Linking COVID-19 Ridership Changes with Tokyo Metro Centralities

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Introduction

Complex Network Theory (CNT) enables the identification of critical nodes through centrality analysis and has been applied to aviation (Kong, 2023), railways (Liu et al., 2020), and multimodal transport systems (Zhou et al., 2021), as well as to metro systems (Vichiensan et al., 2023). However, studies on metro networks often overlook key factors such as passenger volume and travel time, focusing only on topological structure. This study addresses these gaps by incorporating both passenger volume and travel time into the Tokyo Metro network analysis. After redefining weighted centrality metrics, it further examines the relationships between COVID-19-induced ridership shifts and these weighted centrality measures.

Centralities

a) Strength Degree Centrality: Strength degree centrality quantifies the connectivity intensity of a station by summing the weights of all its connected edges. Unlike traditional methods that only consider edge-based weights, this approach incorporates both passenger volumes and comprehensive travel time, calculated as:

$$S(i) = \sum_{j \in \Gamma(i)} \frac{\frac{P_i}{d_i} + \frac{P_j}{d_j}}{2 \cdot T(i,j)},$$

where, P_i and P_j are total passenger volumes of stations i and j, d_i and d_j are the numbers of edges connected to stations i and j, $T(i,j)$ is comprehensive travel time between stations.

b) Betweenness Centrality: Betweenness centrality reflects a station's role in facilitating transfers, computed by the proportion of shortest paths passing through it. This method incorporates passenger volumes to emphasize high-flow routes:

$$B(i) = \sum_{s \neq t \neq i} P_s \cdot P_t \cdot \frac{\sigma_{st}(i)}{\sigma_{st}},$$

where, σ_{st} is the number of shortest paths between stations s and t, $\sigma_{st}(i)$ is the number of these shortest paths that pass through stations i.

c) Closeness Centrality: Closeness centrality evaluates how centrally located a station is. In this study, it incorporates both passenger volume and comprehensive travel time to reflect network accessibility more realistically:

$$C(i) = \frac{\sum_{j \neq i} P_j}{\sum_{j \neq i} P_j \cdot T(i,j)}.$$

Coupling of Pandemic Ridership Shifts and Weighted Centrality Metrics

Based on station-level passenger volumes before and after COVID-19, the Figure 1(a) visualizes the distribution of ridership from 2019 to 2023, expressed as a ratio relative to the 2019 baseline. Figure 1(b) illustrates the outlier stations identified each year, where "above-trend" means ridership recovery was significantly stronger than the yearly average, and "below-trend" means it lagged significantly behind the network-wide recovery pace.

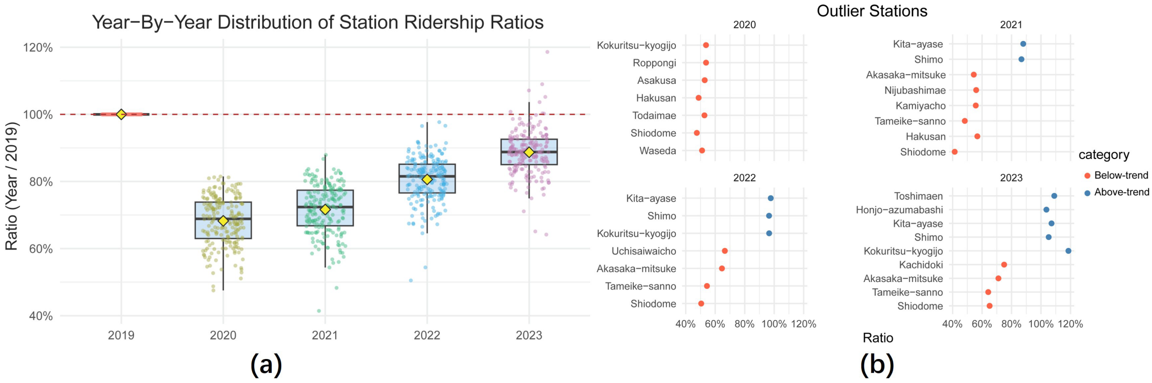

Figure 1. Yearly Ridership Distributions and Outlier Stations.

Figure 1 shows 17 identified outlier stations. To further investigate their relationship with three centralities mentioned above, centrality metrics were calculated using 2019 data, and stations were subsequently ranked according to the value of each centrality, as illustrated in Figure 2.

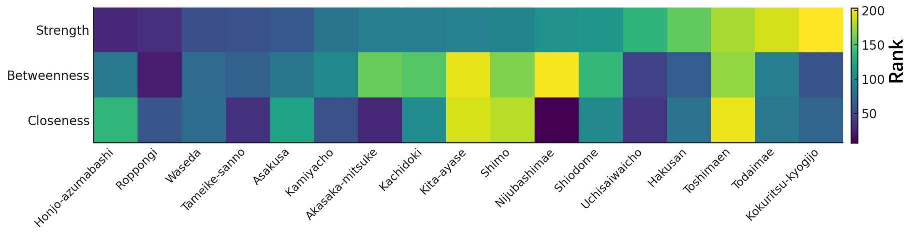

Figure 2. Centrality Rankings of Outlier Stations Across Three Metrics.

Based on their 2019 weighted centrality ranks, the outlier stations were grouped into eight types. Specifically, Table 1 shows these types and their outlier status.

Table 1 Passenger-count outliers for selected Tokyo Metro stations

Category	Station(s)	Outlier status
All/Most Indicators High	Roppongi / Kamiyachō / Waseda / Tameike-sannō / Uchisaiwaichō	Below-trend outlier
All/Most Indicators Low	Toshimaen / Shimo / Kita-ayase	Above-trend outlier
Typical High C/High B	Akasaka-mitsuke/ Nijūbashimae/ Hakusan	Below-trend outlier
Typical Low S	Todaimae	Below-trend outlier
Typical High S	Asakusa	Below-trend outlier
	Honjō-azumabashi	2023 Above-trend outlier
High B & Low S	Kokuritsu-kyōgijō	2020 Below-trend; 2022, 2023 Above-trend
Typical Low B	Kachidoki	Above-trend outlier
Balanced station	Shiodome	Below-trend outlier

As shown in the table, stations with high weighted centrality in 2019 typically reflect areas of intense pre-pandemic activity and experienced sharp ridership declines during both the pandemic and recovery phases. In contrast, stations with low centrality scores showed smaller ridership reductions, indicating greater resilience. Exceptions include Todaimae, likely affected by policies at the University of Tokyo, and Shiodome, which exhibited balanced centrality rankings but experienced a notable decline, possibly due to its office-dense surroundings. Kokuritsu-kyōgijō showed an unusual increase in 2023, potentially due to renewed development plans in the area. These cases suggest that ridership trends are not solely determined by network centrality. Overall, weighted centrality appears linked to pandemic ridership shifts, though further analysis is needed to clarify the relationship.

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