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Spatial exploration and evaluation of rail and long-distance bus network integration with a multimodal node-place model

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Abstract

Improving the integration of rail and long-distance bus services is essential for enhancing regional connectivity and sustainable transport accessibility. Existing node-place models mainly focus on station surroundings and do not consider how buses extend access explicitly to support the transit network. Therefore, this study develops a multimodal network-based approach applied to a case of sub-rural Scotland. Three new integration metrics are designed — travel time-weighted population (demand coverage), feeder bus service availability (supply), and network centrality (regional connectivity). These indicators are then incorporated into a three-dimensional Node-Place framework, which evaluates the integration performance of 102 railway stations across the study area. Results reveal spatial differences in integration performance, identifying well-connected hubs such as Inverness and Stirling, alongside stations like Rosyth and Dunfermline City where demand is not matched by service provision. The analysis also shows opportunities to strengthen east–west regional links and improve multimodal access through targeted interventions, such as co-locating bus termini. By extending the Node–Place

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model to include multimodal catchments and network-level connectivity, the framework captures aspects of integration that are overlooked in rail-only assessments and offers a unified diagnostic tool for identifying where rail-bus integration improvements may have the greatest effect. The method is built on publicly available data, enabling its application in other regions and adaptation to support future demand modelling.

Keywords: Node-place model; Multimodal network; Rail bus integration; Sub-rural area; Long-distance services

1. Introduction

The EU has long advocated multimodal interurban transport to reduce over-reliance on cars, driven by environmental concerns, social inclusion and sustainable mobility. As part of this strategy, the integration of rail and long-distance bus networks is frequently proposed as an effective approach (European Commission, 2011). This integration could provide complementary services by expanding geographic coverage and providing service options.

However, Tyler (2022) reported that the UK still faces several barriers to establishing rail and bus integration as a national policy. Rail and bus services are generally operated independently, making it difficult to coordinate between different entities. The situation is further complicated by the passenger rail franchising system and the deregulation of bus services, which may encourage competition between operators, particularly on routes where bus and rail services overlap. Consequently, progress in improving rail-bus integration has been slower than anticipated and public expectations for such integration remain low (Tyler, 2022). It may become easier in the future, with all rail passenger operations (except open access operators) being returned to government hands and the spread of bus franchising and enhanced partnerships.

Considering these national-level obstacles, more integration progress has been made at the local level in UK, where authorities have greater control. For example, Devon County Council successfully launched the 118 bus service to connect towns with the Okehampton and Exeter rail lines following the reopening of the Dartmoor line (Buses Magazine, 2021). For the long distance service integration, there are additional opportunities. Japan's "B&S Miyazaki" system integrates interurban bus with high-speed rail between

Miyazaki and Fukuoka, attracting new users rather than diverting passengers from existing services. Yashiro and Kato (2019) analysed the success of this system and highlighted the importance of the demand forecasting model during project planning. Such a model could foster collaboration among stakeholders by reducing profitability uncertainty, as it allows them to estimate potential patronage before implementation.

In the UK, the Passenger Demand Forecasting Handbook (PDFH) is a key reference that provides guidance on evaluating factors influencing rail passenger demand (Worsley, 2012). It employs 'elasticity values' to measure how sensitive demand is to changes in these factors. Rail–bus integration in the PDFH is treated as a binary outcome—present or absent—without a method for quantifying integration or their effects on demand. In response, this study develops a network-based framework that evaluates rail–bus integration, enabling quantification in a spatial manner. The framework extends the traditional Node–Place model (Bertolini, 1999) by representing not only the local characteristics of stations but also the wider network connections created by long-distance bus services. The analysis incorporates population indicators and station centrality derived from the multimodal network. This allows the framework to capture additional reach and connectivity that are not visible in rail-only networks or binary assessments such as those adoptd in the PDFH. Bringing these elements together becomes a new exploration tool that helps to identify stations where coordination between rail and bus services is weak. The framework therefore offers a practical tool for prioritising stations for intervention and supporting targeted integration strategies. It also provides a foundation for future demand studies, as it captures a broad set of station-related factors that may influence travel behaviour.

The remainder of the paper is structured as follows. **Section 2** reviews the relevant literature on interurban rail–bus integration and the Node-Place application. **Section 3** introduces the case study area in Scotland and the relevant datasets. **Section 4** outlines the methodological framework, detailing the construction of the integrated rail–bus network, the delineation of multimodal catchment areas, and the application of an extended Node-Place model. **Section 5** reports the main findings while **Section 6** summarises the conclusions and suggests directions for future research.

2. Literature review

2.1. Optimisation and evaluation methods in multimodal transport planning

Optimisation models are widely adopted to support multimodal transport planning, where they help determine stop locations, route layouts and operating frequencies (Shafiq et al., 2025). Specifically, these models are commonly applied in facility location planning, including the identification of suitable sites for new bus stops or interchanges (Shafiq et al., 2025; Alumur et al., 2012; Mahmoudi et al., 2025a). Multimodal network design models can be applied to decide how bus routes should be designed and how frequently they should operate (Mahmoudi et al., 2025b; Deng et al., 2013). They are designed to improve travel efficiency while keeping costs as low as possible by simultaneously setting multiple objectives (Deng et al., 2013; Mahmoudi et al., 2025b; Shafiq et al., 2025).

To solve these optimisation problems, researchers have applied exact methods or metaheuristic algorithms. Exact methods, such as branch-and-bound for mixed-integer programming, can produce exact solutions. However, it becomes less practical as the network grows larger and more complex (Mahmoudi et al., 2025a). In such cases, metaheuristic methods are preferred as they can handle problems involving large numbers of variables, non-linear relationships, and multiple objectives. Even so, they cannot guarantee finding the best possible solution. The results may vary depending on the initial values and the specific design of the algorithm (Mahmoudi et al., 2025b; Shafiq et al., 2025). Another challenge is that both approaches require substantial computing power and technical expertise (Iliopoulou and Kepaptsoglou, 2024; Mahmoudi et al., 2025a).

In addition, evaluation-based approaches are widely adopted to examine the outcomes of predefined multimodal transport schemes. Cost–benefit analysis, for instance, is commonly applied (De Rus and Nash, 2007; Johnson and Nash, 2012; Nash, 2015). This approach converts changes such as travel time savings, increased fare revenue and other externalities such as reductions in emissions, into monetary values. It then applies indicators such as net present value or benefit–cost ratio to evaluate whether a proposed scheme can generate a positive return. Cost–benefit analysis is effective in evaluating the economic feasibility of a given proposal. However, it mainly focuses on assessing predefined schemes rather than identifying where integration between modes is weak. Moreover, as it relies mainly on financial measures, it offers limited understanding of the spatial coordination between rail and bus services (Hayashi and Morisugi, 2000).

Overall, these optimisation- and evaluation-based methods provide important insights but may not be suitable for examining multimodal integration from a spatial perspective. Optimisation models require detailed operational inputs and substantial computational effort, which limits their use in practice. Evaluation approaches such as cost–benefit analysis focus mainly on predefined schemes and economic outcomes, offering little information about how different services interact across space. Although many other studies consider accessibility, network-based or equity indicators to assess particular aspects of integration performance (Geurs and Van Wee, 2004; Von Ferber et al., 2009; Zhang et al., 2018; Shafiq et al., 2025), they tend to be applied independently and do not provide an integrated view. In the UK, rail and long-distance bus services are planned and operated by different organisations (Preston, 2023). Because large-scale coordination across modes is difficult under this institutional structure, a station-level assessment tool becomes essential and necessary for identifying where integration is weak, so that local authorities can intervene in a more targeted way.

2.2. Land use–transport coordination from a Node-Place perspective

Node–Place analysis provides a structured framework by bringing transport and land-use factors together within a single spatial framework. This model assesses stations based on two dimensions: the "node" value—representing transport connectivity—and the "place" value—reflecting the intensity and quality of surrounding activities (Bertolini, 1999). A wide range of indicators has been adopted to evaluate the node and place dimensions. Su et al. (2022) conducted a review of 76 publications and identified 44 relevant indicators covering aspects such as service frequency, population density, and land use diversity. To summarise the performance of each dimension, researchers typically standardise and aggregate indicators into composite node and place scores based on the same weights. However, to address potential multicollinearity among indicators, dimensionality reduction techniques such as Principal Component Analysis (Liao and Scheuer, 2022; Zhang et al., 2019) or Correlation Matrix Filtering (Li et al., 2019) have been applied. To reflect the importance of indicators, weighted aggregation methods such as the Fuzzy Analytic Hierarchy Process have also been adopted (Li et al., 2019).

As shown in **Figure 1**, the resulting node and place scores allow stations to be placed on a two-axis diagram, enabling classification into different groups (Zhang et al., 2019; Olaru et al., 2019; Vale et al., 2018). Stations that are located within the curved area are considered balanced, meaning that their transport functions and surrounding land use levels are relatively well matched. Some of these balanced stations show high values in both node and place dimensions. They are known as stressed stations and usually serve as major transport hubs. In contrast, stations with low node and place values fall into what is called the dependence zone. These stations are commonly found in areas with limited transport services, where residents are more likely to rely on private cars than public transport (Vale et al., 2018). Stations that are located far outside the curved area are considered unbalanced and may require further investigation between transport provision and local development.

