

URBAN TRANSPORT RESILIENCE AND SUSTAINABILITY IN SOUTH KOREA AMID DISRUPTIONS

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Abstract

Urban transportation systems must be resilient to external shocks, such as climate change, public health crises, and evolving urban mobility demands. This study analyzes daily ridership patterns in South Korea (2018-2021), using the COVID-19 pandemic as a stress test to assess transit resilience. By examining statistical relationships between subway, bus, and bicycle usage, the study identifies strong interdependencies between subways (6.4 millions daily riders) and buses (4.56 millions), with a 98% correlation, while bicycles (36,793 daily riders) remain poorly integrated into the transit network. These findings highlight the need for multimodal connectivity, adaptive infrastructure investments, and transit electrification to strengthen urban mobility resilience against future disruptions. The study's insights extend beyond South Korea, offering a data-driven framework for global cities to design sustainable, shock-resistant transportation networks that balance efficiency, resilience, and environmental imperatives in an era of increasing uncertainty.

Keywords: Urban Transport Resilience; Sustainable Mobility; Multimodal Integration; Transit Disruptions; Climate Adaptation

Introduction

Urban transportation networks are vital infrastructures that sustain mobility, economic activity, and social inclusion. However, external shocks such as extreme weather events, public health crises, and shifting urbanization trends frequently test their ability to function effectively. The resilience of these networks, their ability to absorb disruptions, recover efficiently, and adapt to long-term structural changes, is increasingly a focal point in transport policy and urban planning

(Mattsson and Jenelius, 2015). Recent disruptions, particularly the COVID-19 pandemic, have exposed both the fragility and adaptability of transit systems worldwide. While some transportation modes experienced drastic declines in ridership, others remained stable or even saw increased demand, underscoring the importance of multimodal integration, network redundancy, and adaptive policy measures in ensuring urban mobility resilience.

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This study examines daily ridership patterns in South Korea's urban transit system from 2018 to 2021, covering both pre-pandemic and pandemic periods to assess how public transport systems responded to and recovered from a major global crisis. By employing a time-series analysis, this research evaluates fluctuations in subway, bus, and bicycle ridership over multiple years, offering insights into intermodal dependencies, ridership resilience, and evolving commuter behaviour. Unlike studies that focus solely on the immediate impacts of COVID-19, this research situates the pandemic within broader structural challenges facing urban transportation systems, including the need for climate adaptation, transit electrification, and policy-driven multimodal integration.

The findings confirm that subways remain the dominant mode of urban transit, with an average daily ridership of 6.4 millions passengers, reflecting their role in managing high-density commuter flows. However, the strong correlation between subways and buses ($r=0.98$) underscores their interdependency, revealing both a complementary relationship and a shared vulnerability to disruptions. In contrast, bicycle ridership remains largely disconnected from the mass transit network, despite global evidence that bike-transit integration can enhance multimodal resilience and sustainability (Cariolet *et al.*, 2019; Wang *et al.*, 2019). South Korea's urban mobility system continues to rely heavily on motorized transport, with bicycles functioning independently rather than as a well-integrated component of a climate-adaptive transit ecosystem.

The implications of these findings extend beyond technical assessments of ridership trends. The pandemic-induced collapse in subway and bus ridership highlights the broader vulnerabilities of high-density, fixed-route transit systems to external shocks, including future pandemics, extreme weather events, and economic disruptions. By contrast, bicycles emerged as a resilient transport mode, maintaining stable ridership levels during the crisis. This suggests that cycling could play a greater role in urban mobility strategies, particularly as cities seek to reduce car dependency and promote low-carbon transport solutions. These insights point to key policy considerations, including the need for enhanced infrastructure for multimodal integration, real-time transit monitoring for adaptive service planning, and fare structures that incentivize seamless transfers between transit modes.

Additionally, the findings emphasize the urgent need for transport decarbonization. While subways remain a low-emission mode of transport, the continued reliance on medium- and heavy-duty

diesel buses contributes significantly to urban CO₂ emissions (Seo *et al.*, 2016). Expanding electrified bus fleets, integrating bike-sharing systems with subway networks, and leveraging AI-driven congestion management technologies are not merely technical improvements - they are critical policy interventions for building transport systems that are resilient to future disruptions and aligned with global climate commitments.

This research contributes to global discussions on transit resilience and sustainability by providing an empirical, data-driven analysis of how South Korea's urban transport system evolved in response to a major global disruption. It draws from interdisciplinary literature in transportation studies, urban resilience, and environmental policy, building on previous research by Kristoffersson *et al.* (2021); Tengilimoglu and Wadud (2021); Paschalidis *et al.* (2022); Ashkrof *et al.* (2023). By employing quantitative methodologies, including correlation analysis, regression modelling, and ANOVA, this study identifies systemic interdependencies, inefficiencies, and vulnerabilities, offering a framework for policymakers to design more adaptive, resilient, and sustainable urban mobility solutions.

The paper is structured as follows: The Literature Review summarizes research on multimodal integration, transit resilience, and climate-adaptive strategies. The Methodology details quantitative techniques like time-series analysis, correlation studies, regression modelling, and ANOVA to study intermodal relationships and disruptions. The Results section presents findings on transit trends, vulnerabilities, and ridership dynamics. The Discussion links these findings to policy debates on transport planning, resilience, and emissions reduction. Finally, the Conclusion calls for data-driven reforms, electrified transit, and multimodal integration to improve efficiency and disaster resilience.

