibility indicators have a proven track record for facilitating evidence-led urban governance (Ballantyne & Singleton, 2024; Boeing et al., 2022), and that there is significant momentum for transformative planning within Liverpool City Region (Liverpool City Region Combined Authority, 2022), the utility of a two-dimensional transport accessibility indicator has significant value for targeting priority areas as part of the CRSTS and LCRCA's Five Year Climate Action Plan. By leveraging such an indicator, and the information it details about the distribution of transport inequality in Liverpool City Region, policymakers and researchers remain better equipped to build a sustainable and equitable future for residents, by targeting interventions at the people and places that would benefit most.

3. Methods and materials

3.1. Towards two-dimensional transport accessibility indicators

The fundamental concepts of *supply* and *demand*, prevalent in transport and retail geographies, provide a useful theoretical framework to conceptualise a two-dimensional transport accessibility indicator. Proximity to and the quality of transport infrastructure are closely related to the concept of '*supply*', and the engagement of populations can be linked to the idea of user '*demand*' (Mulley et al., 2018; Peungnumsai et al., 2020). Thus, we can conceptualise a transport accessibility indicator as having two dimensions - *supply* and *demand* - as seen below in Fig. 1.

3.2. Supply: exploring availability of sustainable transport infrastructure

To calculate the first dimension of our composite indicator - *supply,* we first measured the proximity of populations to sustainable transportation infrastructure. We did this by estimating the shortest paths between a series of origins (e.g. administrative areas) and destinations (e.g. transport infrastructure). We followed the steps seen below, which are general and can be adapted to suit a variety of different settings and research questions. Section 3.5 provides a detailed description of how these steps were adapted to suit our case study context, and introduces the different datasets used to represent administrative areas and destinations.

- Assign each origin to the closest junction in the case study area's street network, as well as the corresponding euclidean distance from it.
- Filter infrastructure locations within an arbitrary euclidean buffer of the origins, to minimise computational complexity. We used thresholds of 1000 m and 4000 m for bus and rail, drawing inspiration from previous research (Daniels & Mulley, 2013; O'Connor & Caulfield, 2018; Southern, 2023)
- Compute road distances from the origins to the nearest sustainable transport infrastructure in each of the three modes - bus, rail, and cycling - by utilising the corresponding closest junctions in the walkable network.

We considered proximity to transport infrastructure at the finest spatial scale possible, as being important to inform urban planning decisions, so postcode units, the lowest form of administrative geography in the UK, were selected to represent residential locations in calculation of proximity. Once proximity had been calculated, the next stage was to assess the overall quality of the nearest infrastructure in each of the three modes. To assess the quality of bus stops and railway stations, we calculated the average hourly frequency of services at each bus stop and railway station, taking an average value where a bus stop/railway station offers services in two or more directions. For cycling, we applied different scores to the different types of cycle infrastructure (e.g., traffic free, bus lane). Score selection drew inspiration from the LTN 1/20 standards (Department for Transport, 2020), where a higher score represents a higher standard of cycle infrastructure. In particular we used weights of 1 for the best infrastructure (traffic free, segregated cycle lane), 0.5 for a non-segregated cycle lane and 0.25 for everything else, which incorporates the weakest forms of cycle infrastructure, including shared use.

The final stage was to provide an overall representation of *supply*. Since postcode districts in the UK include limited information about the population, Output Areas (OAs) were selected as the spatial scale at which to assemble two-dimensional indicators. OAs describe areas with roughly 40–250 households and contain more detailed population characteristics than postcode districts. Thus, for every postcode-infrastructure pair, we converted the network distances (metres) and quality scores (frequency of service or cycle score) into z-scores, applied weights of 75/25 to reflect the importance of distance versus quality, before adding these together to derive a *supply* score (Eq. (1)), as in previous research (Patias et al., 2021; Singleton et al., 2016). Then, for every postcode, and for each of the three transport modes, the postcode-infrastructure pair with the highest *supply* score was extracted. Finally, these scores were averaged at OA level (Eq. (2)), for use in assembly of the two-dimensional indicator (see Sections 3.3 and 3.4). A simple

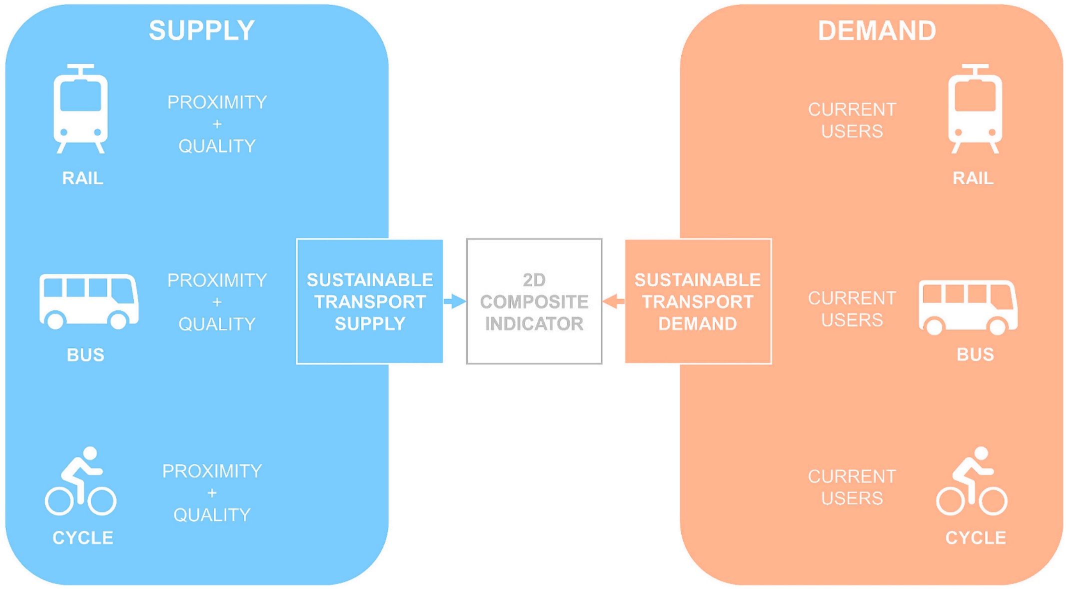

Fig. 1. Conceptual framework of two-dimensional sustainable transport accessibility.