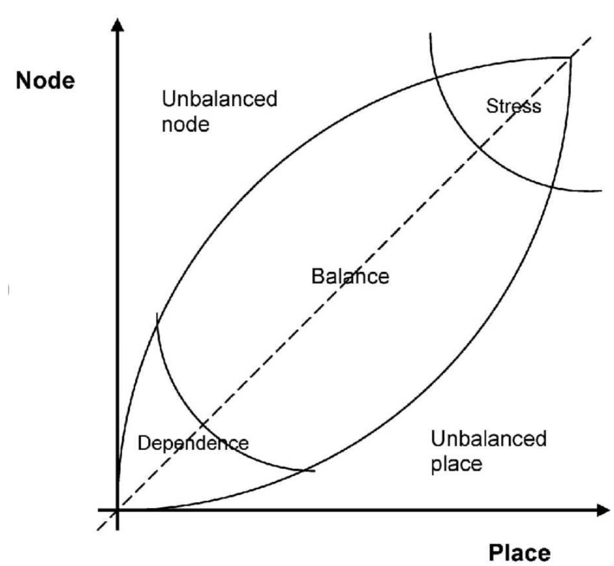

Figure 1: The node-place model (Bertolini, 1999).

The Node-Place model has been widely adopted in transit-oriented development research to help align transport investments with urban development goals (Cao et al., 2020; Caset et al., 2020; Li et al., 2019; Vale et al., 2018). Recent studies have expanded the original Node-Place model by incorporating additional dimensions to capture broader aspects of station area functions.

One key extension involves the inclusion of accessibility indicators, such as destination accessibility and distance to transit, to better reflect travel opportunities around stations (Li et al., 2019; Nigro et al., 2019; Cummings and Mahmassani, 2022). Another expansion is the introduction of network structure metrics, including node centrality, betweenness centrality, and closeness centrality, which assess the strategic role of stations within transport networks (Dou et al., 2021; Liao and Scheuer, 2022; Cao et al., 2020; Zhang et al., 2019). Furthermore, additional dimensions such as urban vibrancy (Yang et al., 2022), morphology (Liao and Scheuer, 2022), and local design attributes (Zhang et al., 2019) have been incorporated in specific studies. These expansions support multi-dimensional evaluation of station areas.

Some recent studies have expanded the Node-Place model by adding travel demand as a third dimension. This helps researchers understand how the influence of transport services and land-use features are linked to actual travel behaviour. Statistical methods such as Pearson's correlation have been applied to analyse the relationship between ridership and Node-Place dimensional scores (Liao and Scheuer, 2022; Singh et al., 2017; Yang et al., 2022). Other studies have applied trip-end models to estimate station-level demand based on the Node-Place indicators (Amini Pishro et al., 2022; Caset et al., 2020; Ramos-Santiago, 2021). These further studies show that the Node-Place model not only provides station classification, but also offer insights into how different factors influence passenger flows. This suggests the the node-place model has potential to support both spatial and behavioural evaluations of multimodal integration.

2.3. Node-Place approach to evaluating rail–bus integration

Most existing studies evaluating rail and bus integration in the Node-Place model focus on the immediate surroundings of railway stations, especially within walking distance. Indicators commonly include the number of nearby bus stops, service frequency, and the distance between these stops and the station (Caset et al., 2020; Olaru et al., 2019; Peng et al., 2023; Su et al., 2022; Vale et al., 2018; Yan et al., 2020; Zhang et al., 2019). Within the Node–Place framework, bus-related measures in the node dimension typically describe how well services connect to the station area, whereas the place dimension is usually represented by the number of activities or the population within a fixed walking distance or time threshold. These measures quantify the degree of local integration around the station and work well in dense urban areas, where bus routes tend to be short, frequent and closely aligned with rail stations.

However, this model might not be suitable when applied to rural or lower-density areas, where people need to travel longer distances using different transport modes. Some studies have tried to extend the Node-Place model by going beyond simple walking buffers. Nigro et al. (2019) was among the first to apply this model to small cities and towns, accounting for different access distances by mode, such as 6 km for car, 4.4 km for bus, 2.6 km for cycling, and 1 km for walking. Similarly, Cummings and Mahmassani (2022) used mode-specific isochrones to define catchment areas when measuring Node-Place indicators for interurban railway stations. In addition, Nigro et al. (2019) separated the node dimension into two parts, one based on rail connectivity and the other based on access through feeder modes. This distinction helps to identify whether service improvements are needed for the rail network itself or for supporting modes. Although these extensions broaden the coverage of possible catchment modes, they still rely on buffer-based assumptions. Since bus services follow corridor-shaped routes rather than circular catchments, buffer-derived populations may not reflect actual service coverage. As Tyler (2020) noted, more than 4.2 million people in Britain live in areas without direct rail access, many of whom could reach a station if suitable bus links were available. Excluding these populations would underestimate station performance within the Node–Place model.

At the same time, focusing only on station catchments does not fully capture another important role of bus services in regional and rural contexts. In many such settings, interurban buses play a role beyond feeder services by directly linking towns that are served by rail but lack direct rail connections between them. This is common in the United Kingdom, where interurban bus routes tend to fill the gaps left by historical railway closures, such as those that occurred after the Beeching Cuts (Luke et al., 2018). Reflecting this broader network role, some studies have incorporated network centrality into the Node–Place model to evaluate how well stations are connected within the rail system (Liao and Scheuer, 2022; Su et al., 2021; Cao et al., 2020; Zhang et al., 2019). However, these approaches are based on rail links alone. A comprehensive evaluation method is needed to consider how buses strengthen and support rail links at the network level.

In summary, the above literature review shows that the Node–Place model has been applied to rail–bus integration with a focus only on the immediate surroundings of stations and on rail connectivity alone. These studies rely on walking- or buffer-based catchments, which do not reflect the wider populations that may access stations through interurban buses. Network connectivity is also measured only on the rail network, meaning that the additional links created by bus routes are largely overlooked. In essence, the Node–Place model has not yet been systematically applied within an explicitly defined multimodal network that represents rail and bus services as integrated components of a single system. As a result, the broader role that buses play in shaping regional accessibility is only partly represented, which may lead to an incomplete assessment of station performance. This issue is especially relevant in non-metropolitan areas, where bus services function as essential regional connectors rather than as purely local feeders (Luke et al., 2018; Tyler, 2020).

2.4. Research gap and questions

A fundamental development is needed for a multi-modal network-based Node-Place model that can capture the role of buses within the hierarchy of regional and local transport planning, supporting both exploration and evaluation of rail-bus integration in a systematic manner. To address this fundamental research gap, this study addresses the following research questions:

1. How can rail and long-distance bus services be represented within a multimodal network for Node–Place analysis?
2. How is rail–bus integration reflected in the functional roles of stations within the multimodal network, as measured by network centrality?
3. How can the spatial impact of feeder services be evaluated beyond conventional walking catchments, particularly in lower-density and non-metropolitan areas?
4. How can the Node–Place model provide an integrated assessment of rail–bus integration that captures multimodal network connectivity and feeder-based accessibility?

3. Study area and Data

Long-distance buses are recognised as a cost-effective alternative in regions where low-density travel makes rail services less feasible (Luke et al., 2018). For this reason, Scotland's eastern regions and the northern Highlands were selected for the case study, as shown in **Figure 2**. These areas are largely rural and shaped by mountains and coastlines, which limits rail provision and makes bus expansion a more practical means of improving connectivity (Government, 2023). The institutional separation of rail and bus services in these regions makes coordination more likely to occur at the local level, which aligns well with the station or route-focused structure of the Node–Place model.

The selected regions cover around 37,751 square kilometres, which accounts for 47.06% of Scotland's total land area. According to the 2011 Census, these regions have a population of 1,719,930 across 756,432 households. The rail network includes 102 stations, 14 rail routes, and 1,198 weekday trips, while the bus network consists of 14,447 stops and approximately 689 routes, supporting 26,893 daily trips. Six key long-distance bus routes connect stations such as Inverness, Fort William, and Dundee—areas without direct rail links.

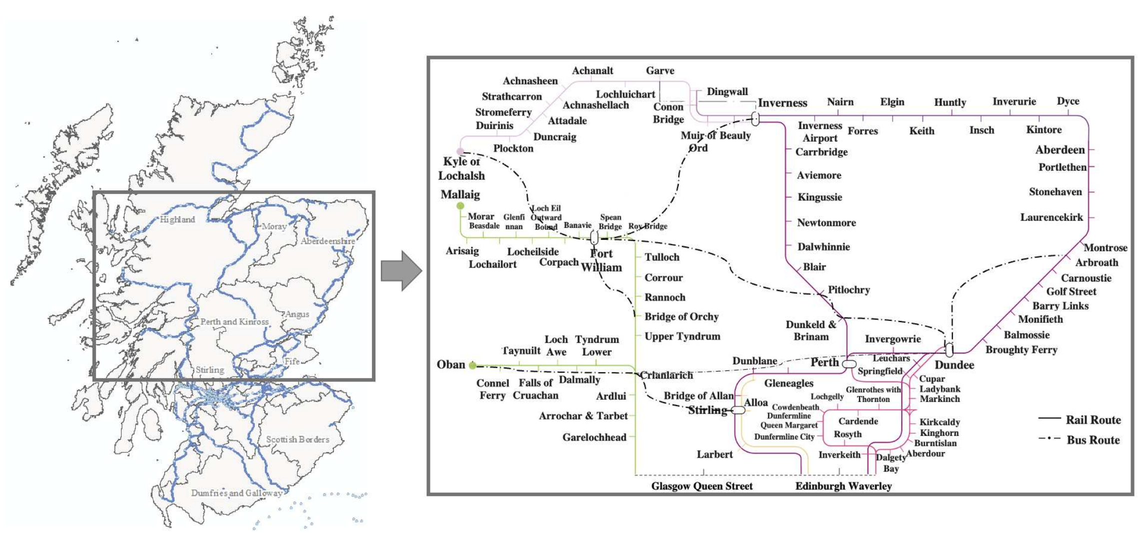

Figure 2: Case study area in Scotland and the rail-bus network.