Literature Review

Urban transportation networks function as complex, interdependent systems that are fundamental to economic stability, social mobility, and disaster response. However, they remain vulnerable to both natural and anthropogenic disruptions, necessitating a deeper understanding of resilience, reliability, and adaptability in transport planning (Mattsson and Jenelius, 2015). Resilience, in this context, extends beyond the ability to withstand and recover from disruptions; it encompasses proactive planning, redundancy, and system adaptability to minimize service failures and ensure rapid recovery. As urban

centres expand and climate change intensifies, incorporating resilience principles into transportation planning has become a pressing imperative.

Concepts of Resilience and Vulnerability in Transportation

Vulnerability in transportation systems refers to their susceptibility to disruptions that impair their functionality and efficiency. Disruptions may arise from infrastructure failures, extreme weather events, socio-political crises, or pandemics, all of which challenge the predictability and stability of transport networks (Mattsson and Jenelius, 2015). Transportation systems comprise interconnected subsystems, such as roads, railways, and public transit, and disruptions in one mode can sometimes be mitigated through modal shifts (Xu and Chopra, 2023). For instance, volcanic ash-related air travel shutdowns have historically led to increased reliance on rail and road transport, illustrating modal substitution and network redundancy (Prata and Rose, 2015).

However, the capacity for adaptation is not universal. Urban regions typically exhibit greater redundancy, offering multiple mobility alternatives, whereas rural areas face heightened vulnerabilities due to limited modal diversity. Moreover, infrastructure investments intended to enhance system resilience may paradoxically introduce new fragilities. This paradox, termed the robust-yet-fragile characteristic, demonstrates that while new infrastructure (e.g. tunnels, bridges) enhances connectivity (see: Mattsson and Jenelius, 2015), it also creates single points of failure, which can compromise network-wide functionality in the event of a disruption (He *et al.*, 2021).

Resilience is typically evaluated using efficiency and robustness indicators. Efficiency measures assess how transport routes degrade following disruptions, while robustness indicators analyze the degree of overall system deterioration. Comparative analyses of major metropolitan areas, such as London and Paris, reveal that seemingly similar transit systems can exhibit vastly different resilience outcomes, depending on network structure and modal integration (von Ferber *et al.*, 2012; Sharifi, 2019). These findings underscore the need to embed redundancy and multimodal flexibility into urban transit planning to enhance resilience against future disruptions.

Empirical Case Studies: Learning from Past Disruptions

Historical disasters provide valuable insights into transport resilience strategies. Kim, Francis, and Yamashita (2018) analyzed major

infrastructure failures, such as the I-35W bridge collapse and Superstorm Sandy, identifying key lessons for resilience enhancement. Their findings emphasize the need for integrating resilience planning into asset management, ensuring that infrastructure investments not only improve service efficiency but also enhance a system's capacity to absorb and recover from shocks. For example, the collapse of the I-35W bridge in Minneapolis caused major traffic disruptions, yet the swift implementation of temporary detours showcased the importance of preemptive contingency planning (see also Seibel and Seibel, 2022).

Similarly, Wang *et al.* (2019) examined transport resilience in Houston during Hurricane Harvey, finding that communities with greater modal diversity exhibited stronger resilience. Their study revealed that multimodal substitution (e.g. from rail roads) allowed commuters to navigate around flooded areas, reducing total system downtime. These findings align with the network topology arguments proposed by Mattsson and Jenelius (2015); Ganin *et al.* (2019), which suggest that higher connectivity in urban areas improves overall resilience capacity.

Further, Aghababaei *et al.* (2021) employed simulation-based resilience assessments to evaluate the impact of network disruptions on South Island's transportation system. Their findings underscored the critical role of high-traffic corridors (e.g. State Highway 1) in maintaining regional mobility during crises. Their use of mesoscopic dynamic assignment models allowed for the simulation of trip reassignment following road blockages, offering data-driven recommendations for more robust emergency response strategies. These empirical insights reinforce the importance of disaster-specific transport resilience strategies.

Technological and Policy Innovations for Resilience

Advancements in digital infrastructure are increasingly being leveraged to enhance transport resilience. Kim *et al.* (2023) explored how smart mobility solutions, such as AI-driven monitoring, IoT-based real-time tracking, and GIS-based evacuation route optimization, improve urban transport adaptability. These intelligent transportation systems (ITS) have demonstrated significant potential in reducing system failures during climate-induced extreme weather events.

Beyond technology, policy interventions play a vital role in shaping resilient transportation networks. Cariolet *et al.* (2019) emphasized the importance of pre-disaster resilience mapping, advocating for spatial vulnerability assessments to proactively identify high-risk transport nodes.

Meanwhile, Seoul's Climate Companion Card initiative, which provides unlimited public transit access, has proven effective in shifting commuter behaviour away from private vehicle reliance, thereby reducing congestion and emissions (Seoul Metropolitan Government, 2024). Expanding this initiative to include micro-mobility services (e.g. shared bicycles, e-scooters) could further increase multimodal resilience while reducing environmental impact.

Research Gaps and Future Directions

Despite advancements in transport resilience research, significant gaps remain in how these frameworks apply to rapidly urbanizing regions. While prior studies have explored resilience metrics in major metropolitan areas (Wang *et al.*, 2019), there is a lack of research on mid-sized cities and their adaptive transit planning strategies (Sun *et al.*, 2018).

