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Istanbul Rail Transit Ridership Changes: The Impact of Station Characteristics and Network Growth (2013–2023)

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ABSTRACT

The expansion of Istanbul's rail transit network from 2013 to 2023 has significantly reshaped the city's transportation landscape. This study explores how station characteristics and network growth have influenced changes in rail transit ridership over this period, offering valuable insights for urban planners and policymakers. By examining station location, line type, ridership levels, and opening dates, the research aims to uncover the key factors driving these shifts. The analysis focuses on five phases of network growth, using non-parametric statistical methods to assess the impact of these variables on ridership patterns. In this context, the study aims to define the relationship between station characteristics and ridership trends and highlight the main factors contributing to ridership changes. The findings reveal that station location played a critical role, with European-side stations initially experiencing higher ridership due to their proximity to economic hubs. However, as the network expanded into suburban areas, particularly on the Asian side, ridership growth in these stations accelerated, narrowing the gap. Additionally, the research explores the roles of metro, tram, and commuter rail lines, each contributing to distinct ridership behaviors due to their varying speeds, frequencies, and service areas. Notably, ridership demand levels revealed a widening disparity, with high-demand stations experiencing significant increases while low-demand stations stagnated. This phenomenon can likely be attributed to factors such as network expansion, urban development, and shifting travel patterns favoring heavily used stations. Newly opened stations also exhibited initial fluctuations in ridership, while older stations showed steady, moderate growth. The study concludes that understanding these factors is essential for optimizing future transportation planning in rapidly expanding cities like Istanbul. The insights from this research provide a framework for enhancing rail infrastructure, improving connectivity, and promoting sustainable urban mobility, with direct implications for planners, designers, and city officials.

İstanbul Raylı Ulaşım Yolculuk Sayısı Değişimleri: İstasyon Özellikleri ve Ağ Büyümesinin Etkisi (2013–2023)

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ÖZET

İstanbul'un 2013'ten 2023'e kadar olan raylı ulaşım ağının genişlemesi, şehrin ulaşım manzarasını önemli ölçüde şekillendirmiştir. Bu çalışma, istasyon özelliklerinin ve ağ büyümesinin bu dönem boyunca raylı ulaşım yolcu sayısındaki değişiklikleri nasıl etkilediğini araştırarak, şehir plancıları ve politika yapıcılar için değerli bilgiler sunmaktadır. İstasyon konumu, hat türü, yolcu sayısı ve açılış tarihleri gibi değişkenleri inceleyerek, araştırma bu değişimlere neden olan ana faktörleri ortaya çıkarmayı hedeflemektedir. Analiz, bu değişkenlerin yolcu sayısı üzerindeki etkisini değerlendirmek için beş aşamalı ağ büyümesine odaklanmakta ve parametrik olmayan istatistiksel yöntemler kullanılmaktadır. Bu bağlamda, çalışma istasyon özellikleri ile yolcu sayısı trendleri arasındaki ilişkiyi tanımlamayı ve yolcu sayısındaki değişimlere katkıda bulunan ana faktörleri vurgulamayı amaçlamaktadır. Bulgular, istasyon konumunun kritik bir rol oynadığını göstermektedir; Avrupa yakasındaki istasyonlar, ekonomik merkezlere yakınlıkları nedeniyle başlangıçta daha yüksek yolcu sayısına sahip olmuştur. Ancak, ağın özellikle Anadolu yakasında banliyö bölgelerine yayılmasıyla birlikte, bu istasyonlardaki yolcu sayısı artışı hızlanmış ve fark daralmıştır. Ayrıca, metro, tramvay ve banliyö tren hatlarının rolleri de incelenmektedir; her biri farklı hız, sıklık ve hizmet alanları nedeniyle çeşitli yolcu davranışlarına katkıda bulunmaktadır. Dikkat çekici bir şekilde, yolcu talep seviyeleri arasındaki farkın genişlediği görülmektedir; yüksek talep gören istasyonlar önemli artışlar yaşarken, düşük talep gören istasyonlar durağan kalmıştır. Bu fenomen, muhtemelen ağ genişlemesi, kentsel gelişim ve yoğun kullanılan istasyonları tercih eden değişen seyahat desenleri gibi faktörlere atfedilebilir. Yeni açılan istasyonlar da yolcu sayısında başlangıçta dalgalanmalar göstermişken, daha eski istasyonlar istikrarlı, ılımlı bir büyüme sergilemiştir. Çalışma, bu faktörleri anlamanın, İstanbul gibi hızla büyüyen şehirlerde gelecekteki ulaşım planlamasını optimize etmek için hayati önem taşıdığını sonucuna varmaktadır. Bu araştırmanın bulguları, demiryolu altyapısının güçlendirilmesi, bağlantıların iyileştirilmesi ve sürdürülebilir kentsel hareketliliğin teşvik edilmesi için bir çerçeve sağlamaktadır; bu da doğrudan planlamacılar, tasarımcılar ve şehir yetkilileri için etkilere sahiptir.