formal representation of these steps can be seen below in Eqs. (1 and 2). The result of the process was a set of three *supply* scores, at OA level, describing the average accessibility and quality of sustainable transport infrastructure.

$$S_{i,j} = D_{i,j} + V_{i,j} \tag{1}$$

$$S_{i,k} = \mu(S_{i,j}) \tag{2}$$

Where:

$S_{i,j}$ composite supply score for sustainable transport mode i in postcode *j*.

$D_{i,j}$distance from postcode j to nearest sustainable transport infrastructure for transport mode i *(*e.g., *cycling)*.

$V_{i,j}$quality of nearest sustainable transport infrastructure for sustainable transport mode i in postcode *j*.

$S_{i,k}$ average composite supply score for sustainable transport mode i in Output Area k.

3.3. Demand: incorporating population characteristics

When integrating population characteristics into our indicator, we considered the engagement of populations with sustainable transportation, based on the idea that increased proximity to the infrastructure does not directly translate into increased usage. The aim was to gather a series of variables which could be used to weight the *supply* side of our indicator (see Section 3.2), and capture areas where higher *demand* for sustainable transport may not be matched with good infrastructure (i.e., *supply*). To minimise the complexity of systematically evaluating the population characteristics associated with each of the transport modes, as in previous literature (see Frank et al., 2021; Owen et al., 2023), we opted for *demand* to be based on actual travel behaviours. The justification for doing so was that in our efforts to provide a generalisable methodological framework, which can be utilised in different settings and between different modes of transport, there was a need for demand based on a series of readily available measures (i.e., observed usage), instead of trying to control for covariates associated with mode-specific demand, often varying between localities, which was beyond the scope of this research. Thus, we used data from the latest 2021 census to capture engagement with sustainable transportation. In particular, using the '*Method of travel to work*' census tables, we calculated the populations (%) who use each of the three sustainable transport modes as their main commuting mechanism.

The most recent census, dated 2021, has a number of significant limitations, particularly in recording the commuting patterns of populations in the midst of a global pandemic (Gibbs et al., 2023). Concurrently, the previous census, dated 2011, was deemed too old to support a 'true' representation of sustainable transport *demand*. To tackle this, we estimated demand from the census data, controlling for differences between the 2011 and 2021 surveys, by calibrating census data against the National Travel Survey (NTS). The NTS is the primary source of data on individual travel among residents of England (Tortosa et al., 2021). Whilst the individual-level records are useful, the coverage of households that are sampled does not support aggregation to OA or spatial microsimulation. Yet, the NTS does provide a broader view on how mode usage is changing annually, and in specific regions, as seen below in Fig. 2.

When extracting the number of trips made across the three modes of interest from the NTS, it emerged that 2020 saw a dramatic change in the commuting behaviour of the population, compared with previous years. At the same time, these trends appeared to be somewhere between pandemic and pre-pandemic levels in 2022 (see Fig. 2A). Thereby, we calculated the average change between 2021 and 2022 to obtain an estimate of how far current transport mode usage was away from levels seen at the time of the last census. These differences were used as scaling factors to adjust the 2021 census estimates, as outlined in Eq. (3) below. The results of the adjustment performed can be observed in Fig. 2B; the distribution of values for the three transport modes was hypothesised to be more representative of current *demand* for sustainable transport at small-area level. These values were then carried forward as the *demand* population ($Q_{i,k}$*)*, to be combined with the composite *supply* indicator in Section 3.4.

$$Q_{i,k} = \left(Pop_{i,k} \times t_i\right) + Pop_{i,k} \tag{3}$$

Where:

$Q_{i,k}$ demand population for sustainable transport mode i in Output Area *k*.

$Pop_{i,k}$ 2021 census population for sustainable transport mode i in Output Area *k*.

t_i scaling factor for sustainable transport mode *i*, calculated as % difference between 2020 and 2022 NTS (bus: 13.6%; rail: 36.4%; cycle: 0%).