Moreover, the equity dimensions of resilience remain underexplored. While some research has assessed efficiency, redundancy, and vulnerability metrics, few studies examine how resilience investments disproportionately benefit or exclude low-income communities. This equity gap raises concerns about spatial justice in transport planning.

Additionally, the role of AI-driven predictive analytics in resilience planning requires further study. While technologies such as IoT and AI-based transit monitoring have been proposed (Kim *et al.*, 2023), there is limited empirical research evaluating their real-world effectiveness under crisis conditions.

Closing these research gaps would be key to improving the resilience of transportation. A comprehensive, equitable approach using new technologies and consistent methodologies is critical to creating adaptable, sustainable transportation systems that can meet future challenges.

Data and Methodology

Data

This study examines urban transportation patterns in South Korea through an empirical analysis of publicly available datasets covering daily ridership for buses, subways, and bicycles from January 1, 2018, to December 31, 2021. This period captures both pre-pandemic and pandemic phases, allowing for a longitudinal examination of transit resilience, modal interdependencies, and adaptive responses to external disruptions. By leveraging open-access government datasets, the

study ensures methodological transparency and reproducibility.

The primary data sources include the Seoul Metropolitan Government, which provides daily transit ridership data collected from fare card transactions across all urban and suburban transit networks, the Korea Transport Institute, which publishes statistical summaries on modal usage patterns, infrastructure capacity, and transit policies, and the Korea National Statistical Office, which offers supplementary demographic and economic datasets for contextualizing transit demand variations. These datasets are structured, recorded in CSV format, and contain timestamped daily usage counts for each mode, ensuring temporal precision for trend analysis (Figure 1).

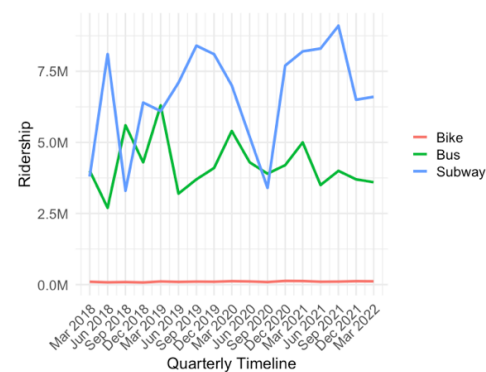


Figure 1. Quarterly Ridership Trends for Buses, Subways, and Bicycles (2018–2022)

Note: Figure 1 shows quarterly ridership trends for buses, subways, and bicycles in South Korea from January 2018 to March 2022. The trends highlight pre-pandemic stability, the impact of the COVID-19 pandemic, and the varying roles of each mode in urban transportation.

The study defines its unit of analysis as daily ridership per transit mode, with subway ridership measured through turnstile transactions, bus ridership recorded via electronic fare card usage, and bicycle ridership obtained from Seoul's public bike-sharing system (Ttareungi). This approach enables a direct comparison of ridership trends across different transportation modes while maintaining a high degree of accuracy and consistency.

Before conducting statistical analysis, the dataset underwent preprocessing to ensure reliability. Missing values were addressed using linear interpolation for short-term gaps (one to three days) and historical means for longer gaps, as this method has been shown to minimize distortion in time-series trends.

Given the different scales of ridership data (millions for subway and bus vs. tens of thousands for bicycles), a log transformation was applied to normalize distributions and improve model stability. Seasonal adjustments were made using a seasonal decomposition of time series (STL decomposition) to account for systematic fluctuations due to public holidays, fare adjustments, and policy changes. To assess the impact of COVID-19 on transportation patterns, a binary indicator variable was introduced, assigning a value of '1' to pandemic periods and '0' to pre-pandemic periods. This preprocessing ensured that the dataset was robust and well-structured for statistical modelling.

Notation

The following notations are used throughout this study to describe the statistical methods and variables applied in the analysis of urban transit resilience and intermodal interdependencies :

- X, YX, Y - Daily ridership values for two transportation modes (e.g., bus, subway, or bicycle).
- $\bar{X}, \bar{Y}$ - Mean daily ridership for each respective mode.
- r - Pearson's correlation coefficient, indicating the strength and direction of the linear relationship between two transit modes.
- R^2 - Coefficient of determination from the regression model, representing the proportion of variance in the dependent variable explained by the predictors.
- β_0 - Intercept term in the Ordinary Least Squares (OLS) regression model, representing the expected bus ridership when all predictors are zero.
- $\beta_1, \beta_2, \beta_3$ - Regression coefficients measuring the effects of subway ridership, bicycle ridership, and the COVID-19 indicator on bus ridership.
- ε - Error term accounting for unexplained variability in the regression model.
- p - Probability value used in hypothesis testing; a result is considered statistically significant when $p < 0.05$.
- F - The test statistic used in ANOVA to determine whether differences in group means (e.g., pre- and post-pandemic ridership) are statistically significant.

This notation system provides a consistent framework for interpreting the statistical analysis and supports the clarity and replicability of the study's methodology.

Method

This study employs a quantitative analytical approach, integrating correlation analysis, Ordinary Least Squares (OLS) regression, and Analysis of Variance (ANOVA) to evaluate transit interdependencies and resilience to external shocks. These statistical methods were selected based on their ability to detect associations, estimate predictive relationships, and assess significant differences in ridership trends across pandemic and non-pandemic periods.