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INTRODUCTION

In the ever-evolving landscape of urban transportation planning, cities worldwide are increasingly turning to modern railway systems to alleviate traffic congestion and reduce the environmental impact caused by heavy reliance on personal vehicles (Kenworthy & Newman, 2015; Weiner, 2016, p. 1). Istanbul, a bustling metropolis known for its rich historical and economic significance and unique geographical location, exemplifies this trend amidst unbridled urban sprawl and rapid population growth. As the city has expanded to cover 5,461 square kilometers and accommodate over 15.6 million residents by 2023 (TUİK, 2024), the demand for efficient public transportation has surged, necessitating substantial investments in its railway network.

Over the past decade, Istanbul Metropolitan Municipality and urban transport planners have responded with unprecedented growth in the city's railway infrastructure, marked by the rapid opening of new stations and lines (IBB, 2023a). This expansion not only enhances accessibility but also reshapes the performance and dynamics of the entire transit network, significantly influencing station characteristics and ridership patterns (Kim et al., 2018; Meng et al., 2018). With new lines put into operation, the urban rail transit system capacity is improved, which greatly affects the passenger flow distribution of the existing network. The transportation pressure of the existing network is relieved due to the increased transportation capacity, and new stations share passenger flow with existing stations. On the other hand, the higher transportation accessibility induces new latent trips for existing stations and attracts more passengers from other modes (Liu et al., 2017). Ridership preferences and behavior are influenced by the type of railway line (whether metro, tram, or train), as each has unique characteristics such as speed, frequency, distance traveled, and pricing policies (Kusakabe et al., 2010). These differences contribute to variations in passenger flows depending on the type of line in operation. Despite transportation policies aimed at narrowing these disparities, the locational features of the lines within the network and their connections with other lines play a major role in influencing flow changes for different types of lines. Understanding how factors such as station ridership volume, line type, location, and opening date affect changes in passenger flow distribution at the station level is critical for optimizing transportation resources and planning future network expansions.

This study aims to illuminate the pivotal role of station characteristics in shaping ridership changes as Istanbul's railway network continues to evolve. Focusing on the dynamic growth of Istanbul's railway infrastructure, we analyze trends from 2013 to 2023, segmented into five distinct periods. By employing non-parametric and categorical analysis methods, we assess how various station attributes impact changes in passenger numbers across these intervals. Our goal is to offer insights that will inform effective urban transportation strategies and promote sustainable development in this vibrant global city.

LITERATURE REVIEW

Rail transit ridership change refers to the variation in the number of passengers using a rail transit system (such as a metro, train, or tram) over time. These changes can reflect short-term fluctuations (daily or weekly) or long-term trends (yearly or over decades). Transit ridership change has garnered significant attention in the public transit field, and many studies have attempted to explain it (Balcombe et al., 2004; Driscoll et al., 2018; Taylor et al., 2009). Both descriptive and causal analyses of previous studies have examined a range of factors related to transit ridership (Taylor & Fink, 2003), these elements can be broadly divided into two categories (Stanley, 1995; Thompson & Brown, 2006):

External factors, which are mostly exogenous to the system and its managers, such as changes in service area population and employment, levels of automobile ownership, economic conditions, urban density, land-use diversity, demographic characteristics, etc.

Internal factors, which are factors that transit managers have some control over, such as fare policies, service levels, service reliability, and so on.