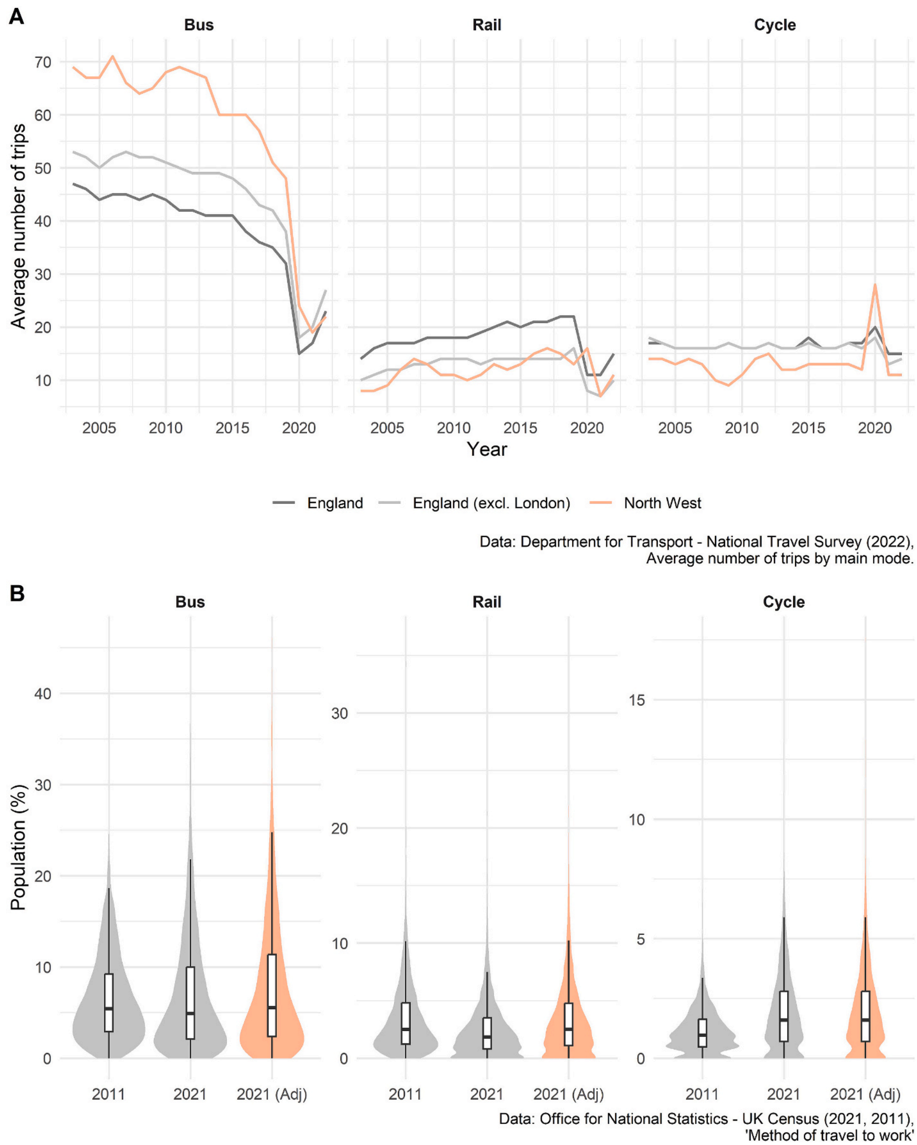

Fig. 2. Temporal trends in trips made by bus, rail and cycle recorded by NTS (2A), and adjustment of 2021 census estimates (2B) using scaling factors from the NTS data (2022–2021 difference). Adjusted 2021 values are those used as $Pop_{i,k}$ in Eq. (3).

3.4. Assembling the two-dimensional indicator of sustainable transport accessibility

The final stage was to combine the *supply* and *demand*-side indicators into a meaningful two-dimensional representation of sustainable transportation accessibility. The composite *supply* indicator ($S_{i,k}$) and the *demand* population ($Q_{i,k}$) were used as inputs for each of the three modes at OA level. As we were interested in identifying places and neighbourhoods where investment in new infrastructure (i.e., better *supply*) could support a transition to greater sustainable transportation equity, our indicator ($A_{i,k}$) was constructed in a way which highlights where *demand* ($Q_{i,k}$) outstrips *supply* ($S_{i,k}$) for each of the three transport modes (Eq. (4)). The final composite scores, as introduced in Section 4, are relatively easy to understand; higher values denote OAs where *demand* is relatively larger than the *supply* of sustainable transport infrastructure.

$$A_{i,k} = Q_{i,k} - S_{i,k} \quad (4)$$

Where:

$A_{i,k}$ sustainable transport accessibility score for mode i in Output Area k.

$Q_{i,k}$ demand population for sustainable transport mode i in Output Area k.

$S_{i,k}$ composite supply score for sustainable transport mode i in Output Area k.

3.5. Data and case study considerations

Before introducing the scores and discussing them in detail, it is important to outline the different datasets used in our application, demonstrating the applicability of this analytical framework in other settings. A variety of different datasets were used to capture sustainable transportation opportunities (*supply*). The locations of bus stops were derived from up-to-date General Transit Feed Specification (GTFS) schedules obtained from the UK Bus Open Data Service,[1] and similarly, railway stations were extracted from an archived GTFS feed[2] dating back to 2019. Location information about cycle infrastructure was provided by LCRCA, comprising an up-to-date spatial database of active travel routes through Liverpool City Region. These routes were deemed

[1] https://www.bus-data.dft.gov.uk
[2] https://www.transit.land/feeds/f-gc-rail~delivery~group~planar~gtfs

more accurate than other open cycle route datasets like OpenStreetMap (Ferster et al., 2020), encompassing new routes introduced as part of the Emergency Active Travel Fund in 2020 (Dunning et al., 2021).

Concerning the quality of the transport infrastructure for bus and railway services, GTFS schedules were also used to calculate the average hourly frequency of services for bus stops and train stations between 8 a.m. and 5 p.m. The rail GTFS schedules, although almost three years old, were deemed to accurately reflect the current schedules. The 'Type' variable in the LCRCA cycle route dataset was used to differentiate good cycle infrastructure (e.g., traffic free, segregated cycle lane) from poor cycle infrastructure (e.g., shared use), through construction of weights based on the official LTN-120 standards. An overview of these different data layers can be seen for a specific part of the city in Fig. 3.