Correlation Analysis

To measure the strength of relationships between subway, bus, and bicycle ridership, Pearson's correlation coefficient (r) was calculated for the three possible combinations: bus-bicycle, bicycle-subway, and bus-subway ridership. This metric quantifies the degree to which ridership levels in one mode align with those in another, providing insights into their interdependencies. The formula for Pearson's correlation coefficient is:

$$r = \frac{\sum(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum(X_i - \bar{X})^2} \sqrt{\sum(Y_i - \bar{Y})^2}}$$

Where:

X, YX , and Y represent the daily ridership values for two transit modes (e.g. bus and subway, bus and bicycle, or bicycle and subway).

$\bar{X}, \bar{Y}$ represent the mean daily ridership for each mode.

Pearson's correlation coefficient was chosen due to the normally distributed ridership data following a log transformation.

Correlation Between Transit Modes

The relationships between different transit modes in South Korea were analyzed using correlation coefficients (r). These results provide valuable insights into the interactions and dependencies within the urban transportation system.

Key Findings

Bus-Subway Correlation $r = 0.98$: A strong positive correlation highlights the high interdependence between buses and subways. Buses frequently function as feeders to subway stations, extending their reach into suburban areas and enabling seamless multimodal travel for commuters.

Bus-Bicycle Correlation $r = 0.014$: A near-zero correlation indicates that buses and bicycles

operate independently, reflecting limited integration between these modes. This underscores the absence of first-mile/last-mile connectivity for bike commuters.

Subway-Bicycle Correlation $r = 0.019$: Similarly, a weak correlation reveals minimal interaction between subway and bicycle ridership. This may stem from insufficient infrastructure, such as bike racks or shared micromobility hubs, near subway stations.

The heatmap below (Figure 2) visually summarizes these correlations, illustrating the stark contrast between the strong dependency of buses and subways and the limited integration of bicycles with public transit.

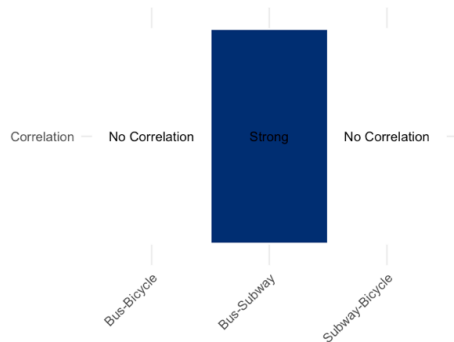


Figure 2. Correlation Coefficients Between Transit Modes

Note: The plot displays the correlation coefficients (r) for Bus-Subway, Bus-Bicycle, and Subway-Bicycle pairs. The strong correlation between buses and subways contrasts sharply with the weak interactions involving bicycles.

Interpretation: The Bus-Subway pair's high correlation ($r = 0.98$) underscores their critical role in urban mobility. In contrast, the near-zero correlations for Bus-Bicycle and Subway-Bicycle pairs reveal significant gaps in the multimodal transportation system. These findings emphasize the need for:

Investments in bike-friendly infrastructure, such as dedicated bike lanes near bus stops and subway stations.

Integration of micromobility solutions with public transit, including bike-sharing systems and last-mile connectivity incentives.

Overall, the strong correlation (close to 1) signifies interdependency, such as between buses and subways, while weak or near-zero correlations indicate independent modal behaviors. This analysis identifies the strengths and gaps in South Korea's urban transit system, particularly highlighting bicycles' untapped potential for multimodal integration.

Ordinary Least Squares (OLS) Regression

To analyze how subway and bicycle ridership influence daily bus usage, while accounting for the effects of the COVID-19 pandemic and economic activity, an Ordinary Least Squares (OLS) regression model was used. OLS regression was chosen because it is straightforward to interpret and effective for estimating linear relationships in time-series data when dependencies are minimal.

The model is represented by the equation below:

$$\text{Bus} = \beta_0 + \beta_1(\text{Subway}) + \beta_2(\text{Bike}) + \beta_3(\text{COVID}) + \beta_4(\text{Economic}) + \varepsilon$$

Explanation of Variables:

Bus: Daily bus ridership (dependent variable).

Subway: Daily subway ridership (independent variable).

Bike: Daily bicycle ridership (independent variable).

COVID: A dummy variable (1 = during pandemic, 0 = pre-pandemic).

Economic: An economic activity index to account for employment and mobility trends.

β_0 : Baseline bus ridership when all other variables are zero.

$\beta_1, \beta_2, \beta_3$: Coefficients that quantify the effect of each variable on bus ridership.

ε : Residual error term (captures variability not explained by the model).

Model Validation Steps:

Multicollinearity Check: Ensured that the independent variables were not too closely related using Variance Inflation Factor (VIF) analysis.

Autocorrelation Test: Checked for patterns in residuals (e.g. time-series dependencies) using the Durbin-Watson statistic.

Homoscedasticity Test: Verified that the variance of residuals was consistent across predictions using the Breusch-Pagan test.

If any assumptions of OLS regression were violated, alternative methods like Generalized Least Squares (GLS) or Autoregressive Integrated Moving Average (ARIMA) would be considered to improve accuracy.

Analysis of Variance (ANOVA)

To test whether COVID-19 caused significant differences in transit ridership, ANOVA was applied to compare mean ridership levels across pre-pandemic and pandemic periods. ANOVA was selected over t-tests due to its ability to handle more than two groups if needed for future expansions of this study.

$$F = \frac{\text{Between-group variance}}{\text{Within-group variance}}$$

where:

Between-group variance measures differences in ridership before and during the pandemic.