This study captures demographic, spatial, and transport-related characteristics from a range of publicly available datasets. Population and employment data from the 2011 Census provide the demographic and economic basis (National Records of Scotland, 2011). Geospatial information—including road networks, car parking locations, and land use—was acquired via OpenStreetMap's API (OpenStreetMap contributors, 2024). Public transport data, such as rail [1] and bus schedules, was collected from official transportation websites (Network Rail, 2024; Department for Transport, 2024). To ensure spatial consistency, all datasets were aligned to the defined catchment areas to support the subsequent analysis. For datasets whose original spatial units did not match the catchment boundaries, data values were allocated based on the proportion of spatial overlap.

4. Methodology

4.1. Constructing a multimodal integrated rail–bus network

To quantify rail–bus integration that goes beyond traditional walkable station catchments, this study develops a multimodal network model that regards rail and long-distance bus services as components of a unified transport system. The model incorporates rail lines, bus routes, and modelled transfer connections. It distinguishes between two primary types of bus–rail integration: direct interurban services that complement rail links between stations, and feeder services that extend access to rail from areas without rail coverage (Arup, 2022; Luke et al., 2018). The established multimodal network supports subsequent indicator development as a basis for understanding multimodal integration at both station and regional levels.

The overall network configuration is illustrated in **Figure 3**. The central panel shows the structure of the Direct Long-Distance Buses (DLD) subnetwork across the entire study region. For simplicity, intermediate stops along these bus routes are not included in the DLD network model. Surrounding the central map, three smaller subfiguress show Long-Distance Feeder Services (LFS) integration at the station level, taking Inverness, Oban, and Ladybank as examples. In these diagrams, green lines represent local feeder routes (under 15 miles), while orange lines denote longer-distance feeders (15 miles or more), following the threshold defined by the UK Department for Transport (GOV.UK, n.d.).

[1] Cross-border rail services such as the Caledonian Sleeper and daytime trains to London were included in the timetable data, and were captured in the indicator of rail routes and rail frequency.

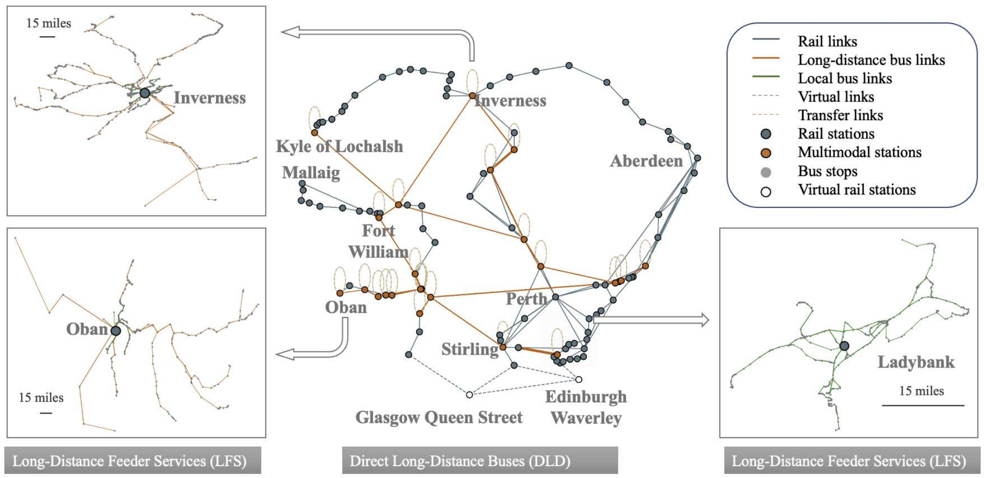

Figure 3: Illustrations of the rail - bus network.

4.2. Multi-criteria analysis framework for evaluating integration

This study adopts a network-based framework of the Node-Place model to evaluate rail-bus integration. As illustrated in **Figure 4**, the framework starts from an explicitly defined multimodal network, in which rail and long-distance bus services are jointly represented. This multimodal network representation enables bus services to be incorporated directly into the assessment of station roles, rather than being considered through simplified catchment assumptions.

Based on the network, three groups of rail–bus integration indicators are derived, namely network centrality, station accessibility and activity-based. In particular, network centrality is measured on a multimodal network that includes both direct bus links and interchange connections, reflecting the role of bus services in linking stations. Station accessibility is measured through bus stop counts, bus routes, and service frequency around each station, capturing the intensity of feeder provision. On the activity side, population is quantified using a travel time-weighted approach, such that demand potential is expressed as a function of network-based access rather than simple spatial proximity.

These rail–bus integration indicators are then incorporated with conventional indicators within this three-dimensional Node-Place structure. Building on the conceptual extension proposed by Nigro et al. (2019), the traditional node dimension is disaggregated into Station Accessibility(SA) and Network Accessibility (NA), allowing local access conditions and wider network roles to be evaluated separately alongside the Activity Index (AI). By integrating these network- and feeder-based indicators within the Node-Place framework, the analysis moves beyond isolated measures to provide an integrated and diagnostic assessment of rail-bus integration.

All network construction and indicator calculations are based on publicly available open data sources, as summarised on the right-hand side of **Figure 4**. Details of the indicator calculation process are provided in **Section 4.4**.

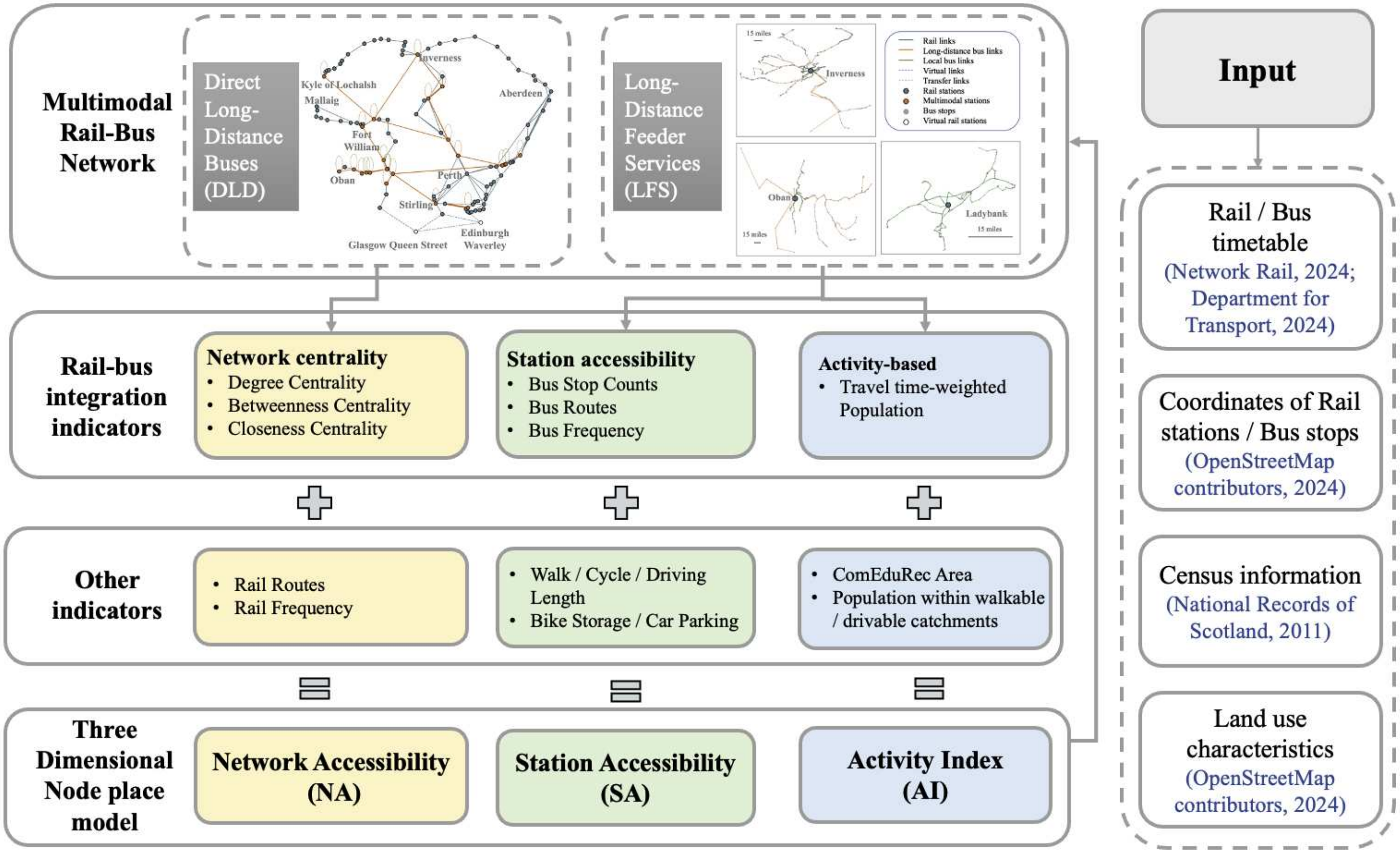

Figure 4: Multi-criteria analysis framework

4.3. Defining multimodal catchment areas for spatial analysis

We define multimodal catchment areas for 102 railway stations in the study area. As shown in **Figure 5**, these catchments represent different ways passengers reach rail services, including a 10-minute driving zone (Type A), a 15-minute walking zone (Type B), and a 7-minute bus–rail transfer zone (Type C) (Ankunda and Venter, 2025; Lauder, 2023; Schakenbos et al., 2016; Tennøy et al., 2022). To prevent overlap between walking and driving zones, an additional category (Type D) captures areas accessible by car within 10 minutes but beyond the 15-minute walking zone. Instead of relying on straight-line buffers, all catchments are computed using network-based travel times, which is more suitable for suburban areas where road layouts and travel times vary significantly (Gao et al., 2022). Besides, this study applies Voronoi diagrams (Thiessen polygons) to assign each location to its nearest station (Yang et al., 2023). While passengers may not always choose the nearest station due to service quality, this method ensures non-overlapping spatial coverage for evaluating station-level accessibility and integration.