4. Results and discussion

4.1. Introducing the two-dimensional accessibility indicators

Fig. 4 introduces the two-dimensional transport accessibility indicator(s) for each of the three transport modes, and for all OAs in Liverpool City Region, highlighting the association between the domain-level *supply* and *demand* indicators, and how these come together to generate a two-dimensional score. To interpret this figure, it is first easiest to examine the darker orange dots, which represent OAs where

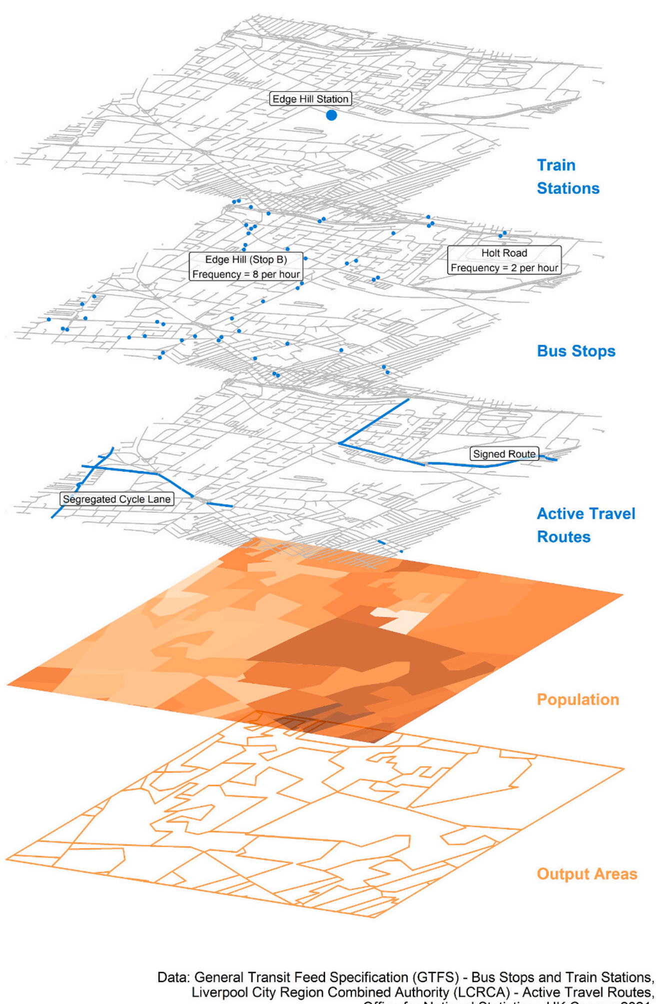

Fig. 3. Overview of different data layers used to capture two-dimensional sustainable transportation accessibility, incorporating elements of *supply* (blue) and *demand* (orange). These are used as inputs to Eqs. (1–4) to produce accessibility scores for each mode of transport.

demand greatly exceeds *supply*, pinpointing places in greater need of investment to improve the *supply* of sustainable transport infrastructure. For example, focusing on a specific point, such as the highest value for 'Cycle' (Fig. 4), the figure highlights that this OA has a population of around 12% that commute to work by bicycle. However, as denoted by the colouring and size of the dot, the 2D accessibility score highlights that this is a place where *demand* is greatly exceeding *supply* in this area (i.e. *demand* > *supply*).

Fig. 4 shows that the *demand* for different types of sustainable transport is generally greater as the corresponding *supply* score increases. Given that the *supply* score ($S_{i,k}$) accounts for both distance to ($D_{i,k}$) and the quality of infrastructure ($V_{i,k}$), these trends suggest that better access to good quality sustainable transport infrastructure is associated with increased usage. However, these associations are not consistent across transport modes. Whilst all three modes exhibit statistically significant correlations between estimates of *supply* and *demand* ($p < 0.05$), the R^2 value for bus ($R^2 = 0.304$) and rail ($R^2 = 0.498$) is much higher than that for cycle infrastructure ($R^2 = 0.131$), indicating a greater spatial mismatch for cycling, which prompts a need to consider alternative metrics of cycle accessibility (e.g., connectivity) to test whether concepts of supply and demand are less relevant in the cycle domain.

These accessibility scores are therefore able to identify locations displaying a spatial imbalance of *supply* and *demand*, namely places where the *demand* for transport is exceeding the *supply* of infrastructure. The largest orange circles in Fig. 4, for example, represent those places where the imbalance of *supply* and *demand* is greatest - between 30 and 40% of the bus population (Fig. 4). However, these scores identify imbalances across the full spectrum of *demand*, thus highlighting the need for interventions in areas that present relatively low *demand* (e.g., 2–5% of the cycle population). This suggests that achieving sustainable transport equity for Liverpool City Region may require moving away from 'top-down' interventions and investments, to consider the benefits of investment in places where there is (some) existing *demand* for sustainable transport, but limited *supply* to encourage further growth.

4.2. Using the two-dimensional indicators to promote sustainable transport equity

In terms of using the 2D scores to develop urban transport interventions, we speculated that there would be places across Liverpool City Region where *demand* exceeds *supply* across multiple modes of transport, given the existence of composite inequality in the region (Ballantyne & Singleton, 2024). Fig. 5 highlights the relevance of this hypothesis, illustrating the interactions between the 2D scores across the three modes of transport. The plot has been coloured to identify OAs where *demand* is exceeding *supply* (orange), based on positive and negative score values, with different sized points used to add a third dimension for cycling. The key interpretations to draw from this figure is that there is a large concentration of OAs where *supply* and *demand* are close to being balanced, seen as the cluster of points around 0, 0. However, when you focus on the outliers for each score – i.e. further away from the centre – that is where the interesting patterns can be identified, including groups of points which exhibit similar transport inequalities.

