# Beyond Access: A Grid-Based Framework for Measuring Service Levels and Inequity in Multimodal Public Transit

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**Abstract**
Conventional transport studies, focused on accessibility, often fail to capture the actual service levels and spatial inequity of public transport. This study develops a novel grid-based multimodal multiplex network framework for South Korea to overcome these limitations. Using nationwide GTFS data, we model each transport mode as a distinct layer on a 1km² grid, incorporating service frequency as a weight to measure service levels. The analysis reveals extreme spatial polarization: service levels are overwhelmingly concentrated in metropolitan cores while vast non-urban areas experience severe service deprivation. This framework provides a robust tool for diagnosing transport inequity with high precision, offering data-driven evidence for policies aimed at building a more inclusive and sustainable transport system.

**Keywords:** Multimodal Public Transport, Multiplex Network, Spatial Accessibility, Spatial inequality, Nationwide spatial analysis

## 1. Intrduction

Transportation services are fundamental to urban functionality, acting as the circulatory system that facilitates the flow of goods and people and enables complex social interactions. Public transport, in particular, is critically important as it provides a broader range of citizens with equitable access to urban opportunities and the freedom of mobility (ITF-OECD, 2023).

Modern cities rely on Public Transport Networks (PTNs) to achieve efficient and sustainable mobility (Kujala et al., 2018). These networks have become critical infrastructure in cities worldwide, offering access to essential services such as employment, education, and healthcare, thereby facilitating diverse activities and social interactions (ITF-OECD, 2023).

In response to rapid urbanization and growing transportation demand, public transport plays a vital role in supporting urban growth and sustainable development (Ding et al., 2019). By enabling large-scale commuter flows, it serves as the foundational infrastructure essential for sustaining core urban functions and enhancing the sustainability of metropolitan areas.

However, despite their importance, PTNs, as complex networks, are inherently characterized by an uneven distribution of service (Mouronte-López, 2021). This structural imbalance, wherein a few hub nodes account for a disproportionate share of network connectivity, not only leads directly to issues of network vulnerability and robustness but also extends to create disparities in service levels and accessibility.

Transport networks fulfill the critical roles of connecting key locations and providing the urban-wide framework for interaction. However, access times from residential areas to essential services and transport facilities vary significantly by region type (Bae et al., 2016).

Specifically, urban areas, with their close proximity to public transport stops and stations, tend to have lower car dependency. In contrast, most low-density regions, such as rural townships (eup and myeon areas), exhibit higher car dependency due to poor public transport accessibility. This reflects a stark disparity in the spatial coverage and service density of PTNs between urban and non-urban areas.

This uneven distribution of transport services risks exacerbating the vulnerability of specific demographic groups. The high demand for subsidized transport options, such as welfare taxis and Demand-Responsive Transit (DRT), in low-income and low-service-density areas serves as empirical evidence of this service imbalance (Kim G. et al., 2019).

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As the demand for mobility is derived from the need to access opportunities (ITF-OECD, 2023), a lack of transport services can exclude people from participating in educational, employment, and various social and leisure activities. This issue transcends a mere physical deficit of transport services, leading to severe socio-economic imbalances such as heightened inequality, restricted access to essential services, and hindered regional development.

In rapidly urbanizing areas where economic gaps are widening, the uneven spatial distribution of social resources can intensify feelings of deprivation among vulnerable populations. This, in turn, may trigger psychological changes and social discontent, potentially affecting social stability (Han, C. et al., 2019). Crucially, the gap in transport accessibility between urban and non-urban areas—which diminishes quality of life and constrains opportunities for social participation—poses a direct threat to the realization of transport rights and social equity (Han, C. et al., 2019; Kujala et al., 2018; Mo C. et al., 2013).

On the other hand, as car-centric urban environments create persistent problems such as traffic congestion and pollution, the importance of public transport is ever-increasing. However, existing methodologies for evaluating Public Transport Networks (PTNs) have significant limitations in capturing the complexity of real-world urban transport systems.

Approaches centered on Origin-Destination (OD) data focus primarily on pairwise connectivity between locations, failing to reflect the overall structural properties of the network or actual service operations data (Koo et al., 2024). Consequently, analyzing a transport network based solely on physical links overlooks the service connectivity actually experienced by users. This leads to a loss of critical information, which not only diminishes analytical accuracy but also hinders the formulation of effective policies (Hong D. et al., 2014).

Furthermore, a substantial body of research in transport network analysis has concentrated on evaluating the performance or structural characteristics of single-mode networks. While this approach can be useful for analyzing the efficiency of a specific transport mode, it overlooks the reality that urban travel occurs within a multimodal environment (Hong J. et al., 2019). Specifically, these models have a fundamental limitation in their inability to adequately incorporate user choices and inter-modal connectivity that arise during the transfer process.

Another fundamental reason why existing network analyses fail to capture real-world complexity lies in their methodological choices: namely, the selection of spatial units for analysis and an overemphasis on the dimension of accessibility. Many previous studies, driven by convenience or data availability, have utilized administrative districts such as eup, myeon, and dong as nodes or units of spatial aggregation (Hwang M. et al., 2023; Byeon P. et al., 2016; Park G. et al., 2023; Jang D. et al., 2015). This approach is inevitably subject to the Modifiable Areal Unit Problem (MAUP). This means that analytical results can vary significantly depending on the scale and shape by which a region is partitioned and aggregated, which in turn poses a serious threat to the reliability and generalizability of the findings.

Administrative boundaries rarely align with actual travel behaviors or the spatial distribution of urban functions (Kim J. et al., 2019; Hwang M. et al., 2023), and their areas vary widely even within the same hierarchical level. Consequently, constructing and analyzing networks based on these arbitrary boundaries inherently limits the ability to capture micro-spatial patterns and carries a significant risk of distorting analytical results.

Furthermore, accessibility in public transport is typically defined by the mere presence of physical infrastructure and the potential reach it provides. While the goal of enhancing spatial accessibility through infrastructure improvements is commendable, it overlooks a critical dimension of service quality. For instance, even if a transport service allows for a 15-minute trip to another area, it is of little practical value if the actual service volume is insufficient. The essence of public transport lies not merely in providing the possibility of movement, but in guaranteeing the freedom and quality of mobility. Therefore, examining the quantitative dimension of available services, in addition to their qualitative aspects, becomes a critical subject for investigation.

To address these limitations, this study first redefines user-centric service in terms of the **"Through-Route"**: the set of all pairs of stops that can be reached on a single, transfer-free journey. This concept will serve as the fundamental unit of connection (the link) in our network analysis. Furthermore, to reflect the complex interactions and transfers between various transport options, this study will construct a multi-modal network by leveraging a **multiplex network** structure—a powerful analytical framework from complex network theory. In this model, each mode of transport (e.g., bus, subway, rail) constitutes a distinct layer, while inter-layer connections representing transfers are established through shared grid-based nodes.