Many studies have found that external factors typically have a greater impact on changes in ridership than internal factors (Du et al., 2023; Liu et al., 2019). Nevertheless, for example, increased population growth may alter the demand for transit services, which in turn may lead to changes in service provision levels. Therefore, there is no strict dividing line separating internal from external factors (Taylor & Fink, 2003). This indicates that factors change simultaneously through emerging correlations and interactions, collectively influencing changes in ridership—whether positive or negative.

Rail transit network growth, particularly physical expansion, is one of the most critical and multifaceted factors influencing the dynamics of urban transit systems. When a new station or line becomes operational, it triggers a series of interconnected changes that significantly alter the distribution of passenger numbers. Previous studies have found that these changes are influenced by several effects (Du et al., 2023; Liu et al., 2019; Werner et al., 2016), including:

Natural Ridership Growth: One of the most straightforward effects is the natural increase in ridership. As cities expand and experience social and economic development, the number of people using transit naturally rises (Calvo et al., 2019).

Diverted Ridership: This refers to the movement of passengers from one line to another, often occurring when the catchment areas of multiple stations overlap. This is especially prevalent in transit systems with dense networks where passengers have multiple route options. The accessibility and convenience offered by the new station influence passengers' route choices, leading to a redistribution of ridership across the network (Liu et al., 2017).

Induced Ridership: This less predictable impact results from shifts in travel mode when passengers who previously used private vehicles, bicycles, or other modes switch to the rail transit system. It may also include the creation of entirely new trips that wouldn't have occurred without the new transit infrastructure. The increased accessibility, reduced travel costs, or greater convenience provided by the new station or line drive these changes (Gunn et al., 1992; Liu et al., 2017; Sperry & Dye, 2020).

Amidst these complex effects, existing stations experience changes in passenger numbers due to shifts in traveler behaviors and patterns. As passengers reorganize their travel routes and transition across different lines, their interactions with the network as a whole are transformed (Du et al., 2023; Li et al., 2020).

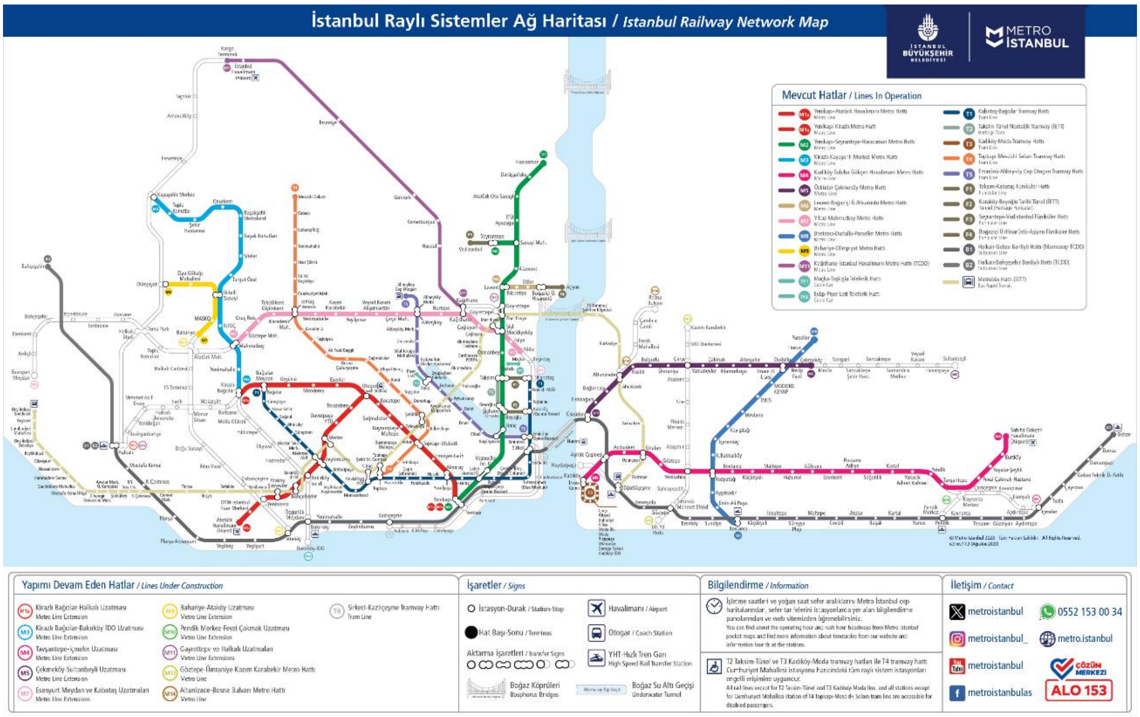
Numerous studies have demonstrated that the opening of new rail lines or stations significantly impacts the functional characteristics of existing stations within a transit network. Stations may assume new roles, such as becoming transfer or terminal points, and the characteristics of the lines they are connected to may also change, as the integration of new stations often requires a reorganization of the line's operations, including adjustments to travel schedules and frequency. Transit agencies may need to modify timetables to ensure better coordination with other intersecting lines, especially when a new station becomes a crucial transfer point (Fu & Gu, 2018; Peng et al., 2021; Werner et al., 2016; Zhao et al., 2013). Ultimately, these changes to station functionality, line characteristics, and travel behavior contribute to shifts in ridership across the network. The interaction of these factors can lead to increased demand at certain stations while decreasing it at others, reflecting the dynamic nature of rail network evolution over time.