OAs in the top right of the plot point to inadequate *supply* of bus and rail services, and in some cases also cycling infrastructure (larger bubbles). For example, looking at Barnston, all three 2D scores point to high imbalances between *demand* and *supply*; these are driven by a combination of relatively long (average) walking distances to bus (2.2 km), rail (2.8 km) and cycle infrastructure (3.8 km), as well as poor quality infrastructure - i.e. the nearest train station (Heswall) offers one train service per hour per direction, and the nearest cycle infrastructure is classified as 'Shared Use' (low quality). Fig. 5 reveals a second cluster (bottom right) including places where two types of transport infrastructure are lacking, but one is considered optimal. For example,

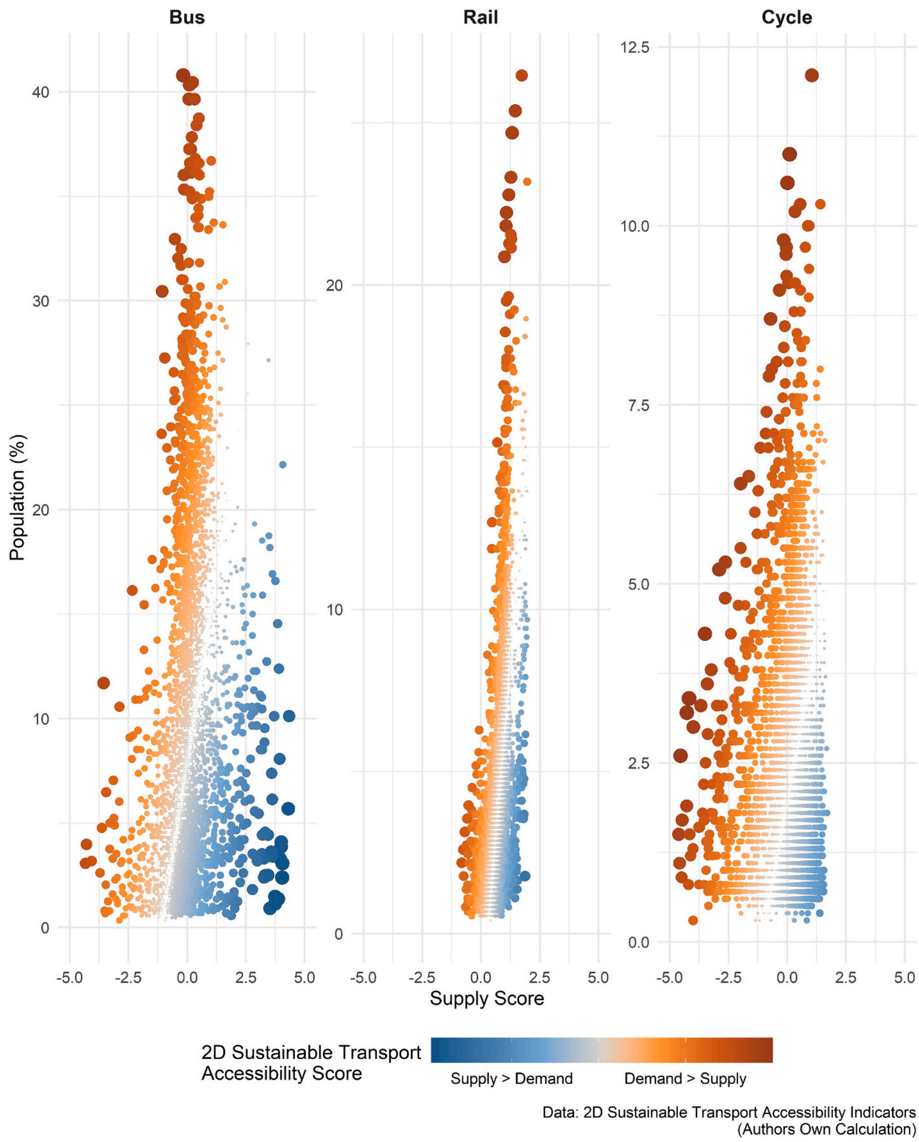

Fig. 4. Distribution of *supply* and *demand*-level scores, and relationship to the two-dimensional sustainable transport accessibility indicators for each transport mode. Each dot represents a single OA, and the *demand*-level scores have been plotted using the population estimates ($Pop_{i,k}$) instead of the z-scores to aid interpretation.

Newton le Willows (WA12 9SB) is identified as having good bus services for a relatively large number of people. However, the local rail and cycle infrastructure is relatively poor, with long walking distances to cycle infrastructure (2.2 km) and poor-quality rail services operating from the local train station (2 per hour per direction), despite roughly 6% of people in this area commuting by train. Taking a different approach, looking at the bottom left corner, we can explore the characteristics of places with good *supply*. For example, Liverpool City Centre is seen to have good rail and bus infrastructure which support the population, however the relatively high active travel score here points to a need for increased cycle infrastructure to meet *demand*.

Our 2D sustainable transport accessibility scores (Fig. 5) help understand why transport accessibility ought to be viewed as a multi-modal phenomenon. There are many places in the Liverpool City Region where the *supply* of infrastructure is not meeting *demand* for more than one mode of transport By taking the average 2D score value ($A_{i,k}$) across the three transport modes and mapping the resulting score (Fig. 6), we can identify where these places are geographically located. Whilst it might have been useful to consider neighbourhoods that experience categorically high values across the three indicators, controlling better for extremes, the approach we use makes it easier to pinpoint areas within specific numerical thresholds, which has proven vital for identifying areas for investment in previous research (Ballantyne & Singleton, 2024). By focusing on regions of the map highlighted in dark orange and brown, we are able to pinpoint neighbourhoods where *supply-demand* imbalances are present across multiple modes of transport (cycle, rail and bus), thus providing a systematic approach to selecting priority locations for transport investment. For example, places, such as Halton Lodge seen in Halton (6D), Everton (6B), Barnston, North of Heswall (6 A) and Huyton Farm, North-West of Huyton (6C) are identified areas as experiencing multi-modal transport inequality. Furthermore, multi-modal transport inequality is also existent in Sefton (6E), notably in the areas of Bootle, Aintree and Ainsdale, as well as western St Helens (6F) and parts of Rainhill and Earlestown.