To further enhance analytical reliability and spatial resolution, this study diverges from the common practice of using arbitrary administrative boundaries. Instead, we employ a uniform 1km² grid across the entire nation as the fundamental spatial unit. Each grid cell functions not only as a proxy for a "public transport living zone" but also as a node in the multimodal network model. This large-scale network will be constructed using a comprehensive, nationwide public transport database based on the General Transit Feed Specification (GTFS), thereby relying on big data rather than on samples or estimations.

Moreover, for the links connecting these nodes, our model incorporates service frequency as an additional weight, moving beyond traditional metrics like distance or time. This approach allows us to examine not only the mere possibility of movement but also to investigate the freedom and quality of mobility available to citizens. This framework will provide a robust foundation for effectively embedding the high-resolution mobility patterns and activity information afforded by big data into our unit of analysis. On this methodological basis, this study seeks to address the following research questions:

1. How can a multimodal public transport network model be constructed to holistically integrate various transport modes and the dynamics of their transfers?

2. When analyzed using the proposed high-resolution, grid-based model, what is the spatial distribution of public transport service quality, and what novel perspectives does this offer compared to conventional analyses based on administrative units?

3. What are the policy implications of incorporating the quantitative dimension of service level into traditional, accessibility-focused public transport analyses?

In conclusion, this study proposes a novel analytical framework—a grid-based, multimodal public transport network analysis—designed to overcome the methodological limitations of prior research. Through this framework, we aim to achieve a comprehensive understanding of the complex structural properties of the nationwide multimodal public transport network, the spatial distribution of its service levels, and the quantitative aspects of service that extend beyond conventional accessibility analysis.

This endeavor, by integrating insights from complex systems science, spatial analysis, and transport planning, seeks to deepen our understanding of urban transport systems. It aims to inform effective policy directions for promoting sustainable urban development and transport inclusion. The findings are expected to contribute by precisely identifying transport-disadvantaged areas, providing data-driven evidence for the efficient allocation of limited resources, and ultimately, suggesting concrete improvements to route planning and transfer systems to mitigate regional service disparities.

## 2. Literature Review

### 2.1 Introduction

This chapter builds the theoretical foundation for this study by critically reviewing the literature on public transport performance and equity. It delves into three core research streams to establish the necessity and originality of the proposed framework.

First, it traces the conceptual shift in transport planning from mobility to accessibility and, more recently, to equity and justice, arguing that conventional accessibility metrics are insufficient and a Level of Service (LoS) perspective is required.

Second, it interrogates the limitations of prevailing network models, demonstrating why multi-layer network theory offers a more robust alternative to single-mode or aggregated representations.

Third, it examines the Modifiable Areal Unit Problem (MAUP) as a persistent challenge in spatial analysis and validates the methodological superiority of a grid-based framework.

Through this review, the chapter identifies a critical gap at the intersection of these domains and culminates by presenting the academic and policy significance of this study's integrated approach.

### 2.2 From Accessibility to Equity and Level of Service

#### 2.2.1 The Normative Shift in Transport Planning

The core paradigm of transport planning has undergone a decisive shift from a "mobility-centric" approach, which prioritizes vehicular flow, to an "accessibility-centric" one that emphasizes connectivity between people and places (Cervero, 2005). This reframed transport systems as social institutions that directly impact quality of life and opportunity, prompting calls in contexts like South Korea to reorient infrastructure policy from efficiency toward equity (Jang et al., 2015).

More recently, this evolution has progressed further, establishing transport equity and spatial justice as central academic and policy agendas (Ruiz-Pérez et al., 2023). This discourse moves beyond simple resource allocation to scrutinize how transport systems may cause or exacerbate the social exclusion of vulnerable populations (Pereira et al., 2021; Smith et al., 2018).

This concern is prominent in South Korean policy, where concepts like the "Transport Inclusion Index" and "inclusive mobility" have been developed to address accessibility gaps and counteract new forms of inequality (Bae et al., 2016; KOTI, 2022). Consequently, ensuring equitable access to essential opportunities for all citizens stands as a core normative goal of modern transport policy.

#### 2.2.2 The Limits of Conventional Accessibility Metrics

While traditional accessibility measures, such as cumulative opportunity and gravity models, have been instrumental in visualizing the uneven distribution of opportunities (Rodrigue et al., 2013), they suffer from several pronounced limitations.

First, they focus on potential reachability while overlooking the actual level of service. The mere existence of a network connection does not guarantee high-quality service (ITF-OECD, 2023). This limitation is starkly illustrated by the problem of "ghost buses"—routes with such low frequency as to be practically unusable. This disconnect suggests that conventional efficiency-driven logic, such as cost-benefit analysis, can create structural problems by failing to adequately consider regional equity, sometimes leading to unintended consequences like the "straw effect" where investment in core areas drains vitality from the periphery (Kim et al., 2020).

Second, and relatedly, they fail to integrate the quantitative dimension of service, particularly operational frequency. As frequency directly impacts user waiting times and travel flexibility, its omission leads to analyses largely disconnected from the actual user experience (Han et al., 2019). Recognizing this, transport authorities have begun to advocate for "minimum service standards" that include frequency as a key component (Kim et al., 2020).

#### 2.2.3 A New Perspective: Integrating Level of Service (LoS)

To overcome these limitations, this study argues that integrating a Level of Service (LoS) perspective is essential. LoS is a multidimensional concept representing the quality and quantity of transport service, with operational frequency as a core, measurable indicator. The increasing availability of standardized public transport big data like the General Transit Feed Specification (GTFS) makes such LoS-based analysis practically feasible (Kujala et al., 2018). GTFS timetable data allows for the extraction of service frequencies, enabling weighted network analysis that reflects the actual supply of service (Háznagy et al., 2018; Ha & Lee, 2017). This integration is the crucial step to realizing the philosophy of "Beyond Access," shifting the focus from supplier-side infrastructure to the quantity and quality of service that users actually experience.

### 2.3 Representing Multimodal Complexity

#### 2.3.1 Network Science as an Analytical Toolkit

Network science provides a powerful toolkit for quantitatively analyzing the underlying topological properties of transport systems, which can be abstracted as a set of nodes and links (Newman, 2018). Centrality analysis, in particular, is widely used to identify critical hubs and transfer points (Ding et al., 2019), and has been applied extensively in the South Korean context (Koo et al., 2024; Hong et al., 2019). Furthermore, these tools are used to assess network robustness and vulnerability by simulating the impact of node or link failures (Mouronte-López, 2021; Meng, 2024).

#### 2.3.2 The Challenge of Multimodal Representation

Despite the utility of these tools, their application has been hampered by two conventional limitations in representing real-world multimodal systems. First is the oversimplification of the network through aggregation. Aggregating distinct transport modes into a single layer has been empirically shown to severely distort structural properties and produce critical analytical errors, as it erases the unique operational characteristics of each mode (Aleta et al., 2017). Second is the bias toward single-mode analysis, which overlooks the complementary relationships between different modes and fails to model the complex dynamics of transfers. These modeling failures contribute directly to the disconnect between measured accessibility and the actual LoS experienced by users.