Within-group variance accounts for daily fluctuations within each period.

A statistically significant pp-value (less than 0.05) indicates that pandemic-related ridership shifts were unlikely due to random variation. Post-hoc tests (e.g. Tukey's Honest Significant Difference) were used to pinpoint which transit modes experienced the most significant disruptions.

Data Analysis Tools and Software

The study employed R-Studio, a widely used statistical computing environment, for all data processing and analysis. The analysis utilized specialized R packages, including:

ggplot2 → Visualization of ridership trends and statistical distributions.

dplyr → Data manipulation and preprocessing.

stats → Statistical modeling, including correlation analysis and ANOVA.

lm → OLS regression estimation.

To ensure reproducibility, all data preprocessing steps, and R scripts were documented, allowing for verification and replication.

Summary

By leveraging open-access transportation data and applying robust statistical methods, this study provides a longitudinal perspective on urban transit resilience in South Korea. The combination of correlation analysis, OLS regression, and ANOVA allows for:

Quantifying interdependencies between subways, buses, and bicycles to assess multimodal integration.

Measuring the impact of COVID-19 on transit ridership and determining whether disruptions were statistically significant.

Evaluating policy implications for future transit planning, particularly regarding electrified public transport, multimodal connectivity, and resilience to external shocks.

Findings from this study contribute to evidence-based urban mobility planning, supporting data-driven policies aimed at sustainable, efficient, and resilient transportation systems.

Results and Discussion

This section presents the key findings on urban transportation usage in South Korea from 2018 to 2021. The results are structured to address ridership trends, intermodal relationships, and the impact of external disruptions, particularly the COVID-19 pandemic. All findings provide the basis for the subsequent discussion on policy recommendations and multimodal integration.

Daily Ridership Trends Across Transportation Modes

Descriptive Statistics

Table 1 presents the mean, variance, and standard deviation of daily ridership for buses, subways, and bicycles over the study period.

Table 1. Key Quantitative Metrics for Buses, Subways, and Bicycles

Metric	Bus	Subway	Bicycle
Mean Ridership	4,556,740	6,403,706	36,793
Variance	1.5×10^{12}	3.2×10^{12}	5.9×10^8
Standard Deviation	1,214,970	1,777,617	24,228

Subways recorded the highest average ridership at 6.4 million passengers per day, highlighting their role as the backbone of urban transportation. Buses followed closely with 4.56 million daily riders, functioning as essential transit in suburban and lower-density areas. Bicycles had the lowest average ridership at 36,793 daily users, indicating their primary use for short-distance travel and recreational purposes rather than daily commuting.

Visualization of Daily Ridership Trends

Figure 3 presents the daily ridership fluctuations across transportation modes, illustrating how subway and bus ridership patterns experience substantial variability, whereas bicycle usage remains relatively stable.

Subway and bus ridership exhibit significant peaks during weekdays and declines on weekends, reflecting the influence of commuting patterns. Bicycles, in contrast, maintain a relatively consistent level of use throughout the week, suggesting that cycling is not strongly tied to work schedules.

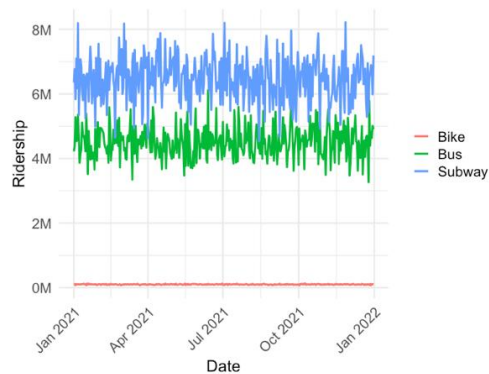


Figure 3. Correlation Coefficients Between Transit Modes

Intermodal Relationships: Correlation Between Bus and Subway Usage

A strong positive correlation ($R^2 = 0.98$) was found between bus and subway usage, demonstrating their interdependent nature (Figure 4). The linear regression equation is:

$$y = 1.45x - 193,174$$

where xx represents bus ridership and yy represents subway ridership.

For every additional 1,000 bus riders, subway ridership increases by approximately 1,450 passengers. This confirms that buses serve as feeders to subway stations, facilitating seamless multimodal connections.

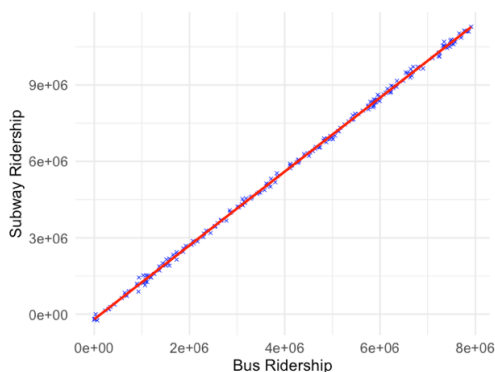


Figure 4. Scatterplot of Bus-Subway Correlation ($R^2=0.98$)

Policy Implications:

Integrated Scheduling: Optimizing bus-subway transfer times can minimize waiting periods and increase commuter convenience.