CASE STUDY: The Evolution of Istanbul's Rail Network and Its Influence on Ridership Dynamics

Istanbul, a vibrant metropolitan city connecting Europe and Asia, presents a unique case for analyzing the impact of rail transit network growth on changing ridership trends. Long a transportation hub with a rail system dating back many decades, the city has seen the rapid expansion of its rail network in recent years, with the most significant growth occurring over the past ten years. As of April 1, 2024, Istanbul's rail network includes approximately 277 stations,—including stations of metro, train, tram, funicular, and cable car lines_ (Metro_istanbul, 2024) (Figure 1). This rapid expansion has led to fluctuations in passenger flows, reshaping ridership distribution across the city. Station characteristics, such as location, connectivity, and function within the network, have played a critical role in these changes. This dynamic interaction between network growth, station-specific factors, and demand volume illustrates the complexity of managing urban mobility in the rapidly expanding city of Istanbul.

Figure 1

Istanbul railway network (2023) (Metro_Istanbul, 2023)



Rail Network Expansion by Phases

Between 2013 and 2023, the Istanbul Metropolitan Municipality launched several new lines and extensions of existing routes, with numerous stations opening each year (Figure 2). For the purposes of this study, the growth of Istanbul's rail network from 2013 to 2023 can be divided into five key phases (Figure 3) (IBB, 2024; Türkiye_Yüzyılı, 2024):

Phase 1 (2013-2015): This phase witnessed the rapid expansion of the metro network, with a focus on connecting major urban areas to boost ridership. Highlights include the opening of the M3 Kirazlı-Başakşehir/Metrokent line and the M9 İkitelli Sanayi-Olimpiyat line. Additionally, major stations were opened on the M2 line, such as Yenikapı and Haliç. The M1 line was extended with the Otogar-Kirazlı segment and was split into two services (M1A and M1B). This period also saw the operationalization of the Marmaray Line, connecting Ayrılık Çeşmesi and Kazlıçeşme, providing a crucial rail link between the European and Asian sides via the Marmaray Bosphorus crossing, significantly increasing accessibility across the city.

Phase 2 (2015-2017): New stations were added, and lines such as the M6 Levent-Boğaziçi Üniversitesi/Hisarüstü and M4's second stage (Kartal-Tavşantepe) were launched, extending service to new areas.