In thinking about how to promote sustainable transport equity, as well as how to direct investment from the CRSTS (see Section 2.3), Fig. 6 provides a tool to maximise outcomes by highlighting places where multiple transport inequalities intersect spatially. Fig. 6 identifies OAs across the six Local Authority Districts where transport infrastructure investments will likely result in increased uptake by local populations - as captured by positive scores, which represent higher *demand* for sustainable transport, but lower *supply*. In particular, we argue that

Fig. 5. Distribution of the 2D sustainable transport accessibility scores for the three transport modes, highlighting how transport inequalities are intersecting negatively across Liverpool City Region based on imbalances in *supply* and *demand*.

improving the availability and quality of services in these areas will encourage an additional segment of the population to consider shifting away from private car usage to more sustainable transportation options.

However, as shown in Figs. 4–6, the type of investment needed in each place depends on the relationship between *demand* and *supply* across the three transport modes, and more importantly the element(s) of sustainable transport *supply* which appear to be lacking (e.g., more bus stops, better quality bus services). As the *supply* component of the 2D transport accessibility indicator comprises two individual elements - distance to infrastructure (metres) and infrastructure quality (score), unpacking the domain scores can provide valuable and detailed information to guide interventions aimed at alleviating transport inequalities across different areas. To this end, we took the top 10% of OAs across Liverpool City Region exhibiting the highest average 2D scores across the three transport modes, to demonstrate how our scores can be used to guide specific types of transport infrastructure investments.

Fig. 7 shows our *supply* score ($S_{i,k}$) which emerges from the interaction of the two constituent components, namely (1) average distances to, and (2) quality of, transport infrastructure. Fig. 7 shows that Barnston is a place where *supply* across the three modes of transport is relatively poor. Yet, more bus stops (7 A), rail stations (7B) and cycle paths (7C) seem to be needed in this area, to reduce the distances residents have to walk to use these transport types. In contrast, in areas such as Kensington (L7 8RY), rail provision appears to be relatively good displaying a high frequency score (7B), with residents in this area able to reach a relatively good rail service within a reasonable walking distance, as captured by a smaller than average distance score. However, our scores also suggest that this area may need significant enhancement to cycle infrastructure (7C) both in terms of better provision and quality of more cycle routes, as existing routes in this area seem relatively poor, as captured by a low cycle score for this OA.

5. Conclusion

This study developed a set of two-dimensional accessibility indicators, which bring together elements of *supply* and *demand* to identify places where existing transport infrastructure is hindering further transitions towards sustainable transport equity. The indicator is assembled for three (sustainable) transport modes - bus, rail and cycling - by calculating the proximity of administrative areas to transport infrastructure, the overall quality of infrastructure (i.e., *supply*), and the level of *demand* for these different modes of transport. This provides a