#### 2.3.3 The Alternative: A Multi-layer Network Framework

The most promising alternative is the multi-layer network framework, which models different transport modes as distinct but interconnected layers (Alessandretti et al., 2022). This approach is methodologically superior as it: (1) preserves the unique characteristics of each transport mode (Aleta et al., 2017); (2) enables a sophisticated modeling of transfer dynamics through inter-layer links, which is crucial for assessing system-wide properties like resilience (Xu & Chopra, 2023; Ma et al., 2019); and (3) facilitates a more realistic measurement of service level by simulating journeys across multiple modes (Baggag et al., 2018; Alessandretti et al., 2016). Therefore, this study adopts the multi-layer framework as a necessary choice to represent the complexity of the multimodal system with greater precision.

### 2.4 The Dilemma of Spatial Analysis

#### 2.4.1 The Modifiable Areal Unit Problem (MAUP)

The selection of a spatial unit for analysis is a critical decision that decisively influences research findings. The conventional use of administrative districts is subject to the Modifiable Areal Unit Problem (MAUP), a persistent challenge in spatial science where analytical results change depending on the scale and zonation of the units used for aggregation (Rey & Franklin, 2022). This practice is problematic because administrative boundaries rarely align with actual travel behavior, vary drastically in size and density, and mask micro-level patterns, thereby posing a serious threat to analytical reliability (Bae Y. et al., 2016; Hwang M. et al., 2023).

#### 2.4.2 The Alternative: A Grid-Based Framework

To overcome MAUP, this study adopts a uniform grid-cell as the unit of analysis. This approach is superior for three reasons. First, it ensures objectivity and comparability by mitigating scale and zonation biases. Second, it holds theoretical validity by employing a systematic and neutral “spatial container” to analyze human mobility, which is known to be constrained by geographic context rather than being scale-free (Alessandretti et al., 2020). Third, it aligns with cutting-edge research trends, both internationally and domestically, where grid-based analysis is becoming a standard for leveraging high-resolution data (Hwang M. et al., 2023; Ha & Lee, 2017). The combination of this grid-based framework with the multi-layer network model constitutes the core methodological innovation of this study.

### 2.5 Synthesis and Originality of the Study

This critical review reveals that while the fields of transport equity, network science, and spatial analysis have advanced, they have largely proceeded in disconnected silos. A critical research gap emerges at their intersection: there is an absence of an integrated framework that can simultaneously (1) measure the quantitative level of service, (2) capture multimodal complexity, and (3) overcome the MAUP with a precise spatial unit.

Therefore, this study aims to fill this gap by proposing and applying a Grid-Based Multimodal Multiplex Network Framework. This novel approach simultaneously addresses the three core challenges by incorporating service frequency into a multi-layer network built upon a uniform grid. This integrated framework will enable the identification of service-vulnerable areas with unprecedented precision, broadening the methodological horizons of transport planning and contributing significantly to policies aimed at promoting national balanced development and transport inclusion.

## 3. Methodology

This chapter details the methodology designed to diagnose the spatial performance and equity of the nationwide multimodal public transport network in South Korea. The methodology comprises three main parts. First, it describes the process of constructing a nationwide, multi-layer public transport network database by integrating various data sources into a standardized format. Second, it establishes the analytical framework by defining a comprehensive set of indicators to measure the network's efficiency, connectivity, and accessibility. Finally, it outlines the process for identifying transport-vulnerable areas by synthesizing these multifaceted indicators.

### 3.1 Research Framework and Process

This study adopts a systematic research process, as illustrated in Figure 3.1, to overcome the limitations of prior research and to address the proposed research questions. The process consists of four main stages: (1) data collection and preprocessing; (2) construction of the multiplex network model; (3) calculation and analysis of network indicators; and (4) interpretation of the results and formulation of policy recommendations. Each stage is sequentially and logically linked to the results of the preceding stage, ensuring the reproducibility of the research and the reliability of the analytical results.

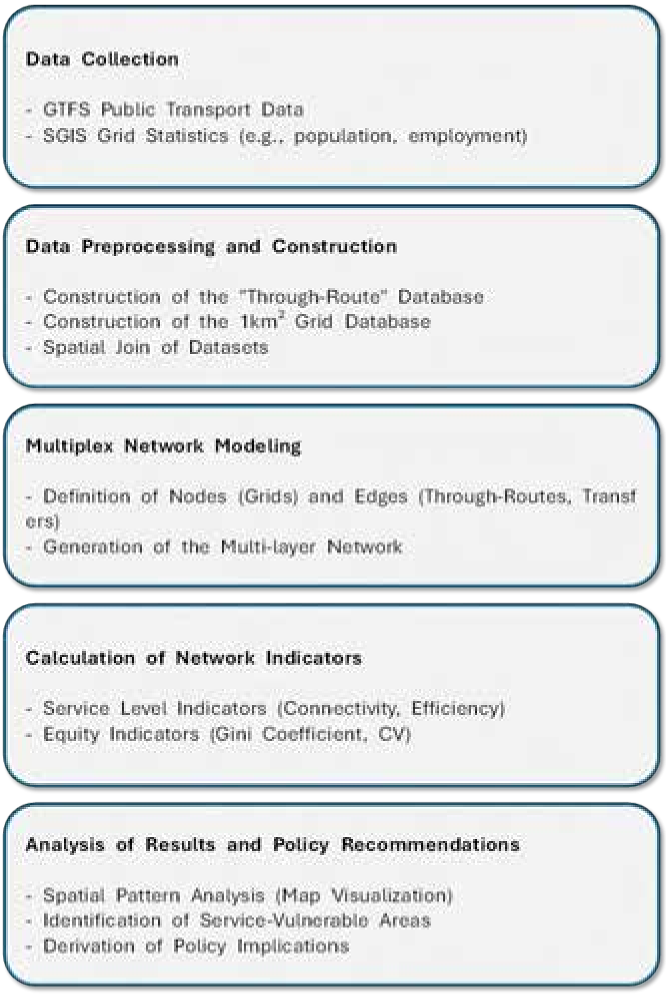


**Figure 3.1** Research Process Flowchart

**3.2 Data Construction and Preprocessing**

A reliable, detailed, and standardized database is a prerequisite for a nationwide analysis of a multimodal public transport network. To this end, this study integrates "Through-Route" information for each mode of transport—derived from TMAP's public transport data which adheres to the General Transit Feed Specification (GTFS) format—with grid-based socioeconomic data from various public and private sources. This process aims to establish a clear and robust foundation for the network analysis.