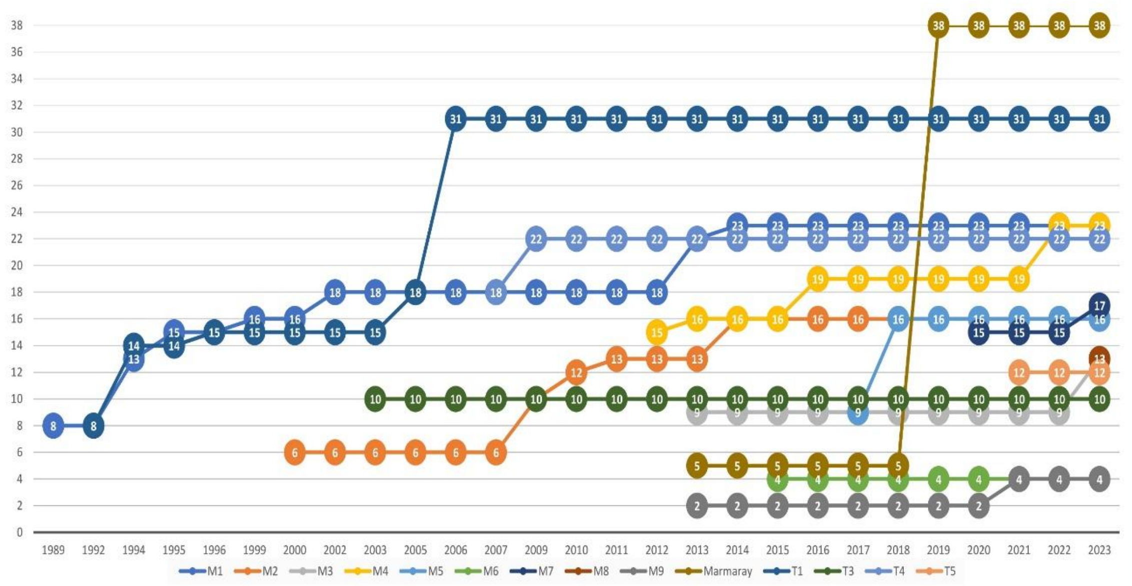
Phase 3 (2017-2019): The expansion focused on underserved areas and key transit corridors on the Asian side. The M5 Üsküdar-Çekmeköy metro line, operational in two phases during this period, played a pivotal role in expanding Istanbul's rail network, enhancing access to suburban areas.

Phase 4 (2019-2021): Despite the challenges posed by the COVID-19 pandemic, the network continued to expand, with the first stage of the M7 Kabataş-Esenyurt metro line opening between Mecidiyeköy and Mahmutbey. The Marmaray system further expanded with the full completion of the suburban commuter line, enhancing cross-city travel. By 2019, night services were introduced on six lines. This period focused on improving service continuity and coverage.

Phase 5 (2021-2023): Post-pandemic recovery saw renewed growth, with the opening of the first stage of the T5 tram line, followed by the M9 Bahariye-Olimpiyat line and further expansions on the M4 Kadıköy-Sabiha Gökçen Airport line. By 2023, stations such as Fulya and Yıldız on the M7 line, the M8 Bostancı-Dudullu line, and additional extensions on the M3 line were completed, marking the conclusion of several large projects. The Marmaray and high-speed rail networks were further integrated into the city's overall transportation system, providing faster and more efficient travel across Istanbul. Further improvements were made to night services and system capacity to meet rising demand.

Figure 2

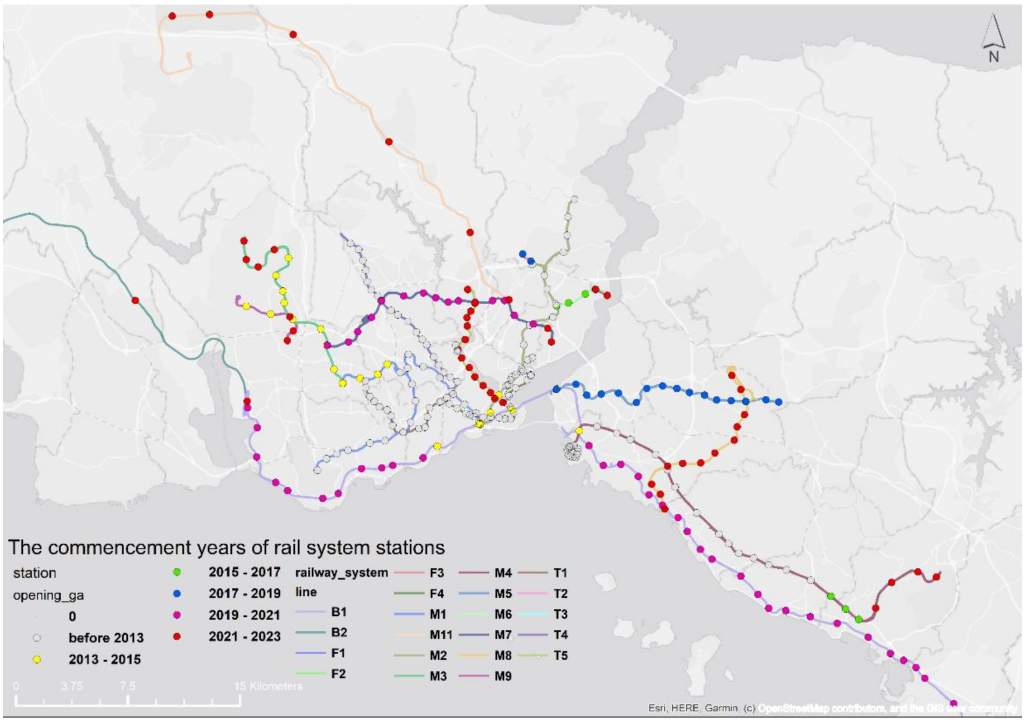
Evolution of Rail Line Stations in Istanbul (1989-2023): Growth and Expansion of the Network