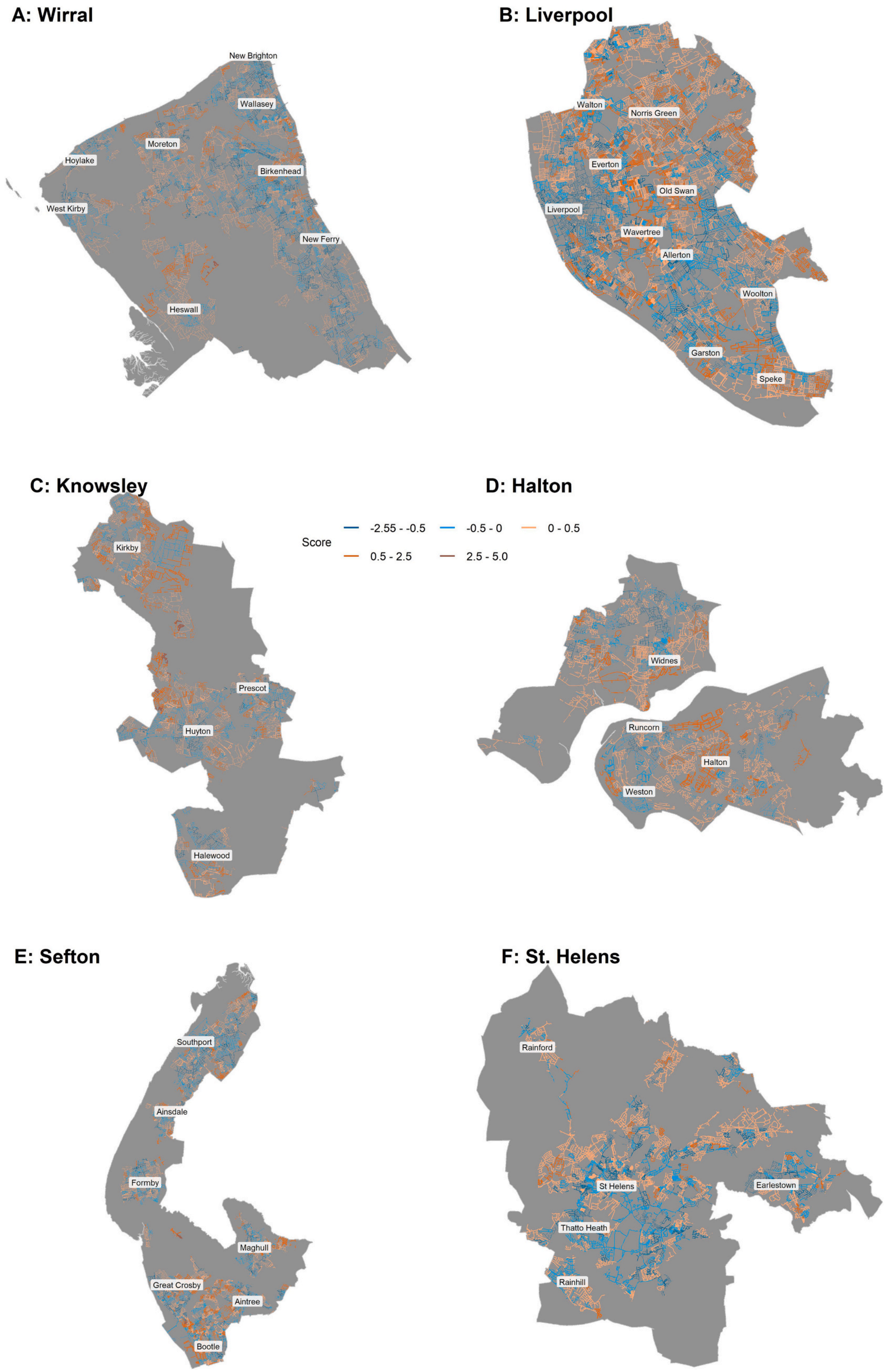

Fig. 6. Geographic distribution of composite transport inequalities across Liverpool City Region, displaying average 2D sustainable transport accessibility score across modes. The score has been mapped to deliberately exclude largely rural areas and green spaces (as in Ballantyne & Singleton, 2024), and mapped onto the road network for enhanced cartographic representation.

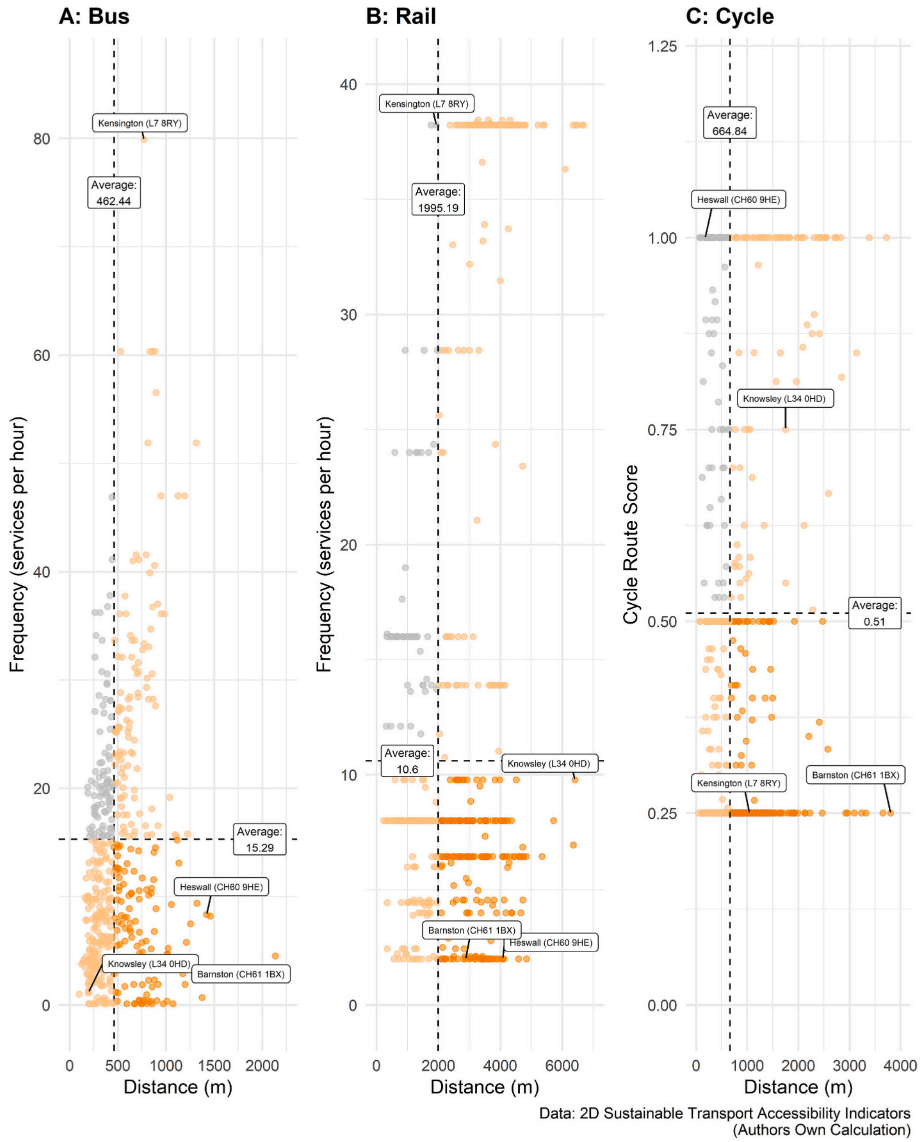

Fig. 7. Distribution of *supply* score inputs across the three transport modes, pointing to the types of interventions needed to address transport inequalities in each place. Each dot represents an OA, where only those OAs with the highest average 2D accessibility score are plotted to highlight where transport inequalities are greatest. Dots in the bottom right corner of each grid (darker orange) can be considered in need of both additional infrastructure (i.e. more bus stops) and better-quality infrastructure (i.e. more frequent services), whereas top left points (grey) can be considered to have good access to good quality infrastructure.

unique way of measuring sustainable transport accessibility. By accounting for *demand*, the indicators are able to identify places where there is existing engagement with sustainable transport. By combining these *demand* estimates with infrastructure *supply* measures, the indicators reveal places where (sustainable) transport infrastructure is inadequate, limiting further uptake of sustainable travel behaviours. To demonstrate this, we advance a policy case study for Liverpool City Region, highlighting how to use the analytical framework and two-dimensional indicators to explore these *supply-demand* imbalances, evidencing the utility of this framework at a time of significant momentum for transformative urban planning in the region.