**3.2.1 The GTFS-Based Nationwide Public Transport Database**

The foundational data for this research is a 2024 nationwide GTFS dataset provided by TMAP. As a global standard for publishing public transport schedules and associated geographic information, the relational structure of GTFS, comprising files such as stops.txt, routes.txt, trips.txt, and stop_times.txt, allows for a detailed reconstruction of the transport network's spatial and temporal dimensions. The dataset covers the entirety of South Korea and is highly multimodal, including not only intra-city modes like local buses and subways but also inter-city modes such as express/intercity buses, rail, maritime services, and aviation.

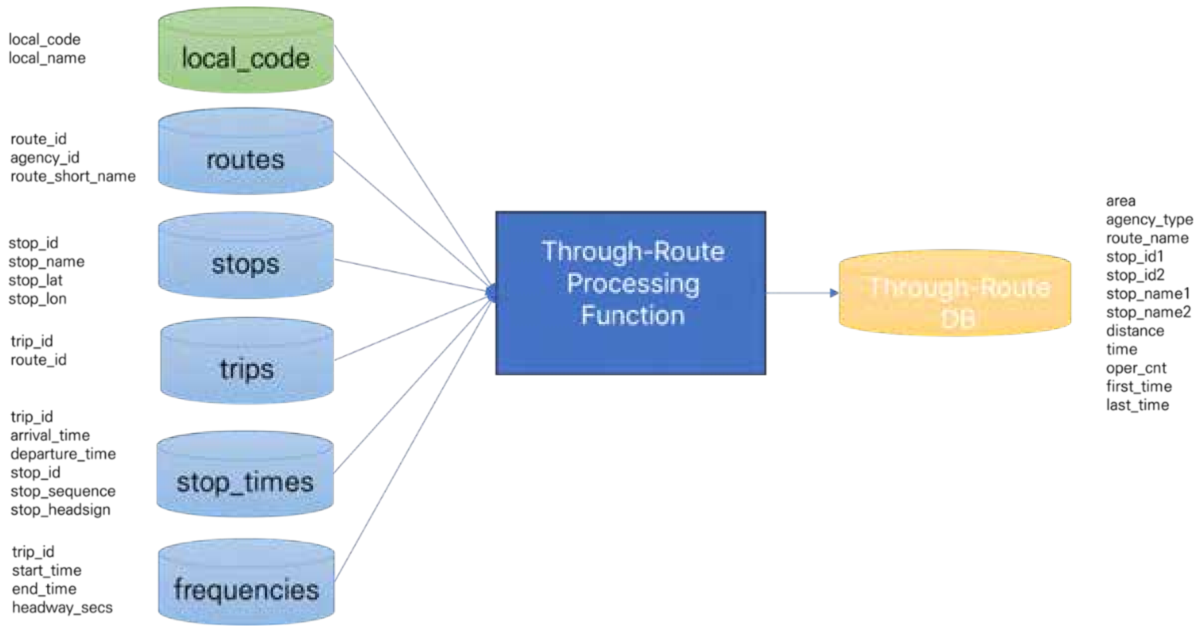


**Figure 3.2** GTFS based Public Transport Through-Route DB Processing Process

**Table 3.1** Summary of the number of routes and stops in the analysis dataset

| Mode | Number of Routes | Number of Stops |
|---|---|---|
| Metro | 57 | 1,082 |
| Bus | 24,973 | 192,411 |
| Express Bus | 11,851 | 1,426 |
| Train | 13,918 | 235 |
| Flight | 103 | 13 |
| Marine | 2,375 | 340 |

### 3.2.2 Construction of the "Through-Route" Database

To analyze the network from a user-centric perspective, this study first constructed a "Through-Route" database. A "Through-Route" is operationally defined as the set of all pairs of stops that can be reached on a single, transfer-free journey on a given route. This concept serves as the fundamental unit of direct service connectivity. The construction process was as follows:

1. Extraction of Stop Combinations: Utilizing the routes, trips, and stop_times files, all possible sequential origin-destination stop pairs were extracted for each individual trip.
2. Calculation of Travel Attributes: Based on the stop_times data, the travel time for each through-route was calculated. The travel distance was computed using the coordinates from stops.txt. Furthermore, the total number of daily services for a standard weekday was calculated for each route using data from the frequencies.txt or trips files.
3. Calculation of Transport Capacity: The transport capacity for each through-route was calculated by establishing a standard vehicle capacity for each transport mode and multiplying it by the total number of daily services.

### 3.2.3 The Grid-Based Socioeconomic Database

As discussed in Chapter 2, to overcome the Modifiable Areal Unit Problem (MAUP) inherent in analyses using administrative boundaries, this study adopts a 1km×1km grid system that covers the entire nation. The data were sourced from the Korean Statistical Geographic Information Service (SGIS) for the year 2022, with key variables including total population, age demographics, number of households, and the number of businesses and employees. Each public transport stop was mapped to its corresponding 1km² grid cell. A spatial join was then performed to link the transport network data with the socioeconomic attributes of each grid, creating a rich, multi-layered dataset for analysis.

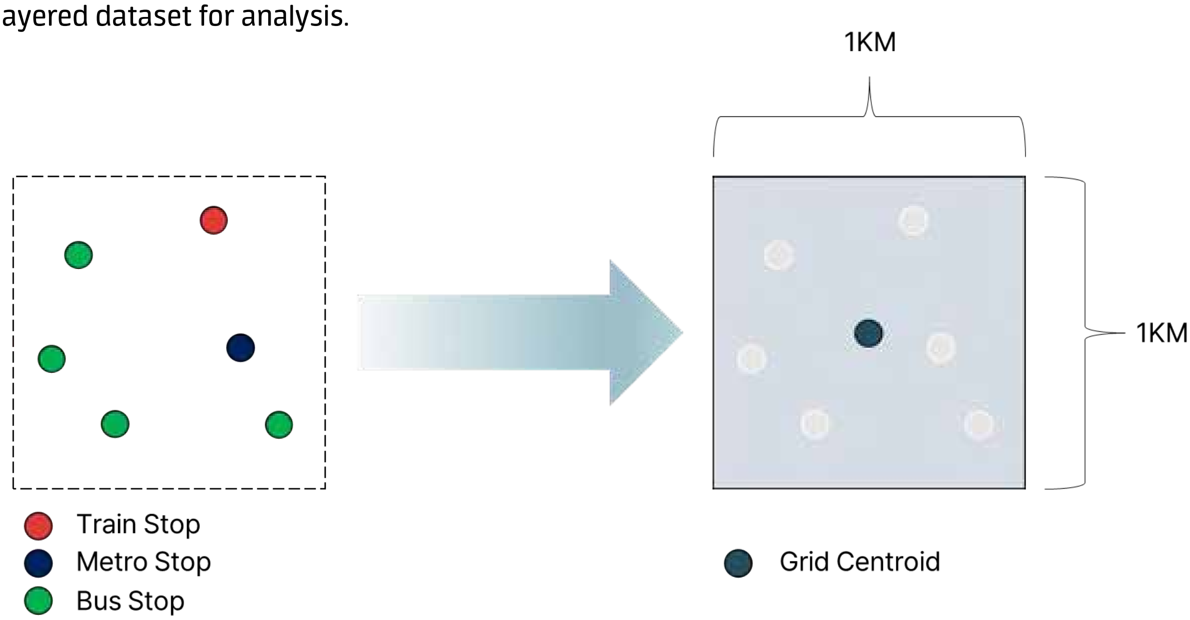


**Figure 3.3** Conversion of origin and destination points of public transportation (stop unit – grid unit)

## 3.3 Construction of the Multiplex Network Model

### 3.3.1 Definition of Nodes

The nodes of this network model are defined as the 1km² grid cells containing at least one public transport stop. Each node is attributed with the socioeconomic data constructed in Section 3.2.3, including its grid ID, population, number of employees, and Functional Urban Area (FUA) type.