These phases reflect how the rail network has adapted to the city's needs, responding to both short-term challenges and long-term growth strategies. The expansion of Istanbul's rail transit network has necessitated revisions to its operational management policies, including adjustments to service schedules, frequencies, and other internal processes to maintain efficiency. Additionally, Istanbul's economic inflation has led to rapid changes in fare policies, with fare prices increasing 11 times from 2013 to the end of 2023, six of these increases occurring in the last three years (Blog_Artı, 2024). These changes not only reflect broader economic pressures but also present challenges in ensuring equitable access and maintaining ridership levels amid rising costs.

Figure 3

Phased Growth of Istanbul's Rail Network: 2013-2023

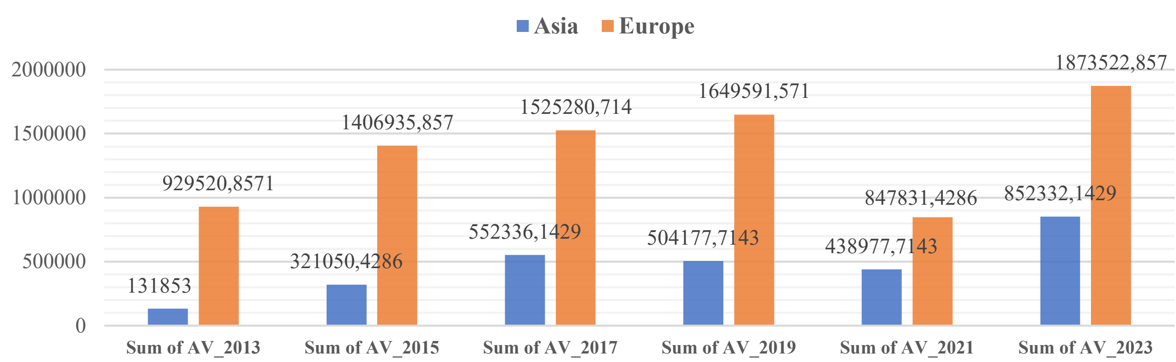


The Impact of Station Characteristics on Changes in Ridership

In Istanbul, the interplay between station characteristics and ridership changes reflects broader trends in urban transit and development dynamics, particularly when examined through the lenses of location, station opening dates, ridership levels, and line types. While most studies have focused on the station's distance from the city center (He et al., 2019; Zhao et al., 2014), the city's unique geographical division between Europe and Asia also distinctly affects transit ridership patterns. According to the years studied (Figure 4), Stations on the European side, typically denser and more integrated with historical and economic centers, often exhibit higher ridership levels. High-activity areas like Taksim, Şişli, and others on the European side attract both daily commuters and visitors, increasing ridership. In contrast, the Asian side has historically been more residential, with stations that cater primarily to local residents rather than commuters traveling to business districts. However, newer developments and expanding urban areas contribute to fluctuating ridership dynamics as new lines and stations integrate into the existing network.