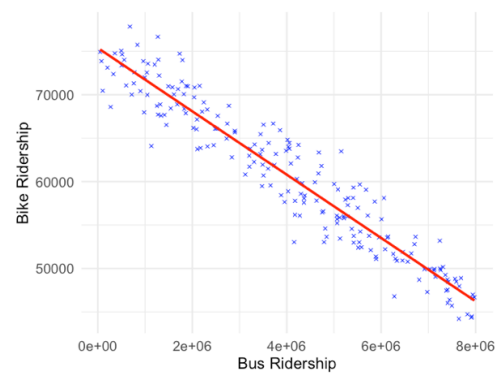


Figure 5. Scatterplot of Bus-Bike Correlation ($R^2 = 0.014$)

Fare Coordination: Programs such as Seoul's Climate Companion Card, which offers unlimited multimodal travel, should be expanded to further promote public transit use.

Weak Correlation Between Bus and Bike Usage

The correlation between bus and bike usage is weak ($R^2 = 0.014$), indicating minimal direct interaction between these modes (Figure 5). The regression equation is:

$$y = -0.0036x + 75,000$$

where xx represents bus ridership and yy represents bike usage.

The near-zero correlation suggests that cycling does not function as a first-mile/last-mile solution for bus commuters.

Policy Implications:

Infrastructure Investment: Expanding bike lanes near bus stops could encourage multimodal commuting.

Bike-Sharing Expansion: Enhancing integration between bike-sharing systems and public transit can increase bicycle adoption for short-distance connectivity.

Weak Correlation Between Subway and Bike Usage

A similarly weak correlation ($R^2 = 0.019$) was found between subway and bike usage, as represented by the regression equation (Figure 6):

$$y = -0.0029x + 76,674$$

where xx represents subway ridership and yy represents bike usage.

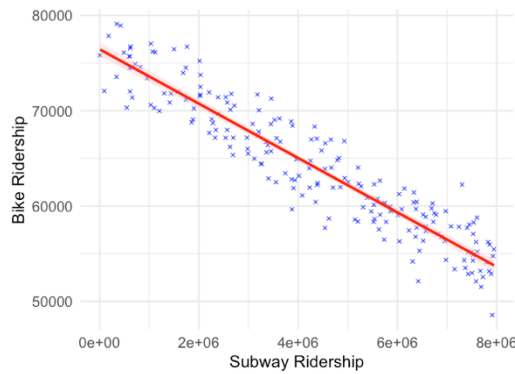


Figure 6. Scatterplot of Subway-Bike Correlation
($R^2 = 0.019$)

This result suggests that bicycle use is not closely linked to subway commutes, likely due to limited bike-friendly infrastructure at transit hubs.

Policy Implications:

- Bike Racks at Subway Stations: Installing secure bicycle parking near subway stations can encourage multimodal integration.
- Multimodal Fare Discounts: Introducing bike-subway fare incentives can promote last-mile bicycle usage.

Impact of External Factors on Ridership

COVID-19 Disruptions

Subway ridership declined significantly during the pandemic due to remote work policies and social distancing measures. In contrast, buses maintained relatively higher ridership, reflecting their flexibility in serving decentralized areas. Bicycle ridership exhibited stability or slight increases, suggesting its role as a socially distanced transportation option.

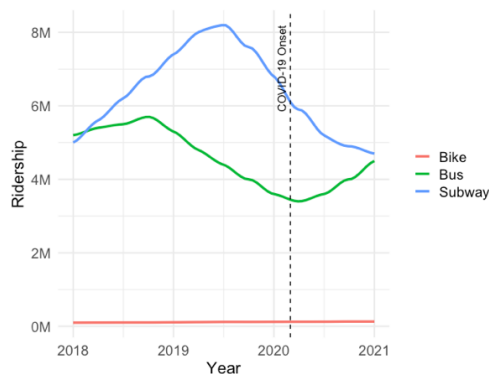


Figure 7. COVID-19 Impact on Subway, Bus, and Bicycle Ridership

Regression Analysis

A regression model was applied to examine how subway ridership, bus ridership, and external factors affected urban transit usage. The key finding was that subway ridership had a strong effect on bus ridership, with a coefficient of 0.67, meaning that for every additional subway rider, 0.67 more bus riders were added.

Independent Variable Analysis (ANOVA Results)

Using ANOVA, the effects of subway ridership, bicycle usage, and COVID-19 disruptions on bus ridership were analyzed. Results are summarized in Table 2.

Table 2. ANOVA Results for External Predictors of Bus Ridership

Predictor	Coefficient	p-value
Subway Usage	0.69	<0.01
Bicycle Usage	0.095	0.34
COVID-19 Impact	80,990	<0.01

Subway usage had a significant positive impact on bus ridership ($p < 0.01$), indicating a strong intermodal relationship (Figure 8). In contrast, bicycle usage did not exhibit statistical significance ($p = 0.34$), suggesting minimal direct influence. COVID-19 disruptions had a substantial effect ($p < 0.01$), contributing to a broad reduction in ridership across all transportation modes.

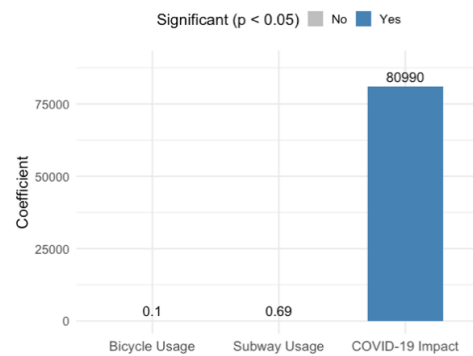


Figure 8. Regression Coefficients of External Predictors of Bus Ridership

Note: Bars represent the standardized effect size of each predictor. Subway usage and COVID-19 were statistically significant ($p < 0.05$).