### 3.3.2 Definition of Edges: A Multi-layer Connectivity Structure

This model possesses a multi-layer structure that treats each distinct mode of transport as a separate layer.

- Intra-layer Edges: These represent connections within each transport mode layer and are generated based on the "Through-Route" data constructed in Section 3.2.2. If a through-route exists from a stop in grid A to a stop in grid B, a directed and weighted edge is created from node A to node B. The attributes of this edge include weights for travel time, service frequency, and transport capacity.

- Inter-layer Connections and Transfers: Conventionally, transfers in network models are often represented by artificially generating pedestrian links between stops of different modes located within a certain proximity. While this method allows for the explicit addition of transfer penalties, it also introduces artificial links to the original data, which can distort analyses of network connectivity.

Therefore, to avoid this issue, this study does not add artificial transfer links. Instead, it leverages the inherent structure of the multiplex network itself to account for transfers. By fixing the spatial grid cell as the node, transfers are implicitly modeled as movements between different layers at the same node. All stops located within a single 1km² grid cell—a walkable catchment area—are considered mutually accessible, thus enabling transfers between all transport modes present within that grid.

**3.3.3 Final Model Specification and Implementation**

The constructed network can be represented as a directed, weighted graph G = (V, E), where V is the set of transport hub grid cells, and E is the set of multi-layer edges representing through-routes. For the analysis, this study primarily utilizes the Graph-Tool and GeoPandas libraries in Python, which are optimized for the analysis of large-scale networks.

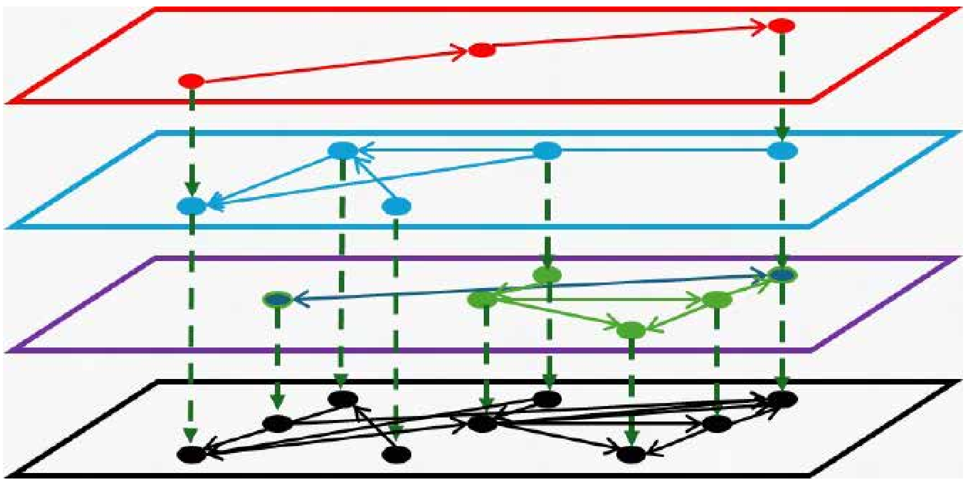

**Figure 3.4** Multimodal-Multiplex Network Model

**3.4 Selection of Analytical Indicators**

To diagnose transport network vulnerability, this study analyzes the network from three dimensions—service level, equity, and structure—using the following selected indicators.

**3.4.1 Service Level Indicators**

- Weighted Degree Centrality: To move beyond a simple count of connections, this study employs weighted degree centrality, often referred to as node strength, to measure the total volume of service associated with each node. This metric is calculated by summing the weights of all links connected to a node

$$s_i = \sum_j w_{ij}$$

where $s_i$ is the strength of node i, and $w_{ij}$ is the weight of the link between node i and node j. In this study, the weight $w_{ij}$ represents the service frequency or total transport capacity of a given through-route. Therefore, a high node strength indicates that a grid cell is not just connected to many other locations, but that it is served by a high volume of public transport services, marking it as a key hub in terms of service supply.

- Harmonic Closeness Centrality: This measures the overall efficiency of the network and the temporal accessibility of a specific node by using travel time as a weight.

$$H(v) = \sum_{u \neq v} \frac{1}{d(u,v)}$$

• Cumulative Opportunity Accessibility: This indicator suite measures the practical outcome of the transport service by calculating both the raw number of accessible opportunities and the per capita accessibility within predefined time thresholds.

First, the raw accessibility score calculates the total number of jobs accessible from a given location, providing a measure of the place's potential. The formula is:

$$A_i^T = \sum_j O_j \cdot f(C_{ij}) \quad \text{where} \quad f(C_{ij}) = \begin{cases} 1 & \text{if } C_{ij} \leq T \\ 0 & \text{if } C_{ij} > T \end{cases} \quad \cdots (\text{Eq. } 3.8)$$

where A_i^T is the raw accessibility score for node i, O_j is the number of jobs at node j, C_{ij} is the shortest travel time, and T is the time threshold (15, 30, 45, 60 minutes).

Second, to advance a person-centric equity analysis, we calculate the Per Capita Cumulative Accessibility. This metric normalizes the raw accessibility score by the population of the origin node, reflecting the level of competition for opportunities and providing a more nuanced measure of individual-level access. It is calculated as:

$$PA_i^T = \frac{A_i^T}{P_i} = \frac{\sum_j O_j \cdot f(C_{ij})}{P_i} \quad \cdots (\text{Eq. } 3.9)$$

where PA_i^T is the per capita accessibility for node i, and P_i is the population of node i.