Figure 4

Ridership Distribution Across Istanbul's Rail Network: Asia vs. Europe (2013-2023)

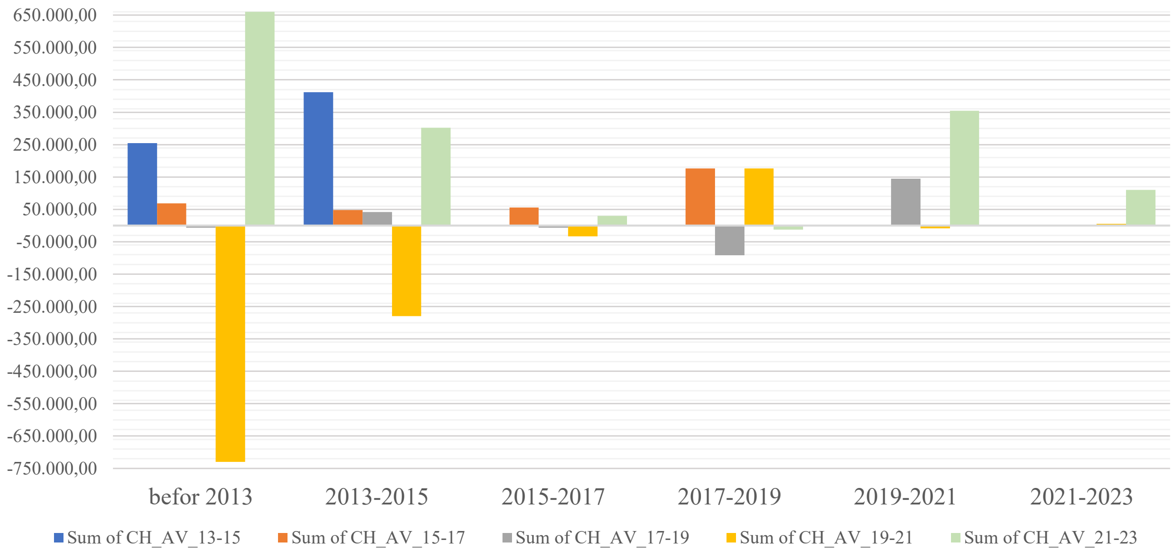


The timing of station openings can significantly impact these patterns; newer stations might initially experience lower ridership, which escalates as the surrounding areas develop and become more accessible. This causes newer stations to experience initial fluctuations in ridership, unlike older stations in established neighborhoods, which display more stable ridership dynamics and patterns (Park et al., 2016). The station's age provides a clear understanding of how new stations are integrated into the rail network. The studied periods shown in Figure 5 reveal significant fluctuations in ridership, which correspond with strategic developments in the city's rail network. The first period (2013-2015) shows a massive increase in ridership, indicated by a high positive value. This suggests that new stations opened during this time likely catered effectively to underserved areas or improved connections between key urban zones, thus attracting a large number of new riders. Conversely, the following period (2015-2017) shows a sharp decrease, possibly reflecting a stabilization in ridership after the initial surge or the influence of other factors, such as operational adjustments or socio-economic changes affecting transit usage. Analyzing further, the 2017-2019 period reveals mixed results, with slight decreases and increases in ridership, indicating a period of adjustment where ridership patterns might have been influenced by further network expansions or the maturing of routes introduced in earlier phases. Subsequent periods from 2019 to 2023 exhibit dynamic values, with both increases and decreases, as the effects of COVID-19 restrictions and their aftermath influence these changes, although some stations show different trends, such as those opened during the (2017-2019) period.

Ridership levels in Istanbul provide insights into the transit demand and the station's effectiveness in serving its area. High-ridership stations are frequently located in central business districts or key interchange nodes connecting multiple public transit types, including metro, tram, train, and bus services. Conversely, stations with lower ridership may serve peripheral or less developed areas but play a crucial role in long-term strategic urban planning for promoting sustainable transit-oriented development. (as shown in the Figure 6).