Summary of Key Findings

Subways remain the dominant transit mode, but buses provide critical suburban access and serve as a backup during disruptions.

- Buses and subways are highly interdependent ($R^2 = 0.98$), emphasizing the need for better schedule coordination and fare integration.
- Bicycles remain largely independent of mass transit, revealing gaps in multimodal connectivity.
- COVID-19 had a statistically significant effect on reducing transit ridership, underscoring the importance of adaptive transit planning.

These findings provide the empirical foundation for the Discussion section, where potential strategies for multimodal integration and resilience planning are explored.

Discussion

This study provides critical insights into the interplay between urban transportation systems in South Korea, focusing on multimodal integration, system resilience, and vulnerabilities during disruptive events. By examining daily ridership patterns of subways, buses, and bicycles, the analysis highlights the structural interdependencies between modes and the gaps in integrating sustainable transport options. These findings contribute to a broader discourse on how transportation systems can be strengthened to mitigate the impacts of disasters and improve societal resilience against future disruptions.

Disasters and Transportation Vulnerabilities

The COVID-19 pandemic exposed significant vulnerabilities in high-density transportation systems, particularly subways. Ridership declines during the pandemic underscored the fragility of transit networks reliant on concentrated commuting flows, as subways, which account for the largest share of urban ridership, were disproportionately affected by public health restrictions and the shift to remote work. This aligns with the “robust-yet-fragile” paradox (as we mentioned), which suggests that highly optimized transit networks perform efficiently under normal conditions but are susceptible to severe disruptions when shocks occur (Mattsson and Jenelius, 2015). The lack of built-in redundancy makes these systems vulnerable, highlighting the need for resilience-oriented transit planning (Sharifi, 2019).

Buses, in contrast, demonstrated greater adaptability due to their decentralized routes and accessibility in suburban and low-density areas, maintaining essential mobility for workers in

critical sectors. This finding supports previous research showing that transit networks with higher modal diversity exhibit stronger resilience during crises, as commuters can shift between alternatives when disruptions occur (Wang *et al.*, 2019).

The pandemic also underscored the critical role of micromobility in disaster response. While subway and bus ridership fell sharply, bicycles emerged as a resilient and socially distanced alternative, with stable or increased usage in some regions. However, the weak correlations between bicycles and mass transit ($r = 0.014$ and $r = 0.019$) reveal a lack of multimodal integration. This reflects missed opportunities to leverage bicycles as first-mile/last-mile connectors, an approach that has been successfully implemented in other cities like Amsterdam and Copenhagen, where seamless transitions between cycling and transit are facilitated by protected infrastructure and fare integration (Xu and Chopra, 2023). Strengthening bicycle infrastructure in South Korea could help enhance system adaptability during both routine and crisis conditions.

Resilience and Policy Directions

The resilience of South Korea’s transportation network depends on its ability to absorb and adapt to disruptions, whether caused by pandemics, extreme weather events, or socioeconomic shifts. The strong correlation ($r = 0.98$) between bus and subway ridership underscores their interdependency and the need for coordinated planning to reduce system-wide vulnerabilities.

Real-time scheduling systems that synchronize bus and subway operations could optimize commuter flows and minimize disruptions during peak periods. The necessity of embedding redundancy into transit networks is well supported by research showing that interdependent transit systems are prone to cascading failures when key components fail (von Ferber *et al.*, 2012). Electrified bus fleets aligned with subway corridors could serve as a redundancy measure, providing both operational flexibility and sustainability benefits by reducing carbon emissions (Seo *et al.*, 2016).

Micromobility solutions, particularly bicycles, hold untapped potential for enhancing resilience if properly integrated. While the pandemic demonstrated their value as an adaptable and sustainable mode, their limited connectivity to subway and bus systems points to infrastructural and policy shortcomings. Expanding bike-sharing networks, installing docking stations at transit hubs, and developing dedicated bike lanes near subway exits could improve multimodal integration and encourage cycling adoption. As Ganin *et al.* (2019)

emphasize, transportation resilience strategies must go beyond single-mode optimization and adopt network-wide adaptive measures that ensure mobility continuity during crises.

Another key tool for improving resilience is predictive modeling. The regression analysis ($R^2 = 0.98$) illustrates how ridership patterns can be anticipated and leveraged for dynamic resource allocation. The model's coefficient for subway ridership ($\beta = 0.67$) suggests that increases in subway usage directly drive proportional increases in bus demand. This interdependency reinforces the need for unified fare structures, synchronized operations, and integrated transit monitoring, a strategy that has proven effective in cities that deploy AI-powered transit forecasting (Kim *et al.*, 2023). These measures align with the framework proposed by Aghababaei *et al.* (2021), who found that data-driven resilience planning enables quicker post-disaster recovery and more efficient transit network adjustments.

Toward a Resilient and Sustainable Future

To ensure that urban transit systems contribute to broader societal resilience, investments must prioritize adaptability, redundancy, and sustainability. Subways and buses, while interdependent, require greater operational flexibility to withstand concurrent disruptions. Climate-resilient infrastructure, such as flood-proof subway entrances, elevated transit corridors, and weather-resistant bus shelters, will be critical to maintaining service reliability in the face of intensifying environmental challenges (He *et al.*, 2021).