**3.4.2 Equity Indicators**

• Gini Coefficient and Lorenz Curve: These are used to quantify the degree of inequality across the entire network by analyzing the distribution of service level indicators (e.g., weighted degree centrality) among the grid cells.

$$G = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} |x_i - x_j|}{2n^2 \bar{x}}$$

• Coefficient of Variation (CV): This measures the relative disparity in service levels between different regions.

$$CV = \frac{\sigma}{\mu}$$

**3.4.3 Structural Indicators**

• Clustering Coefficient, Largest Connected Component (LCC) Ratio, etc.: These fundamental metrics are utilized to understand the overall topological characteristics of the network.

$$C = \frac{3 \times \text{number of triangles}}{\text{number of connected triplets}}$$

• Largest Connected Component (LCC) Ratio: This measures the proportion of nodes that belong to the largest single connected component of the network, indicating the overall integration of the system.

$$\text{LCC Ratio} = \frac{N_{LCC}}{N}$$

where N_LCC is the number of nodes in the largest connected component and N is the total number of nodes in the network.

**4. Results**

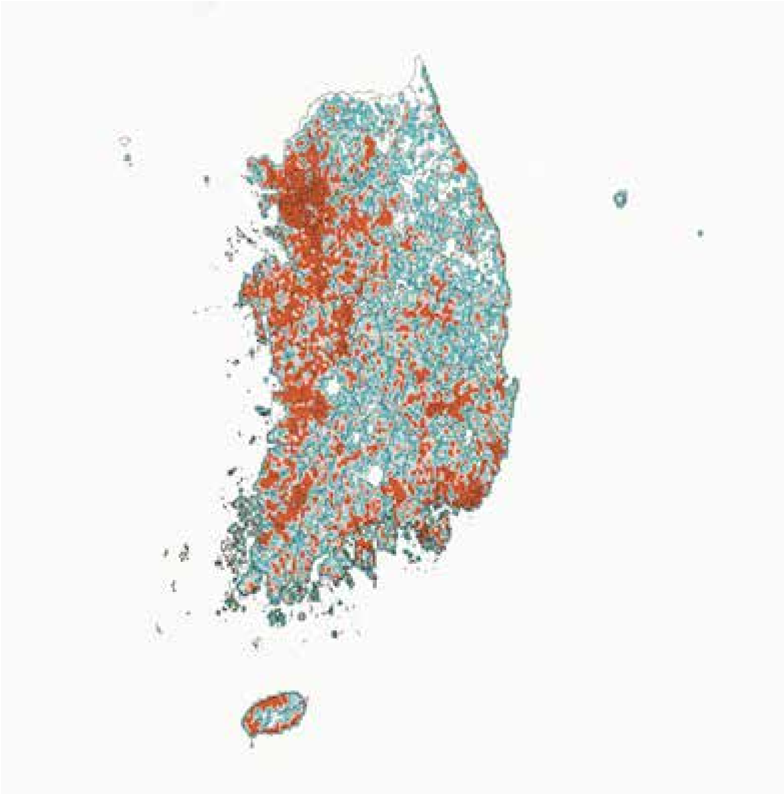

**Figure 4.1** Network Node Distribution

| Category | Name | Value |
|---|---|---|
| Structural Indicators | Number of Nodes | 41,552 |
| | Number of Edges | 2,179,454 |
| | Network Density | 0.001175(0.12%) |
| | Avg. Out-Degree | 84.40 |
| Clustering Coefficient | Avg. Local CC | 0.8449 |
| | Global CC | 0.4338 |
| LCC | LCC Size | 41,552 |
| | LCC Ratio | 99.97% |

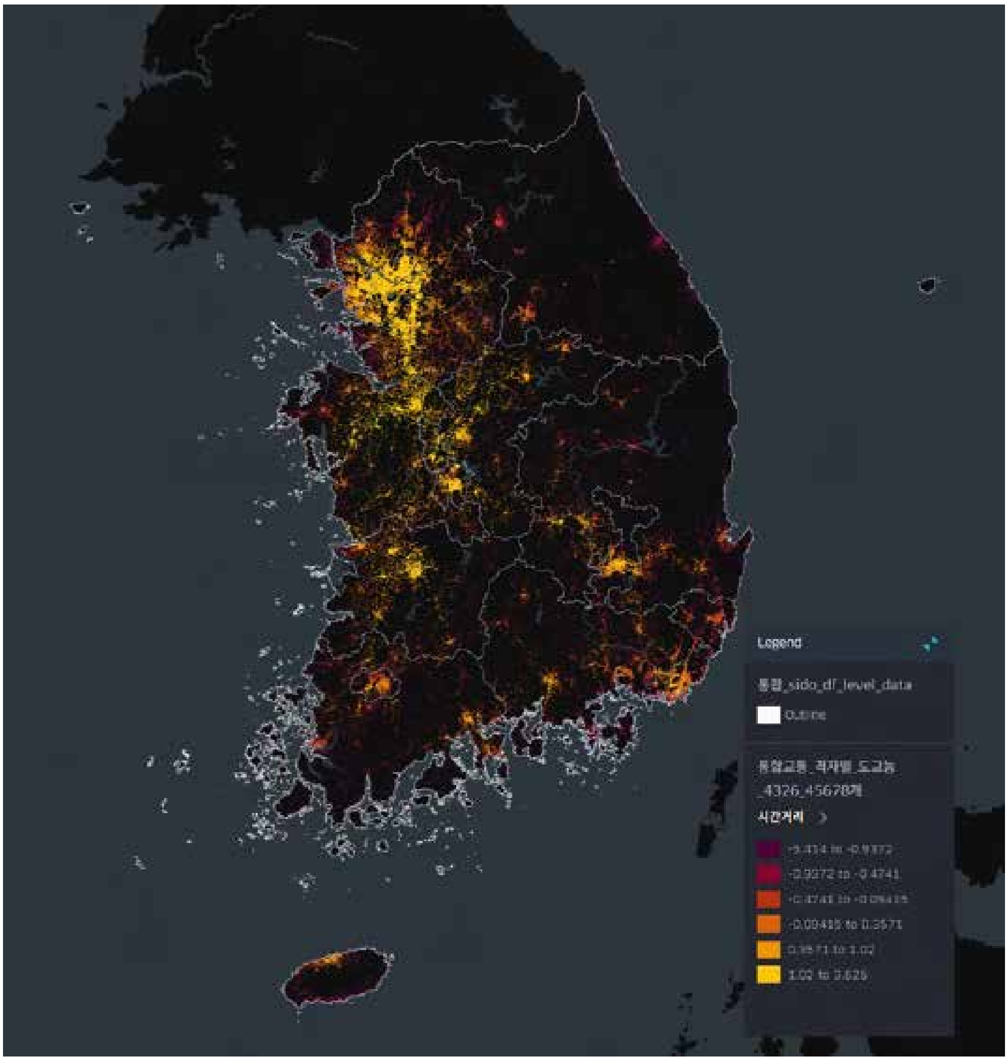


**Figure 4.2** Distribution of Harmonic Closeness Centrality of PTNs

Network efficiency, indicating how quickly any point can be reached from a specific location via public transport, was measured by calculating the harmonic closeness centrality for each grid cell (node) based on the shortest path travel times to all other reachable cells.