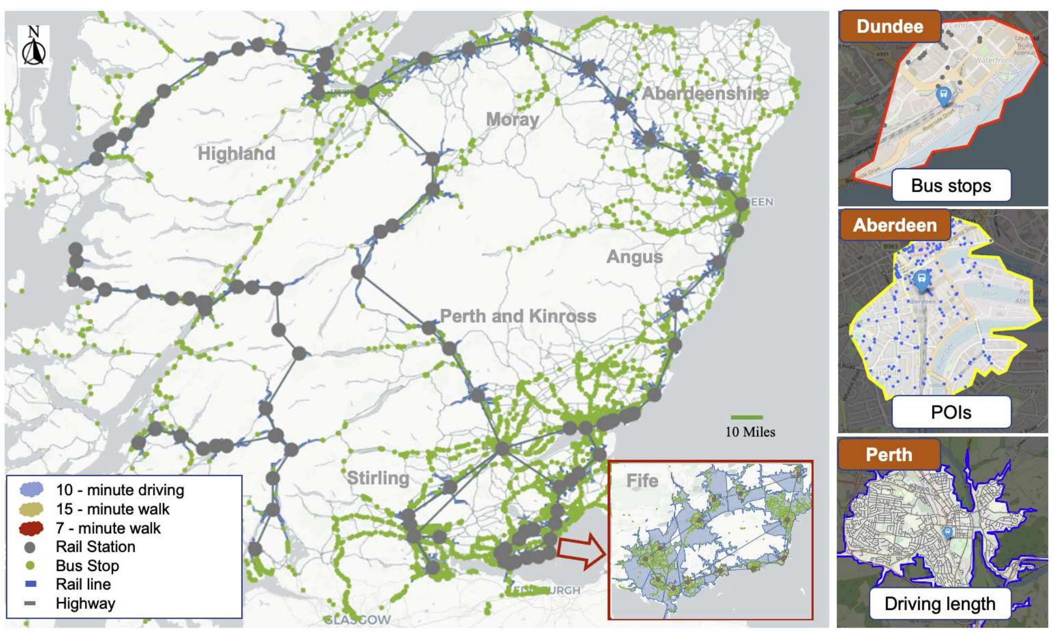

Figure 5: Station-level catchment areas based on network travel times.

4.4. Deriving rail–bus integration indicators from the multimodal network

Network centrality analysis has been applied in node-place studies to examine the structural role of stations within the rail network (Cao et al., 2020; Dou et al., 2021; Liao and Scheuer, 2022; Zhang et al., 2019). In the present studies, we extend this approach to examine how long-distance bus services reshape connectivity within the multimodal network. Degree, betweenness and closeness centrality are computed by modelling the DLD network as an undirected, weighted L-space graph (Von Ferber et al., 2009), in which nodes represent stations and edges represent direct service links. Edge weights are calculated using the Summed Time Penalty (STP) method, which combines the average scheduled journey time with an equivalent time penalty derived from service intervals (Akbarzadeh et al., 2019). The penalties are based on benchmarks in the PDFH and convert different frequencies into perceived time costs (Worsley, 2012). The benchmarks for non-London interurban flows are adopted for this study area. Full definitions and formulas are provided in **Table 1**.

Table 1: Rail-bus integration indicators.

Indicator	**Description**	**Formula**	**Weighting**
Multimodal network with direct long-distance buses			
Degree Centrality (DC)	The proportion of connections a station has to other stations relative to the maximum possible.	$DC_i = \frac{\sum_m \sum_{j\in S, j\neq i} a_{ij}^m}{n-1}$	Inverse of STP
Betweenness Centrality (BC)	The proportion that a station appears on the shortest paths between all pairs of stations in the network.	$BC_i = \sum_{s\neq j\neq i\in S} \frac{\delta_{sj}(i)}{\delta_{sj}}$	STP
Closeness Centrality (CC)	The reciprocal of the sum of shortest-path travel times from a given station to all other stations in the network.	$CC_i = \frac{1}{\sum_{j\in S, j\neq i} d(i,j)}$	STP
Multimodal network with long-distance feeder services			
Bus Stop Counts (BSC)	The number of bus stops within the catchment area.	$BSC_i = \lvert B_i \rvert$	/
Bus Routes (BR)	The number of bus routes passing through the catchment area	$BR_i = \sum_{b\in B_i} br_b$	/
Bus Frequency (BF)	The number of buses departing from catchment area per day.	$BF_i = \sum_{b\in B_i} bf_b$	/

Indicator	Description	Formula	Weighting
Travel time-weighted Population (TTWP)	The total population within bus stop catchment areas along feeder routes, weighted by a travel time decay function.	$TTWP_i = \sum_{b \in B_i} \sum_{f \in FBR_b} \sum_{t \in T_{fi}} P_f \cdot e^{-\alpha t}$	Exponential decay

Notation:
S = set of all stations in the network;
n = total number of stations;
a_{ij}^m = adjacency indicator between station i and j under mode m (1 if a link exists, 0 otherwise);
δ_{sj} = total number of shortest paths between nodes s and j;
$\delta_{sj}(i)$ = number of shortest paths between nodes s and j that pass through node i;
$d(i,j)$ = shortest-path travel time between station i and j;
B_i = set of bus stops within the feeder catchment (Type C) of station i;
br_b = unique feeder routes serving bus stop b;
bf_b = scheduled daily frequency of bus stop b;
FBR_b = feeder bus routes of bus stop b;
f = bus stop f along the feeder bus routes;
T_{fi} = set of travel times from bus stop f to station i (measured in minutes);
P_f = the population located within the catchment area of bus stop f;
α = decay parameter in exponential function, set to 0.01 based on Beria et al. (2017);
STP=Summed Time Penalty, calculated by combining scheduled travel time and the equivalent time penalty derived from service frequency.

To evaluate the effectiveness of LFS integration, this study focuses on two key dimensions: service availability and the travel time-weighted population. These are chosen to capture both the supply side (the presence and intensity of bus services) and the demand side (the potential level of usage based on residential population distribution).

Key indicators in service availability include: (1) the number of bus stops within the station's walking catchment area (Type C), (2) the number of feeder routes serving these stops, and (3) the scheduled daily frequency of those routes. These indicators are commonly adopted in the literature to assess bus service provision around railway stations (Guerra et al., 2012; Cardozo et al., 2012; Gutiérrez et al., 2011). In terms of the demand side, the travel time-weighted population estimates the potential reach of each feeder service by aggregating the populations within the catchment areas (Type C) of all bus stops along the routes. This estimate is adjusted using an exponential distance–decay function to reflect the declining likelihood of reaching the railway station as travel time increases (Beria et al., 2017). The decay parameter is set to 0.01, consistent with the value suggested in the same study. To test the sensitivity of the decay parameter, we compare Activity Index scores calculated using four values (0.1, 0.01, 0.03 and 0.005) through a one-way ANOVA. The results show no statistically significant differences in Activity Index scores ($F = 0.35$, $p = 0.79$), indicating that variations in the decay parameter do not meaningfully affect the results.

4.5. Node-Place based evaluation of multimodal integration

The rail-bus integration indicators are incorporated into an extended Node-Place model to assess each station's role by examining transport provision in relation to surrounding economic and social activities. The other indicators included in the model are widely adopted in previous node-place studies (Cao et al., 2020; Vale et al., 2018; Yang et al., 2022; Zhang et al., 2019). The specific indicators are summarised in **Table 2**, along with descriptive statistics. All indicator values are further transformed using the log(x+1) function to reduce skewness and the influence of extreme values (McCune and Grace, 2002). For illustration purposes, the indicators within each dimension are combined with equal weights to generate the three dimensional scores, consistent with common practice in the existing literature (Cummings and Mahmassani, 2022; Yang et al., 2022). Based on these scores, stations are grouped using K-means clustering, with the number of clusters selected using the elbow method (Rousseeuw, 1987).

Table 2: Node place indicators from three dimensions.