Our study contributes to research on transport accessibility by providing a novel methodological framework to transport accessibility at a small area level. Our proposed framework accounts for both the *supply (*walking distance, quality*)* of transport infrastructure and the engagement of local populations (i.e., *demand*). In contrast, existing literature has until now placed significant emphasis on conceptualising (transport) accessibility as the proximity of local populations to different transport opportunities (e.g., Capasso Da Silva et al., 2019; Frank et al., 2021; Southern, 2023), often overlooking the frequency and connectivity of different transport infrastructures (Calafiore et al., 2022), and the engagement of local populations with sustainable transportation (Geurs & Östh, 2016). Prior research has attempted to balance proximity, quality, and *demand* (e.g., Peungnumsai et al., 2020), yet existing work often views *demand* as the total population surface, instead of considering the engagement of the population with sustainable transportation based on observed travel behaviours, and how the usage of different modes of transport may vary across local areas reflecting differences in lifestyle and population composition. By accounting for engagement, our indicators can ensure that those people and places that would benefit most from sustainable, equitable transitions, are fully represented. Furthermore, although our indicators provide a snapshot of transport inequalities at present, as with many previous *supply-demand* indicator-based research articles (e.g., Peungnumsai et al., 2020; Singleton et al., 2016), through recalculation of the indicators after CRSTS, our methodological framework will help to ascertain new evidence about whether increased investment in transport supply actually generates increased uptake in sustainable transportation.

Additionally, our approach arguably serves as an enhancement to the established methodologies such as PTAL (Public Transport Accessibility Level), through integration of cycling as an alternative (and sustainable) means of transport, and incorporation of *demand* to reflect the areas of greatest need. The latter serves as a major limitation of PTAL, with users examining associations between PTAL scores and measures of *demand*, to identify imbalances in *supply* and *demand* (e.g., Mulley et al., 2018). Utilising the analytical framework proposed here, our research provides a new perspective on how to identify such imbalances empirically, through direct weighting of *supply*-level indicators (such as PTAL) to reflect the underlying *demand* for these services, based on observed travel behaviours. This has become even more feasible given our efforts to demonstrate that the latest UK census data can be successfully re-calibrated, using observed travel behaviours from the NTS to extract *demand* estimates that better represent post-pandemic commuter patterns. Furthermore, our approach can be applied in a variety of different settings to identify imbalances in *supply* and *demand*, and resultant transport inequalities at the city and regional level. By harnessing available transport infrastructure data, either from GTFS, OpenStreetMap and/or other sources, researchers are now better placed to develop indicators that can support transformative planning, through the design of transport systems that promote principles of sustainability and equity.

In terms of policy implications, we have demonstrated how our two-dimensional transport accessibility indicators can contribute valuable insights about the quality of public transport and cycle infrastructure. We propose a framework through which *supply*-level shortcomings in the availability of sustainable transport opportunities can systematically be identified and monitored, contributing to accelerating the transition to a net zero carbon urban transport system. For Liverpool City Region, our proposed framework is particularly timely as LCRCA invests to design a transport system that is both equitable and sustainable, leveraging additional controls afforded within the political remit of LCRCA, such as plans for bus network franchising (Liverpool City Region Combined Authority, 2024). Future research in this area will involve development of a digital twin to support this re-design, which will utilise the framework and insights presented here, and build on the work of Ballantyne & Singleton (2024) to more concretely look at the relationship between transport accessibility and urban inequalities in Liverpool, demonstrating further the policy implications of the indicators we have developed here.

We acknowledge limitations in our proposed framework. Firstly, our analysis places significant emphasis on measuring accessibility to transport-specific services, which provides only a partial view of 'accessibility'. Secondly, our indicators are designed in a way which evaluates the best possible choice of transport infrastructure available to residents in a given administrative area. Whilst this is based on robust (weighted) measures of infrastructure proximity and quality (see Section 3.2), it results in a 'patchy' distribution between adjacent administrative areas, when allocated to different transport infrastructures (e.g. train stations) based on the highest *supply* score. Whilst every administrative area is assigned to different transport infrastructure based on distance and a quality metric, future work could explore the impact of using n number of closest and best quality infrastructure to obtain an 'average' *supply* score for each administrative area. This would likely result in a less 'patchy' distribution of two-dimensional transport accessibility, highlighting 'regions' instead of 'patches' of transport inequality. Furthermore, it would be interesting to see how this distribution is affected by treating the entire road network as contributing to supply for cycling, instead of cycle-specific infrastructure, and the way in which different types of road (e.g., low traffic) near to infrastructure, and the empirical metrics used to quantify this (e.g., connectivity), can alter these patterns further.

Secondly, our indicators treat the three sustainable transport modes - bus, rail and cycle - as being separate from each other, excluding any notion of multimodal transport choice behaviour (Soukhov et al., 2024). Whilst our indicator considers *demand* specific to each of the three modes, it identifies places where additional investment to improve the *supply* of transport infrastructure should increase the uptake (i.e., *demand*) of these services. However, the indicators cannot account for situations where an increase in *supply* for one transport mode (e.g., rail) could generate additional mode shifts away from another sustainable transport mode (e.g., bus). Future work should leverage the analytical framework introduced here, considering more explicitly how the three mode-level indicators can be combined into an overall indicator which balances these decisions, and identifies a series of multi-modal outcomes based on changes to *supply* and *demand*.

CRediT authorship contribution statement

Patrick Ballantyne: Writing – original draft, Visualization, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gabriele Filomena:** Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Francisco Rowe:** Writing – original draft, Methodology, Conceptualization. **Alex Singleton:** Writing – original draft, Resources, Conceptualization.

Declaration of competing interest

Co-author Singleton is a member of the editorial board for Computers, Environment and Urban Systems.

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