The results reveal a concentration of overwhelmingly high efficiency in the Seoul Metropolitan Area (SMA), which appears as a broad yellow area on the map. This suggests a dense and rapid network of interconnected public transport modes, including subways and metropolitan buses. Similarly, other major metropolitan cities such as Busan, Daegu, Daejeon, and Gwangju exhibit high efficiency centered around their urban cores. In contrast, efficiency is markedly lower in non-urban and peripheral regions, including the mountainous areas of Gangwon-do, the northern and eastern parts of Gyeongsangbuk-do, and the southern and insular areas of Jeollanam-do. This indicates that travel to other regions via public transport from these locations requires significantly more time.

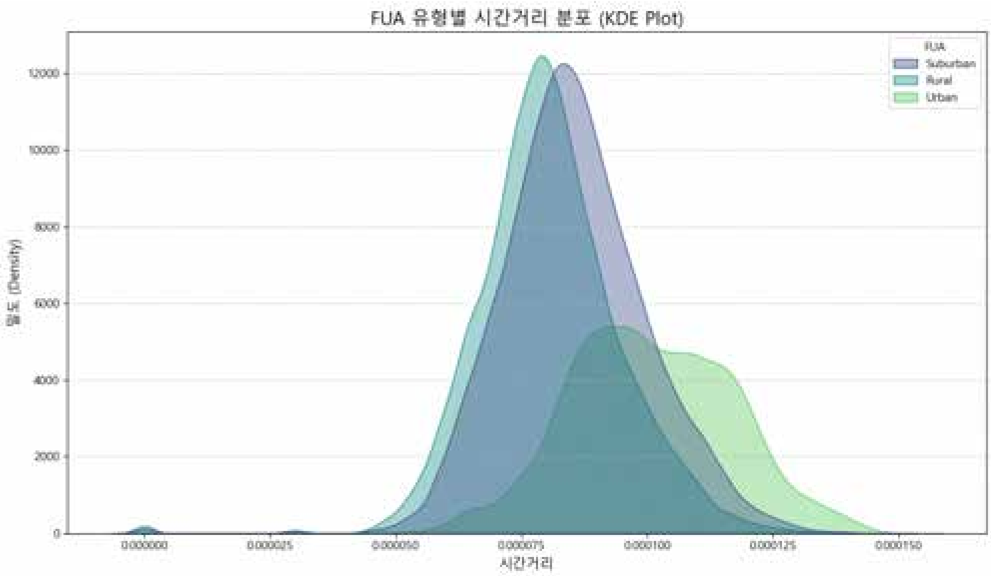


**Figure 4.3** The distribution of public transport efficiency by FUA

The distribution of public transport efficiency across different Functional Urban Area (FUA) types is visualized using a Kernel Density Estimation (KDE) plot (Figure X.X). The plot indicates that urban areas exhibit a distinctly higher level of public transport efficiency, whereas suburban and rural areas show similar, lower-efficiency distributions. This suggests that, in terms of travel time, reaching other regions via public transport is substantially faster from urban areas compared to their non-urban counterparts.

| | |
|---|---|
|  |  |
| Threshold = 15 min | Threshold = 30 min |
|  |  |
| Threshold = 45 min | Threshold = 60 min |

**Figure 4.4** Distribution of Cumulative Opportunity Accessibility (Reachable Job)

The analysis of per capita accessibility reveals the number of jobs reachable by an average resident of each grid cell within specified time thresholds (e.g., 15, 30,45, 60 minutes). Unsurprisingly, areas encompassing Seoul's major business districts—the Central Business District (CBD), Gangnam Business District (GBD), and Yeouido Business District (YBD)—exhibit exceptionally high job accessibility within a 15-minute threshold. As this threshold expands to 30, 45, and 60 minutes, the number of accessible jobs per capita increases, altering the spatial landscape of accessibility.