Indicators	**Type**	**Description**	**M ± SD**
Activity Index (AI)			
POIs	B	AI1: The number of points of interest, including landmarks, parks and other significant locations that may attract visitors or residents.	45.08±67.47
ComEduRec Area	B	AI2: The proportion (in %) of an area dedicated to commercial, educational, and recreational uses to the walkable catchment area.	1.86±2.84
Population	B/ D/ C/ C	AI3/ AI4: The number of people living within the walkable/ drivable catchment area. AI5/ AI6: The number of travel-time weighted population within bus stop catchment area along local/ long distance bus routes.	2392±2732/ 5915±10607/ 110764±172825/ 34690± 72361

Indicators	Type	Description	M ± SD
Employment	B/ D	AI7/ AI8: The number of people aged 16 to 74 in employment within the walkable/ drivable catchment area.	1163±1351 2871±5190
Station accessibility (SA)			
Walk Length/ Cycle Length/ Driving length	B/ B/ D	SA1/ SA2/ SA3: The total distance of paths (in kilometer) accessible by walking/ cycling/ driving within the defined catchment areas.	50.44±41.43/ 40.16±30.93/ 117.76±119.99
Bike Storage/ Car Parking	B/ B	SA4/ SA5: The number of bike storage/ car parking spaces within the walkable catchment area.	13.70±13.85/ 53.98±94.79
Bus Stop Count	C	SA6: The number of bus stops within the catchment area.	6.63±7.15
Bus Routes	C/ C	SA7/ SA8: The number of local/ long-distance bus routes passing through the catchment area.	8.15±8.66/ 3.88±5.53
Bus Frequency	C/ C	SA9/ SA10: The number of local/ long-distance buses departing from catchment area per day.	61.42±98.20/ 16.02±31.87
Network accessibility (NA)			
Rail Routes	/	NA1: The number of rail routes passing through the railway station.	2.35±0.95
Rail Frequency	/	NA2: The number of trains departing from the railway station per day.	44.36±54.10
Degree centrality	/	NA3/ NA4: The proportion of connections a station has to other stations to the maximum possible connections in the rail-only/ rail-bus network.	0.0524±0.0261/ 0.0617± 0.0349
Betweenness centrality	/	NA5/ NA6: The proportion that a station appears on the shortest paths between all pairs of stations in the rail-only/ rail-bus network.	0.0968±0.1201/ 0.0516±0.0807
Closeness centrality	/	NA7/ NA8: The reciprocal of the sum of shortest-path travel times from a given station to all other stations in the rail-only/ rail-bus network.	0.0966±0.0260/ 0.1676±0.0361
Abbreviations: M: Mean; SD: Standard Deviation; Type: Catchment area types; POIs: Points of interest; B: 15-minute walking; C: 7-minute walking; D: within a 10-minute driving but outside the 15-minute walking radius			

The framework relies on several modelling assumptions that should be noted when interpreting the results. The indicators representing activity levels, accessibility and network structure are derived from static datasets, meaning that temporal variations, such as peak and off-peak differences, are not fully captured. The approach also summarises station characteristics using aggregated values. Stations with similar dimensional scores may therefore differ in practice, which highlights the need to consider the indicator components when examining individual cases. In addition, the interpretation of balance across the three dimensions depends on the context of application, consistent with the discussion in Nigro et al. (2019). Balance in this study reflects the conditions of the Scottish case area rather than an absolute benchmark. Even so, the structure of the framework remains flexible. Catchment definitions, decay parameters and other indicator settings can be adjusted to different planning needs or data availiability, and additional dimensions may be added when required. These features allow the methodology to be adapted for other regions and integrated into broader multimodal planning exercises.

5. Results and discussion

We apply the new multimodal network-based Node-Place framework to the Scottish case study. We first show how the inclusion of bus routes reshapes network connectivity, leading to the emergence of new cross-regional links and changes in the stations that function as key nodes within the network. We then examine spatial variation in feeder provision by comparing travel time-weighted population with service frequency, showing where coordination between demand and service supply is relatively strong and where potential gaps are present.

These multimodal indicators are subsequently incorporated into the three-dimensional Node-Place model to assess station performance across activity, local accessibility and wider network roles. Clustering analysis is adopted to identify spatial patterns and functional differences among stations. We further demonstrate how dimensional scores change once feeder-based accessibility and multimodal centrality are taken into account, revealing aspects of multimodal integration that are not captured by an ordinary Node-Place model. Finally, we illustrate how the framework can support early-stage planning by exploring the potential effects of co-locating selected bus termini with nearby railway stations.

5.1. Assessment of network centrality in a multimodal network

In many non-metropolitan regions, long-distance buses provide cross-regional links where rail coverage is limited. Comparing centrality values in the rail-only and multimodal networks helps show how additional bus services change the patterns through which stations are connected. These changes may include the appearance of stations acting as new interchange points, shifts in the stations that lie on the main shortest paths, and the emergence of alternative cross-regional connections. To examine these effects, we analyse how degree, closeness and betweenness centrality vary once long-distance bus routes are included in the network.

Degree and closeness value tend to increase or remain the same once bus routes are added because the new routes create additional links and shorten travel paths. Betweenness centrality (BC) shows a different pattern. As shown in **Figure 6**, in the rail-only network (A), several stations along the Highland Main Line and the West Highland Line lie on many of the shortest paths. Once bus routes are added, the shortest multimodal paths change. Compared to earlier studies that only applied rail-based networks in Node-Place analysis (Liao and Scheuer, 2022; Caset et al., 2020), our findings show how adding long-distance bus services can shift centrality toward previously less important stations. In the integrated rail–bus network (B), stations such as Fort William, Spean Bridge, and Pitlochry show increased BC values (red circle). This pattern suggests that small-town stations can play a stronger role in supporting regional mobility once they are connected to the wider bus network. For example, Pitlochry becomes a transfer point linking the Highland region with Perth and Dundee, while Fort William gains additional connections between northern and southern areas. At the same time, some railway stations experience a decline in BC, as bus services introduce alternative routes that bypass them. These shifts reveal that bus integration not only improves access to remote areas but also redistributes network importance.

We also compare edge-level betweenness centrality before and after integrating long-distance bus services to examine how the structure of travel paths changes across the network. In the rail-only network (A), high betweeness edges (thicker lines) are largely aligned along north–south corridors, particularly those connecting Fort William, Inverness, and Dundee to Glasgow. This reflects the dominant orientation of rail travel in the study area. However, the integrated network (B) introduces greater routing flexibility. Connections such as Spean Bridge–Pitlochry–Perth and Crianlarich–Dundee become thicker, illustrating how bus services enhance cross-regional connectivity and reduce dependence on previous rail corridors. These changes indicate that the integrated network has a more even distribution of the routing pathways. The analysis also indicates areas where integration remains limited. Several northern regions continue to exhibit weak east–west connectivity. Likewise, the east coast corridor remains relatively weak in terms of betweenness values.

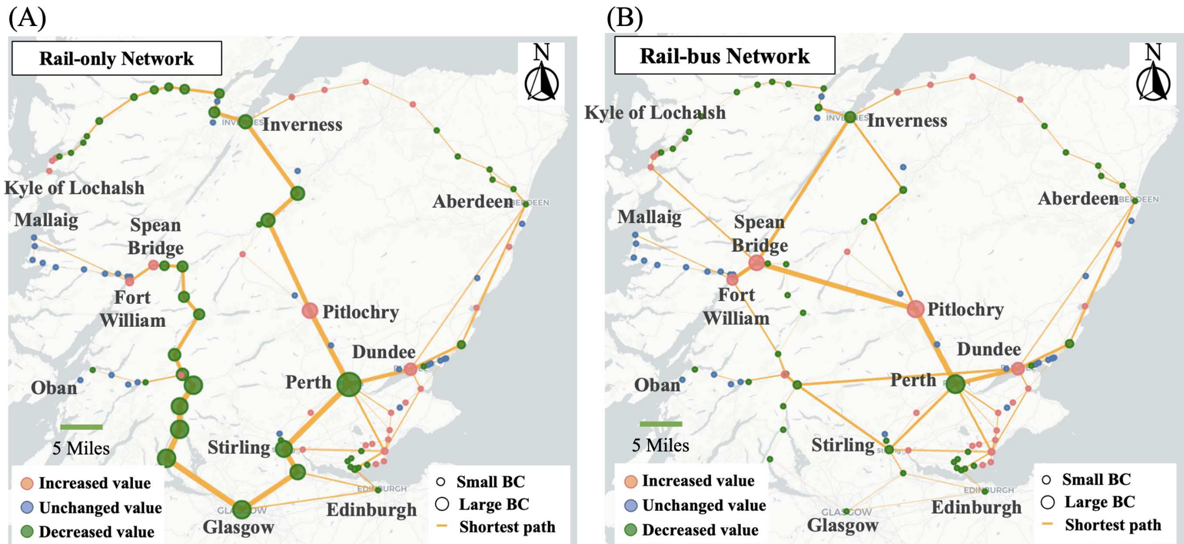

Figure 6: Visualisation of betweenness centrality distribution in the (A) rail-only and (B) rail-bus network.

Identifying these gaps help us identify where better coordination between rail and bus could improve overall connectivity.

5.2. Spatial disparities in long-distance feeder service integration

In this section, we evaluate the integration between railway stations and long-distance feeder bus services using two indicators: the frequency of feeder routes and the population served by these routes, adjusted by a travel time-decay function. This makes it possible to highlight cases where feeder services play an important role in supporting station access when the walkable population is small. It also helps reveal mismatches between potential demand and service supply. Such patterns cannot be observed using walking catchments or single-indicator measures alone.

Figure 7(A) shows clear differences across the study area. Stations such as Aberdeen, Dundee and Stirling have large multimodal catchments and frequent feeder services (Larger, warm-coloured circles). By contrast, stations in sparsely populated regions—particularly in the Highlands—tend to exhibit smaller, cooler-coloured circles, reflecting lower service levels and more limited population coverage. This visualisation helps identify which stations currently act as key integration points, and which ones remain limited in both passenger reach and frequency.