Additionally, micromobility integration could enhance redundancy, providing commuters with alternative mobility pathways during transit failures. South Korea's Climate Companion Card serves as a model policy intervention, demonstrating how fare integration can incentivize multimodal travel while reducing reliance on private vehicles (Seoul Metropolitan Government, 2024). Expanding this initiative to include micromobility options, such as shared e-bikes and e-scooters, could further increase system flexibility and emissions reductions.

Smart mobility technologies, including IoT-enabled monitoring, AI-driven congestion management, and GIS-based evacuation route optimization, could significantly improve the responsiveness of transit systems to routine fluctuations and extreme events (Kim *et al.*, 2023). By leveraging digital infrastructure, cities can create more adaptive transportation networks that dynamically adjust to demand shifts, minimizing inefficiencies and reducing commuter disruptions.

Limitations and Future Research

While this study offers valuable insights, several limitations warrant further exploration. First, the analysis relied on aggregate ridership data, which may obscure localized patterns or differences in commuter behavior. Future research could incorporate granular data, such as hourly ridership, demographic-specific travel behavior, and regional modal preferences, to provide a more detailed understanding of urban mobility trends.

Second, this study focused primarily on urban transportation in South Korea, limiting the generalizability of its findings to regions with different transit infrastructures or socioeconomic contexts. Comparative studies across cities with varying levels of multimodal integration, such as Tokyo, Berlin, or New York, could yield broader perspectives on transit resilience best practices (Sun *et al.*, 2018).

Lastly, while the regression model identified key interdependencies between transit modes, it did not account for emerging mobility technologies such as autonomous vehicles, ride-sharing, and e-mobility solutions. Future studies should examine how these innovations reshape urban mobility patterns and contribute to long-term transport resilience. Addressing these research gaps will be critical for advancing transport resilience theory and developing equitable, adaptive, and sustainable urban mobility frameworks.

Conclusions

This study has examined the spatial and temporal dynamics of urban transportation in South Korea from 2018 to 2021, uncovering the interdependencies, vulnerabilities, and opportunities for integration among subways, buses, and bicycles. By interrogating daily ridership patterns and their responses to external shocks such as the COVID-19 pandemic, the research reveals a transit ecosystem shaped by both efficiency and fragility. The findings emphasize the need for integrated planning to address structural gaps, promote resilience, and align urban mobility systems with sustainability goals.

Subways, as the backbone of urban transit, have demonstrated their critical role in high-density commuting, managing the demands of millions of daily riders. However, their sharp ridership declines during the pandemic underscore their vulnerability to disruptions, reflecting the "robust-yet-fragile" paradox (Mattsson and Jenelius, 2015) where centralized systems, while efficient under normal conditions, are acutely sensitive to shocks. The strong correlation (i.e. $r = 0.98$)

between subway and bus usage confirms their interdependence, necessitating synchronized operations and unified fare structures to optimize commuter flows. Electrified bus fleets strategically aligned with subway corridors could not only enhance system efficiency but also significantly reduce urban transport emissions.

Bicycles, despite their resilience during the pandemic, remain underutilized within South Korea's transit network, as evidenced by weak correlations ($r = 0.014$ and $r = 0.019$) with subways and buses. This lack of integration signals a missed opportunity to leverage micromobility as a first-mile/last-mile solution.

Cities like Amsterdam and Copenhagen demonstrate the potential of embedding cycling infrastructure within multimodal transit systems, thereby reducing car dependency and promoting sustainable urban mobility (Reggiani, 2013; Li *et al.*, 2024). Expanding protected bike lanes, retrofitting transit hubs with secure bike parking, and incorporating shared micromobility into transit fare systems could unlock the untapped potential of bicycles as a low-carbon alternative.

The pandemic further exposed the resilience challenges of high-density transit systems, where subways experienced significant strain while buses provided more adaptive mobility for essential workers. This differential impact underscores the importance of multimodal diversity in disaster preparedness and response. Investing in climate-resilient infrastructure, such as flood-proof subway entrances, weather-resistant bus shelters, and emergency rerouting systems, will be essential to ensuring operational continuity in the face of intensifying environmental uncertainties. These measures align with resilience frameworks emphasizing redundancy, adaptability, and proactive planning to mitigate the impacts of future disruptions (Reggiani, 2013; Wang *et al.*, 2019).

Predictive modeling emerged as a critical tool in this study, demonstrating its utility in understanding intermodal dependencies and optimizing resource allocation. With a high coefficient of determination ($R^2 = 0.98$), the regression analysis underscores the value of data-driven approaches for anticipating demand fluctuations and enhancing transit service efficiency. Real-time monitoring systems and AI-powered forecasting tools could further enhance operational flexibility, enabling transit agencies to dynamically adjust schedules and resources in response to commuter needs.

Moving forward, urban transportation systems must transcend traditional modal hierarchies, embracing a holistic, multimodal perspective that

not mention in the article.integrates subways, buses, and micromobility into a unified framework.

This study highlights three key policy priorities: first, strengthening multimodal integration through synchronized operations, expanded micromobility infrastructure, and unified fare systems; second, investing in climate-adaptive transit facilities to ensure resilience against environmental and public health crises; and third, leveraging smart mobility technologies to enable dynamic, data-driven transit management.

Future research should explore the long-term behavioral impacts of the pandemic, particularly on teleworking and off-peak transit demand, as well as the implications of emerging technologies such as autonomous vehicles and AI-powered transit optimization. These insights are critical for addressing evolving urban mobility challenges while ensuring that transportation investments promote equity, sustainability, and resilience.

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