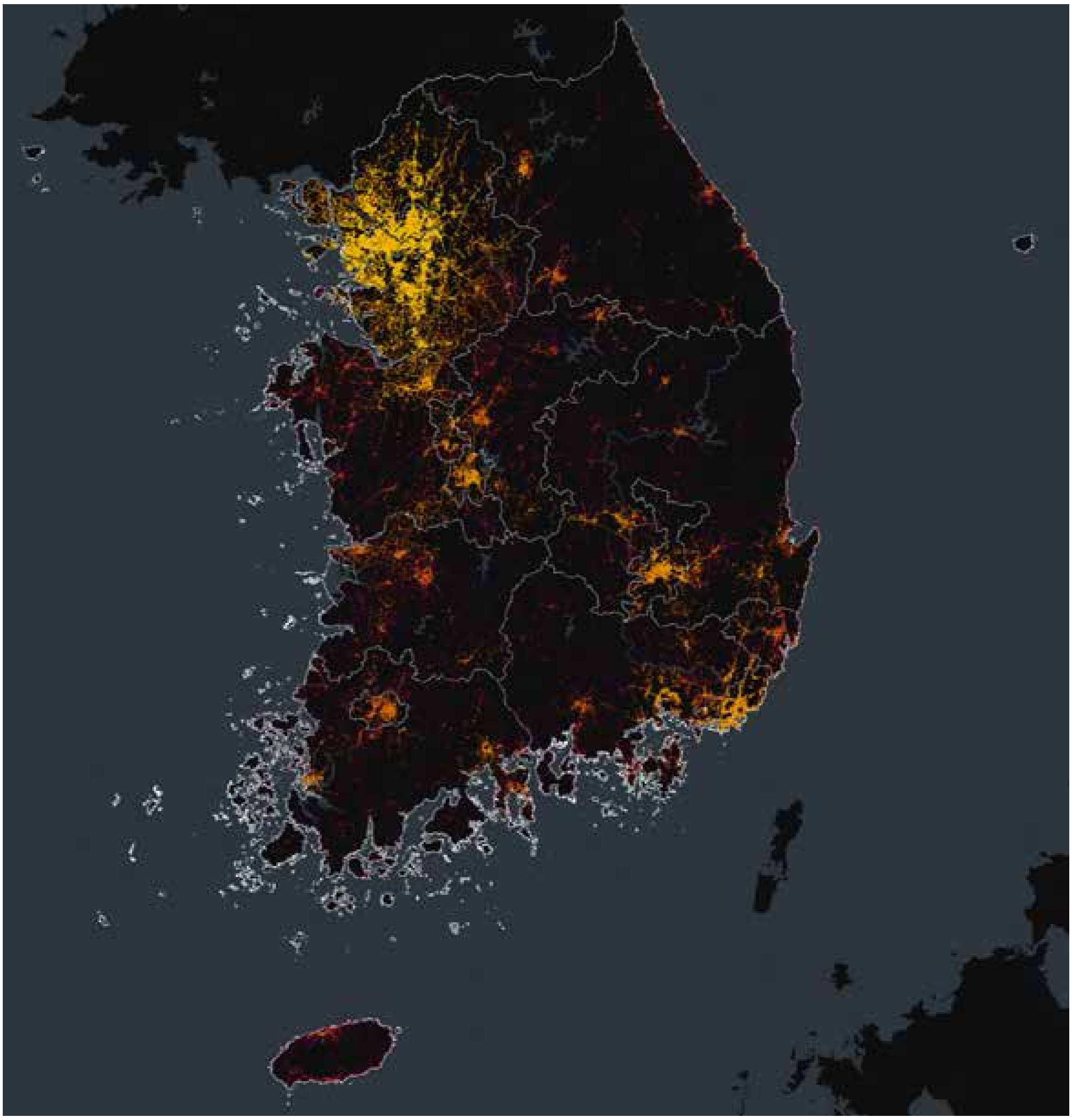

**Figure 4.5** Distribution of Weighted Eigenvector Centrality (Oper capacity)

Transport capacity-weighted eigenvector centrality is an indicator that represents a node's influence within the flow of the public transport network's "people-carrying ability" (i.e., its transport capacity), rather than its influence derived from a simple count of connections or its position on shortest paths. A high score for a given node signifies that it is well-connected to other nodes that are themselves high-capacity hubs. In essence, it measures a node's access to the high-volume corridors of the public transport system.

## 5. Conclusion

### 5.1 Summary of Research and Key Findings

This study was initiated with the goal of expanding the paradigm of public transport service evaluation from a narrow focus on physical "access" to a broader understanding of "service level" and "equity" as experienced by actual users. To this end, we proposed and applied a novel analytical framework designed to overcome the methodological limitations of prior research, namely: analyses focused on single transport modes, the use of administrative units prone to the Modifiable Areal Unit Problem (MAUP), and the neglect of the quantitative dimension of service.

The core methodological contribution of this research lies in the construction of the "Grid-Based Multimodal Multiplex Network Framework," which is built upon GTFS big data. This framework conceptualizes various transport modes across South Korea—including buses, subways, and rail—as distinct layers in a network. It integrates the quantitative level of service into the model by utilizing the "Through-Route" concept and by employing service frequency and transport capacity as weights. Furthermore, by adopting a uniform 1km² grid as the fundamental spatial unit of analysis to overcome the limitations of MAUP, we established a foundation for analyzing the nationwide public transport system with unprecedented precision.

Our key findings reveal that while South Korea's public transport network exhibits a high degree of overall connectivity (LCC Ratio of 99.97%), its service level is distributed in a highly uneven manner. Both network efficiency, measured by harmonic closeness centrality, and the actual service supply, reflected in weighted centrality metrics, showed extreme spatial polarization, with services being overwhelmingly concentrated in the Seoul Metropolitan Area and the urban cores of other major metropolitan cities. In contrast, non-urban and peripheral areas, such as the mountainous regions of Gangwon-do and the outer regions of Gyeongsangbuk-do and Jeollanam-do, were found to be in a state of severe service deprivation. Notably, a comparative analysis demonstrated that our grid-based approach could empirically identify micro-level service disparities and genuinely transport-disadvantaged areas far more clearly than conventional analyses based on administrative units, which tend to mask such issues.

### 5.2 Discussion and Policy Implications

#### 5.2.1 Theoretical and Methodological Implications

The findings of this study offer several important implications for the fields of transport planning and spatial analysis.

First, this research empirically operationalizes and validates the "Beyond Access" concept. By demonstrating quantitatively how inequities become more pronounced when service levels like operational frequency are integrated into the analysis, this study presents a clear direction for the future of transport equity research.

Second, this study makes a significant methodological contribution by fusing three previously fragmented fields of research—transport equity, network science, and spatial analysis—into a single, integrated framework. The proposed "Grid-Based Multimodal Multiplex Network Framework" serves as a robust and replicable model for analyzing complex, nationwide transport systems, and holds the potential to become a new standard for related research.

#### 5.2.2 Policy Implications

This research provides concrete answers to Research Question 3: "What are the policy implications of incorporating the quantitative dimension of service level into network models?"

First, it challenges the traditional efficiency-oriented transport policy paradigm. Infrastructure investment decisions based primarily on cost-benefit analysis (B/C analysis) can exacerbate the kind of severe spatial inequalities identified in this study. Our findings strongly suggest that when allocating limited public resources, social equity criteria, such as guaranteeing a minimum level of service, must be employed as core evaluation standards alongside economic efficiency.

Second, it provides a practical tool for precise, data-driven transport policymaking. The high-resolution maps of service levels and vulnerability generated in this study can be used by policymakers as objective and scientific evidence to clearly identify which areas are genuinely transport-disadvantaged and to determine investment priorities.

Third, it contributes to the formulation of specific policy directions. Based on the analytical results, tailored, area-specific policies can be proposed. For instance, for high-density areas with low service levels, new bus routes or increased service frequency could be recommended. For isolated rural areas, an expansion of Demand-Responsive Transit (DRT) or public-purpose taxis that connect to core network hubs could be prioritized. For areas with high transfer potential but low network efficiency, improvements to transfer centers and enhancements to the connecting transport system could be implemented.

**5.3 Limitations and Future Research**

Despite its significant findings, this study has several limitations, which in turn open avenues for future research.

First, there is the static nature of the data. As this research is based on GTFS data, which contains scheduled timetable information, it does not capture dynamic fluctuations such as delays, cancellations, or traffic congestion. Future research is needed to integrate real-time transport data to analyze the dynamic reliability and stability of the network.

Second, the analysis has a supply-side focus. This study primarily analyzes the supply of public transport and does not explicitly model passenger demand. Future work could produce more sophisticated policy implications by integrating smart card or mobile phone data to analyze the interaction and potential mismatch between supply and demand.

Third, there is an absence of new mobility services. This analysis primarily deals with scheduled, route-based public transport and does not consider connectivity with emerging modes such as shared mobility or personal mobility devices (PMDs). Research that incorporates these services into the multi-layer network model to evaluate the integrated performance of the entire mobility system is required.

**5.4 Concluding Remarks**

This dissertation, under the guiding principle of “Beyond Access,” proposed and validated a novel integrated framework for diagnosing the practical service levels and spatial equity of public transport. The analysis revealed the state of severe spatial imbalance within South Korea’s public transport system at a high resolution, shedding light on micro-level issues that were difficult to capture with conventional analytical methods.

True transport equity is not achieved by simply providing identical infrastructure to all regions. It begins by guaranteeing an “adequate and sufficient” level of service tailored to the characteristics and needs of each region, so that all citizens have an equal opportunity to access the services they need. It is hoped that the data-driven, precise diagnostic methodology presented in this study can make a meaningful academic and policy contribution toward building a more sustainable and inclusive transport system in South Korea.

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