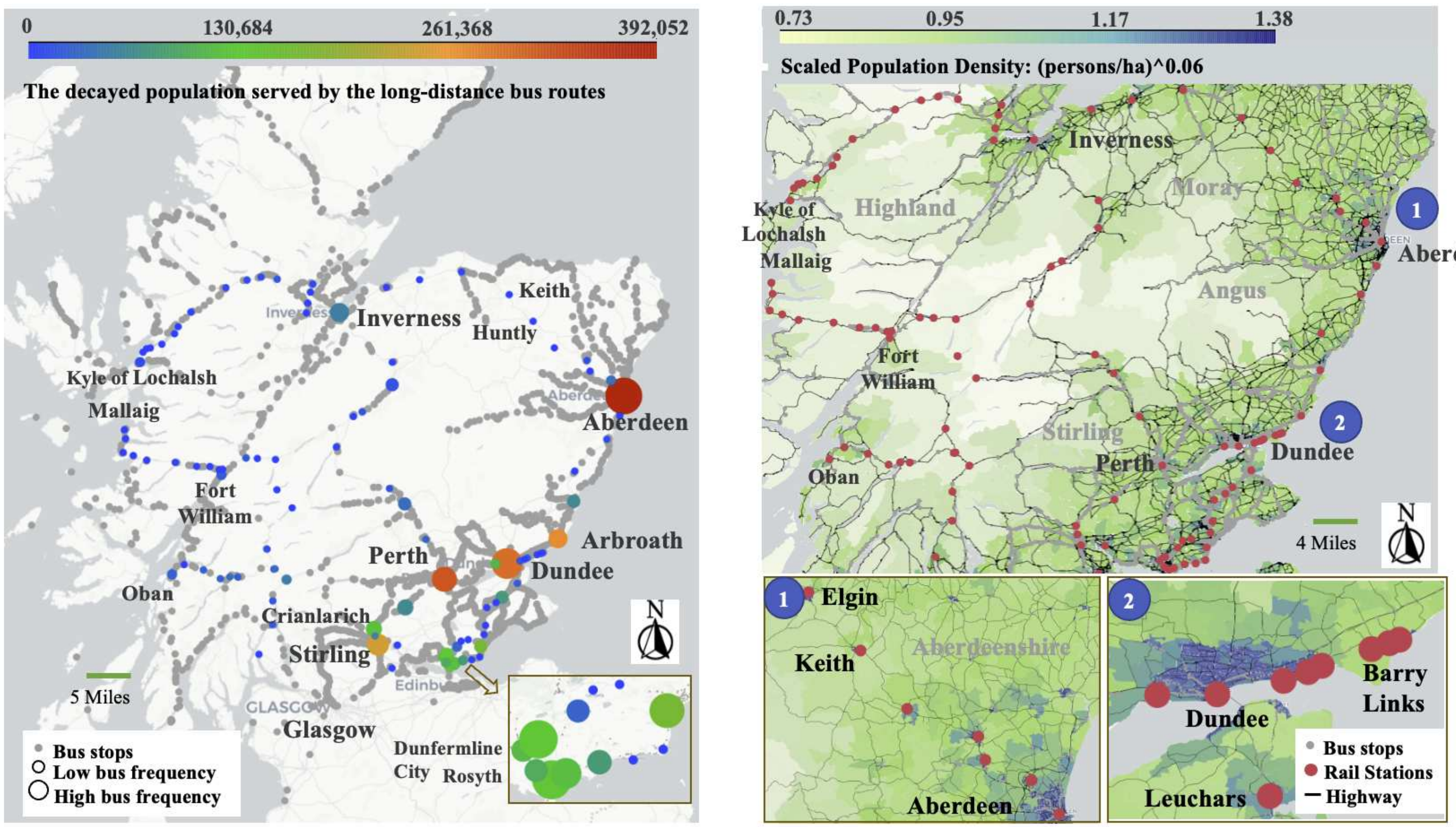

Figure 7: Visualisation of (A) travel time-decayed population served by long-distance feeder buses and their daily frequency at railway stations; (B) population density and transport infrastructure.

We provide background information on population density, road infrastructure, and the spatial distribution of feeder bus stops and railway stations in **Figure 7(B)**[2]. This helps explain whether the spatial distribution of services aligns with where people actually live. Some stations, such as Larbert, Markinch and Nairn, are close to bus stops that are not served by long-distance services. Others, such as Barry Links, Huntly and Keith, lack nearby stops altogether. Distinguishing between these situations helps identify whether weak integration arises from service design or from spatial disconnection. In some situations, low coordination may reflect the presence of a larger hub nearby, which naturally attracts demand from small stations. For instance, residents near Barry Links may prefer accessing the Dundee station, while those near Huntly and Keith may use the Aberdeen station. Such spatial competition could partially explain the low levels of coordination observed at these locations and indicate the complexity of multimodal planning in overlapping catchment zones.

In addition, a comparison between the population served and the frequency of services also indicates several mismatches. For instance, Dunfermline City and Rosyth serve large populations yet receive relatively low feeder frequencies. Perth shows a similar imbalance. These disparities show areas where further investigation may be needed to determine whether current service provision adequately meets local demand needs.

5.3. Evaluating station performance applying the three-dimensional Node-Place model

The multimodal indicators are integrated into a three-dimensional Node–Place structure, which enables each station to be assessed across AI, SA and NA. Specifically, AI captures the potential for generating demand, based on surrounding population size and the availability of local facilities. SA reflects the ease with which passengers can access the station from nearby areas, while NA indicates the station's role in supporting longer-distance travel.

The three dimensions show a relatively balanced structure, as shown in **Figure 8**. AI and SA are strongly correlated (Pearson coefficient=0.886), indicating that areas with higher activity levels also tend to offer better local

[2]The underlying colour represents scaled population density, calculated using a power transformation (population density$^{0.06}$) to enhance visual contrast in the figure.

access. NA, however, shows a weaker correlation with the other two dimensions. These findings indicate that local demand and local accessibility do not necessarily correspond to regional connectivity. Similar patterns were observed by Dou et al. (2021) and Zhang et al. (2019). While these studies focused mainly on urban contexts, our results suggest that similar relationships also exist in non-urban areas.

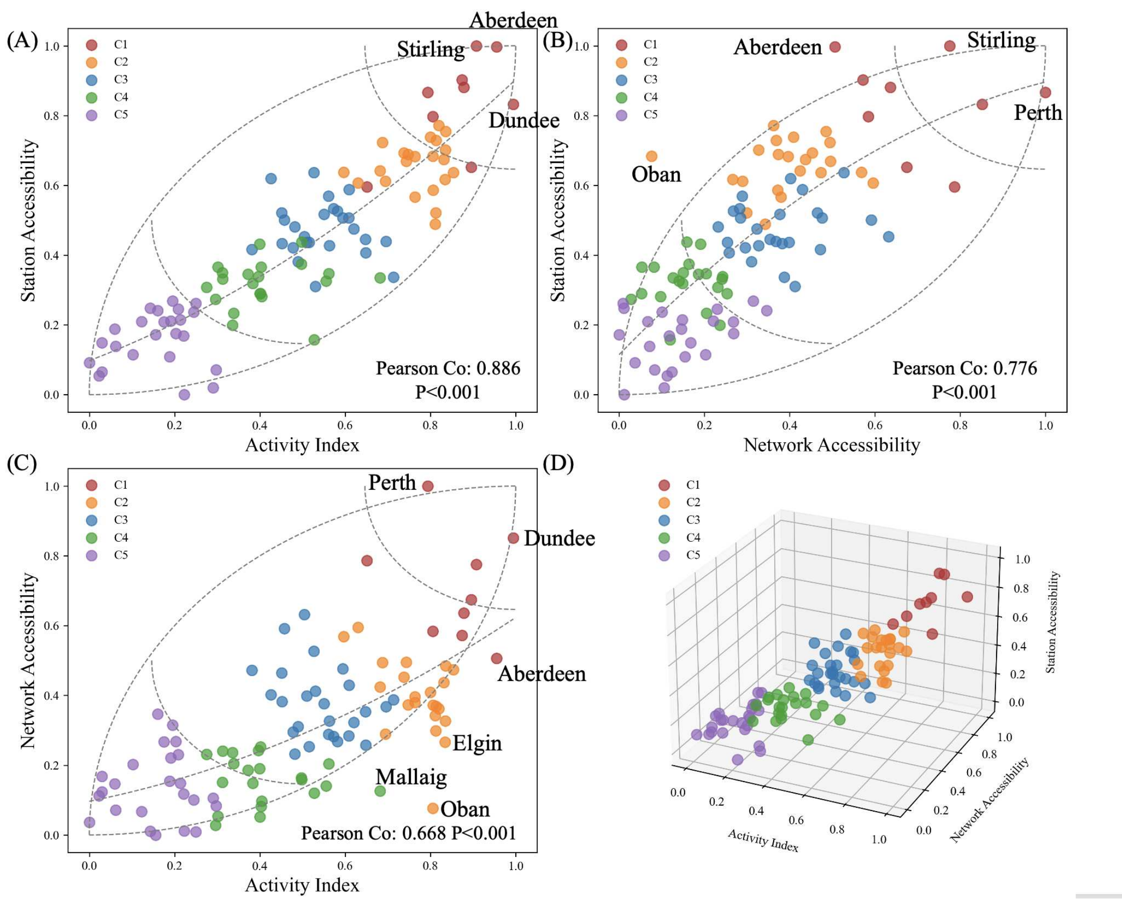

Figure 8: Illustration of the three dimensional node-place indicators.

Cluster analysis groups the stations into five categories (**Figure 8**). Cluster 1 (n = 9) contains stations that score highly across all three dimensions and are located in or close to the stress zone [3]. These stations are mostly found in urban areas and function as major multimodal hubs. Perth, for instance, acts as an important interchange within the rail network, while Inverness supports extensive feeder links to northern settlements including Durness and Kinlochbervie. A special case in Cluster 1 is Pitlochry. Although its scores for SA and AI are low, it is still classified into Cluster 1 because of its high NA score. The station is located along corridors where railways and highways run in parallel, naturally placing them on routes served by both rail and long distance bus services. Similar cases can also be found in Clusters 2 and 3, such as Fort William and Spean Bridge.

Cluster 2 (n = 22) and Cluster 3 (n = 26) are mainly located within or close to the balanced zone of the Node-Place model. Stations in Cluster 2 tend to score higher in AI and SA, with several located slightly outside the balanced curve. This suggests that these stations support strong local activity but remain less integrated within the wider transport network. Many of them are located in Fife and along parts of the East Coast rail corridor, where stations operate on the same railway line and offer similar service frequencies. As a result, their network accessibility values are also similar, largely around 0.4. Some stations in this group, such as Dunfermline City and Dalgety Bay, have AI scores above 0.8. For these locations, improving inter-urban bus connections could help raise their overall network accessibility and meet different types of travel needs. Cluster 3 stations have slightly lower scores across all three dimensions but show a more balanced pattern of development. They are typically located in medium-sized towns or suburban areas.

Spatial patterns of the clusters offer further insight (**Figure 9**). Central stations in Cluster 1 tend to be surrounded by stations from Cluster 2 and Cluster 3. These station groups tend to form small radial patterns, similar to those commonly found in urban transport networks (Zhang et al., 2019; Liao and Scheuer, 2022). Such spatial structures are found across different parts of the study area. This pattern suggests that non-urban regions could benefit from encouraging polycentric development, where multiple centres support each other. This idea aligns with Scotland's National Planning Framework 4, which promotes more balanced regional growth (Scottish Government, 2023).

[3] The "balanced", "stress", and "dependence" zones based on the classification proposed by Bertolini (1999) and were introduced earlier in **Section 2.2**

Cluster 4 (n=21) and Cluster 5 (n=24) are close to the dependence zone of the Node-Place model. These stations are generally located in less developed areas, often in the Highlands or remote rural regions. They typically have lower scores across all three dimensions. Their performance is strongly influenced by geographical constraints and sparse settlement patterns, reducing both demand and service provision.

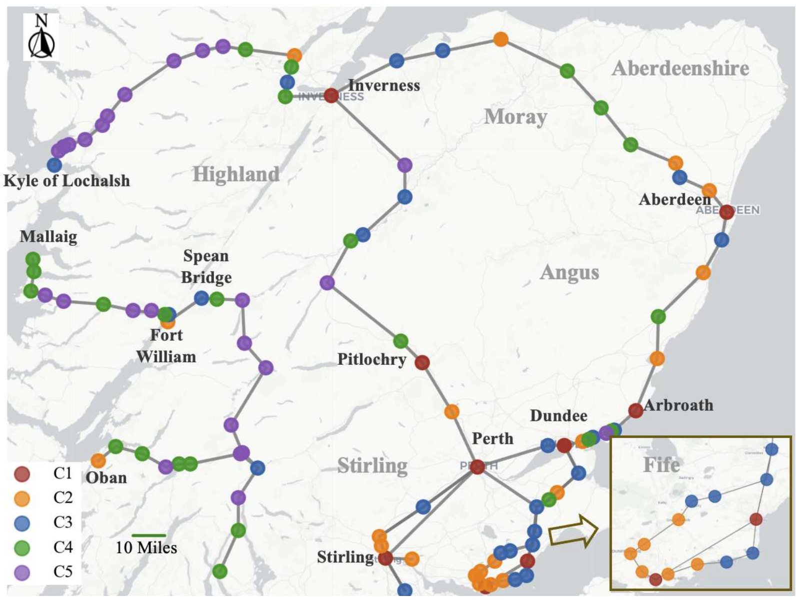

Figure 9: Spatial distribution of clustered railway stations based on Node-Place indicators in the case study area.

However, spatial balance in the Node–Place model does not necessarily imply effective multimodal integration at the station level. As noted by Nigro et al. (2019), the balanced curve functions as a diagnostic reference rather than a normative benchmark. Stations that appear balanced may still perform poorly in practice if interchange conditions are weak. This can be seen in stations such as Keith, Huntly and Barry Links. They fall within the balanced zone of the Node–Place model, yet **Section 4.2** shows that none of them have bus stops within seven minutes of walking distance. Besides, a station that appears balanced in spatial terms may still experience weak integration due to timetable misalignment, long transfer walking distances, service unreliability, fare segmentation or capacity constraints (NEA Transport research and training, 2003; Ewhrudjakpor et al., 2019).

Conversely, stations located outside the balanced curve are not necessarily problematic. Further analysis is needed to understand the underlying causes. For instance, Aberdeen performs well in terms of local activity and accessibility, but its network accessibility is lower. This is mainly due to its strong local bus links within the Aberdeenshire area, where rail accessibility has been reduced by past network closures resulting from the Beeching Cuts. As a result, feeder bus services are mostly concentrated around Aberdeen station. The absence of direct westward highway links limits opportunities for long-distance bus connections to integrate with the Highland Main Line or the West Highland Line, which helps explain its lower NA score. Perth plays an important role in the regional network, yet **Section 4.2** shows that its current feeder services do not match the size of its potential catchment population. These examples show how the framework can point out stations where targeted improvements may be possible. Whether such improvements are feasible would still need to be assessed using further tools such as cost–benefit analysis or geographical feasibility assessment.

These station-level patterns also need to be interpreted in light of the wider institutional context in Scotland. While ScotRail operates most internal rail services under public ownership, long-distance buses remain deregulated and are run by private operators (Preston, 2023). This institutional separation makes network-wide coordination challenging, particularly in relation to timetable alignment and fare integration in the whole area (Tyler, 2022). Because national-level integration is difficult to achieve under these conditions, the extended Node–Place framework provides a practical way to identify gaps at the station and route level. Rather than aiming to optimise the entire network, the framework shows where improvements in local accessibility, feeder connections or interchange conditions are most needed, and where such interventions are likely to have the greater effects.

5.4. Impact of incorporating bus networks on Node–Place scores

To understand how the multimodal indicators change the interpretation of station performance, we examine how they shift the Node–Place dimensional scores (**Figure 10**). Overall, the results show statistically significant changes across the dimensions. For the Activity Index (AI), incorporating bus-accessible populations leads to higher scores across most stations, with a significant paired difference ($p < 0.01$) (**Figure 10(A)**). On average, AI scores rise by 0.0284 once bus catchments are included, reflecting the additional passengers that feeder services bring into station catchments.

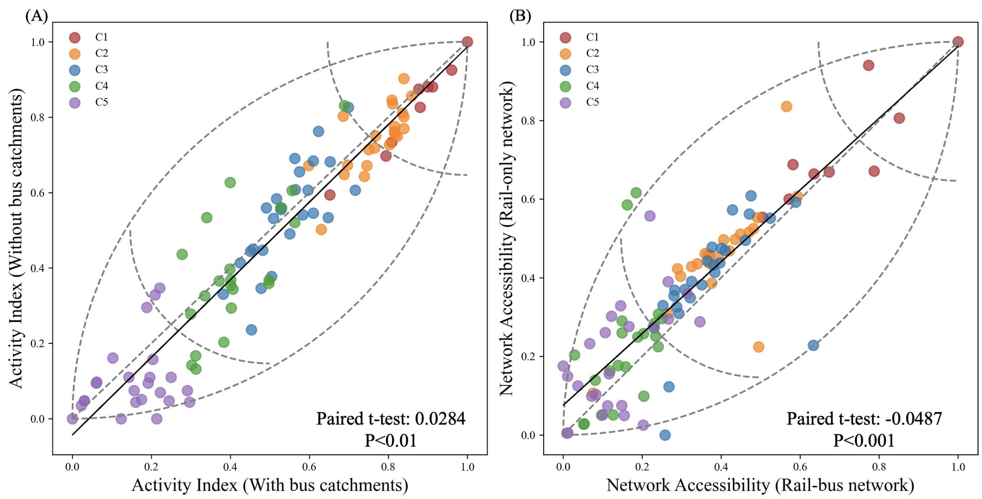

Figure 10: (A) Changes in Activity Index (AI) before and after incorporating bus catchments. (B) Changes in Network Accessibility (NA) between the rail-only and rail–bus networks.

We also compare the Network Accessibility (NA) scores in the rail-only network and in the rail–bus network (**Figure 10(B)**). Paired t-test shows a significant difference ($p < 0.001$), indicating that adding long distance bus links changes how stations function within the transport network, as we discussed in **Section 5.1**. Some of the stations located to the right of the diagonal line, such as Fort William, Spean Bridge, and Pitlochry, show large increases in NA. These stations are connected by long-distance bus routes, thus improving their connections to more station in the network. While urban stations in Clusters 1 and 2 that are already well connected by rail show limited decline, the change is more substantial for stations in Clusters 4 and 5. NA scores based on rail alone may overestimate the network importance of these lower-performing stations. The actual network role could be weaker when bus-based accessibility is accounted.

We further examined the share of bus-related indicators to dimensional scores. The share was calculated as the proportion of bus-related indicators, such as the population covered by feeder routes and bus service frequencies, relative to the total value of AI and SA. **Figure 11** shows a clear regional difference.

In non-urban areas, the share of bus-related indicators is much higher. This suggests that feeder services play an important role in increasing the catchment population and improving access to stations. This pattern supports the idea that bus services are not just an optional service in rural areas. According to Milne and Reid (2022), bus services are essential for maintaining community life and meeting everyday needs in low-density regions. They help people without private vehicles, such as older adults, and low-income groups, to access jobs, services, and social activities. Moseley and Owen (2008) also found that more than a quarter of bus trips in England (outside London) occur in towns or rural areas. In **Figure 11**, stations in urban areas show a relatively small share of bus-related indicators, likely because they already benefit from dense development and nearby services. As most earlier Node–Place studies were based on urban contexts (Peng et al., 2023; Su et al., 2022; Vale et al., 2018; Yan et al., 2020; Zhang et al., 2019), excluding bus-based accessibility may not have had a strong influence on the results. However, if the same framework is applied to rural stations excluding bus services, it may misrepresent the Node–Place assessment by underestimating both activity levels.

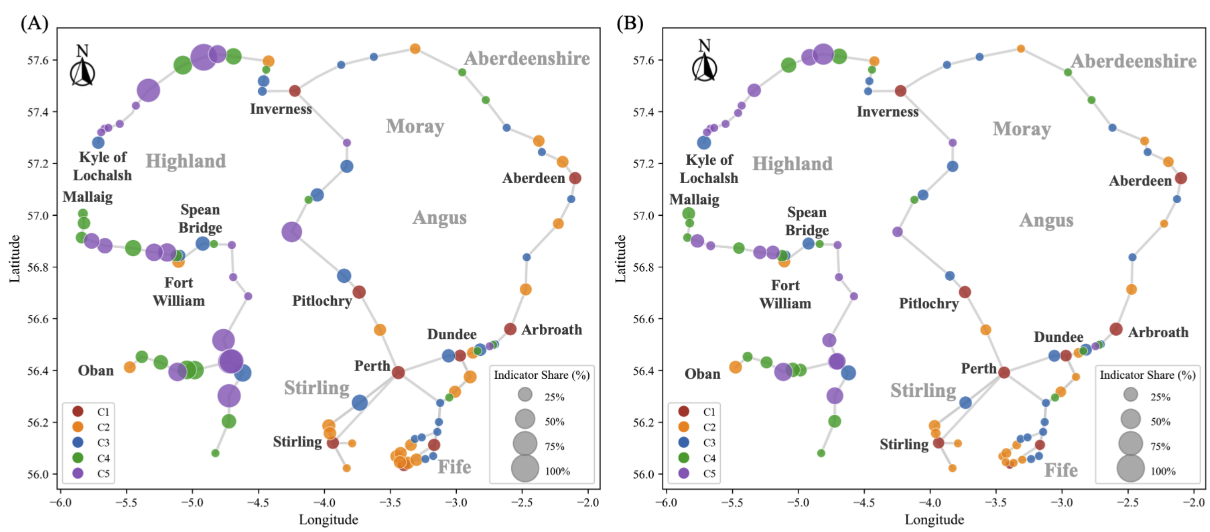

Figure 11: Spatial distribution of indicator shares in Node-Place dimensions. (A) Time-weighted population along bus routes in Activity Index. (B) Bus frequency in Station Accessibility.

5.5. *The effects of bus terminus relocation on station integration*

To explore the potential benefits of improved spatial integration, we conducted a simulation by estimating how the AI, SA, and NA scores would change if selected bus termini were relocated to nearby railway stations. Within the study area, there are 11 major bus termini [4]. We found that 8 were already within walking distance (Type C), while 3 were located further away. These include Dunfermline City, Dundee, and Elgin. In the simulation, we assumed these three bus termini were moved to be co-located with their respective railway stations. Based on this assumption, we reassigned all bus routes, service frequencies, and population coverage originally associated with these termini to the new rail-adjacent location. The indicators were then recalculated using the same method described earlier. The resulting score changes are illustrated in **Figure 12** with directional arrows.

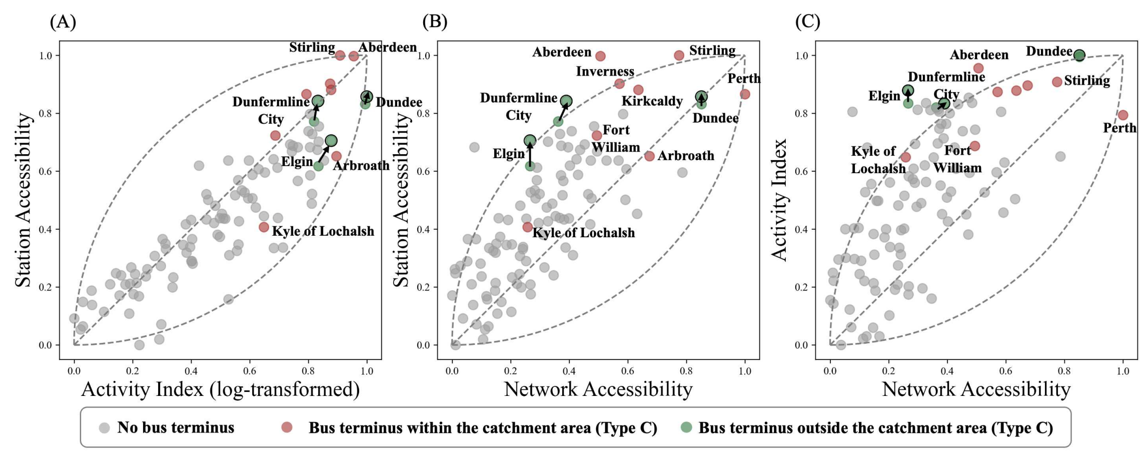

Figure 12: Impact of bus termini relocation on multi-dimensional station performance.

Specifically, Dunfermline City contains 14 bus stands, Dundee has 9, and Elgin has 6. For all three stations considered, relocating the bus termini

[4]Aberdeen, Inverness, Stirling, Kirkcaldy, Dunfermline City, Fort William, Elgin, Arbroath, Kyle of Lochalsh, Perth, Dundee

appears to enhance both AI and SA scores. This is because the presence of a nearby bus terminus is expected to increase the number of available bus services, and thereby attracting additional potential passengers. In the case of Dunfermline City, the NA score also improves due to the introduction of a new long-distance bus route (Dunfermline Queen Margaret-Dunfermline City–Alloa), which increases the station's network centrality.

It is also observed that, following the proposed relocation, three stations slightly fall outside the balance curve, moving in the opposite direction to NA. However, this does not imply that the integration strategy is inappropriate. Rather, the Node-Place model should be understood as a diagnostic tool for identifying potential mismatches between transport connectivity and surrounding activity. The classification of stations as 'balanced' or 'unbalanced' based on the curve is not absolute, but should be interpreted in relation to the specific context and used to guide targeted improvements (Nigro et al., 2019). In the case of Elgin and Dumfernline City, the result may indicate a need to strengthen its network accessibility, such as by introducing new regional connections. Once such improvements are in place, the co-location of rail and bus services could further enhance multimodal connectivity and support more balanced station performance across all three dimensions.

6. Conclusion

In the present study, we propose a new multimodal network-based Node–Place framework that brings rail and long-distance bus networks into a single analytical structure. For the first time, an integrated rail–bus network is introduced into a node-place model that explicitly represents long-distance bus links, feeder catchments and interchange connections. By deriving a travel time-weighted population measure and multimodal centrality indicators, the framework enables a more comprehensive evaluation of station activity, accessibility and network roles. It is particularly relevant in non-metropolitan and low-density contexts, where access to rail depends largely on bus services.

The results show that excluding feeder-based accessibility leads to systematic bias in Node–Place assessments. Comparisons between rail-only and multimodal analyses reveal statistically significant changes in both Activity Index and Network Accessibility once long-distance bus routes and feeder catchments are included. Stations in rural and small-town areas are shown to serve substantially larger populations and to perform different roles within the network than suggested by rail-only analyses. The indicator-share analysis further confirms that bus-related indicators account for a much larger proportion of activity and accessibility dimensional scores in non-urban areas.

Beyond these score shifts, the framework reveals several ways in which rail–bus integration shapes station performance and regional connectivity. The multimodal centrality analysis shows that incorporating long-distance bus services redistributes betweenness and edge-level routing importance across the network. This creates new cross-regional paths and strengthens the network roles of several small-town stations that appear less central in rail-only networks. The feeder integration assessment further highlights spatial disparities in service coordination. Some stations have small walkable populations but rely heavily on feeder services for access. When these multimodal indicators are considered within the new three-dimensional Node–Place structure, the cluster results reveal functional differences across stations. These patterns distinguish major multimodal hubs from stations in remote areas that are constrained by sparse settlement patterns and limited service provision. Importantly, the balanced curve should be interpreted as a diagnostic reference rather than the benchmark of successful multimodal integration. Several stations located within the balanced zone still exhibit weak interchange conditions, including the absence of nearby bus stops. By contrast, some stations outside the curve reflect geographical or historical constraints rather than integration failures.

It should also be noted that the framework can be adapted for different planning priorities or policy targets. For example, the conclusions of this study are based on the defined catchment areas, which can be adjusted to reflect local walking or driving conditions. Decay parameters can also be calibrated using behavioural or empirical data. Because all indicators rely on open data sources, the method can be transferred to other regions where similar datasets are available. This applies not only to rural areas but also to urban settings. In addition, the model supports the visualisation of integration outcomes, which can assist planners in identifying where multimodal improvements may be most effective.

This study has several limitations that should be acknowledged. First, all indicators within each Node–Place dimension were assigned equal weights to maintain transparency in indicator construction, consistent with many previous Node–Place studies (Liao and Scheuer, 2022; Yang et al., 2022). Future research could explore alternative weighting schemes based on expert judgement or statistical methods. Second, the analysis focuses on rail–bus integration and does not include other transport modes, such as ferry services and airport links. These modes form an important part of regional connectivity and may partly explain the relatively strong accessibility scores observed at stations such as Oban and Mallaig. Incorporating these modes in future work would allow a more comprehensive assessment of multimodal accessibility. Future work will also develop a station-level demand model to quantify how rail–bus integration influences rail ridership, providing further evidence to support transport planning and policy decisions.

Declaration of competing interest

There are no conflicts to declare.

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