Figure 5

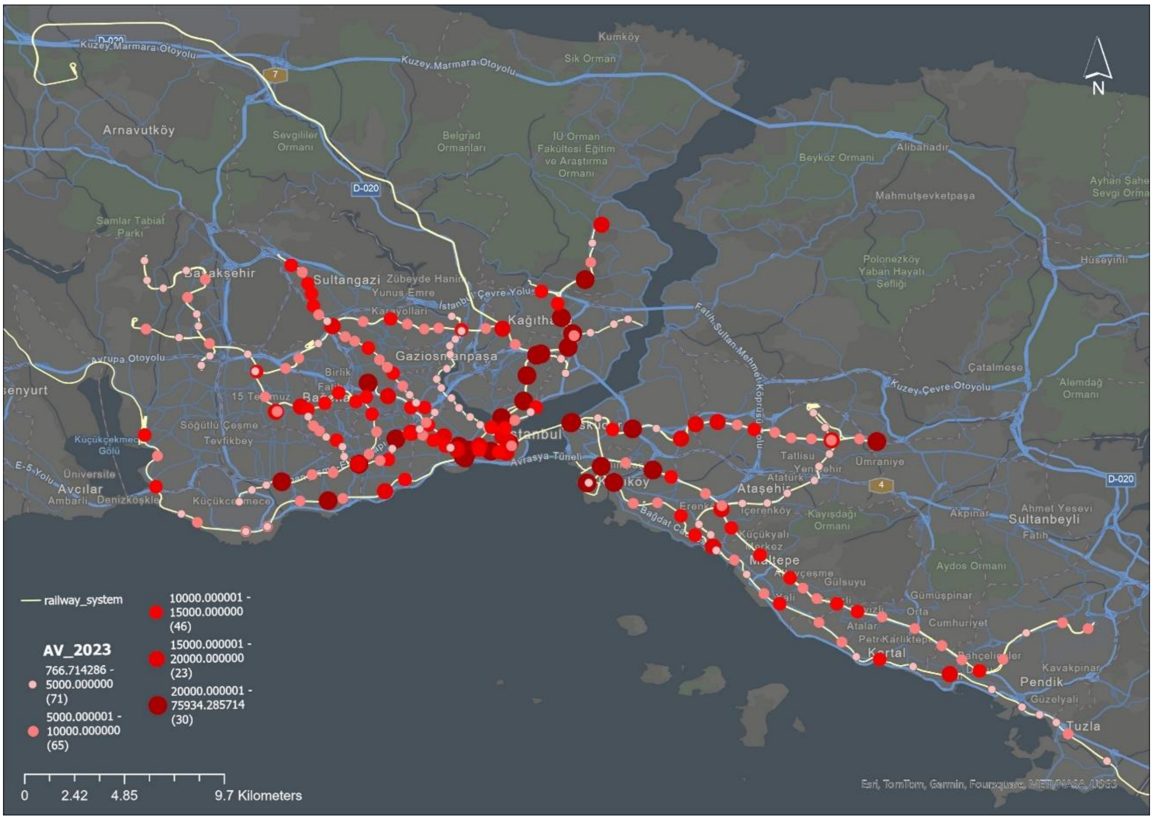
Changing Ridership Across Station Opening Phases in Istanbul's Rail Network: 2013-2023



The type of line—be it metro, tram, or commuter rail—also plays a critical role in shaping ridership trends. Metro lines serve densely populated urban areas due to their speed, frequency, and capacity. On the other hand, tram lines tend to serve slightly lower population-dense areas and shorter travel distances. While trams are slower and have relatively lower capacity, they are often integrated into Istanbul's urban fabric, serving neighborhoods and tourist areas where walking and cycling are more prevalent modes of transport. Trams are less prevalent than metros in Istanbul. Finally, suburban rail lines (such as the Marmaray line) serve passengers traveling longer distances. Although the fare policy makes the line relatively more expensive than other public rail transport, and it has a lower frequency, typical of suburban lines, increasing its frequency at inner-city stations (Ataköy – Pendik) has reduced wait times (TCDD, 2024). The Marmaray line's unique advantage of linking the European and Asian sides also has made it an attractive option, influencing changes in passenger patterns and behaviors. Although each line type serves different but complementary roles in the city's physical and non-physical transport system, their development and operational strategies significantly affect their ability to attract and maintain riders, reflecting on ridership dynamics over time.

Figure 6

Ridership Demand Levels at Stations in Istanbul's Rail Network in 2023



METHODOLOGY

Research Design and Data Collection

This research methodology is designed to address the question: What role do station characteristics—ridership levels, location, line type, and opening date—play in affecting ridership changes within the context of changing internal and external factors and the rapid growth dynamics of Istanbul's rail network from 2013 to 2023. Data was collected based on smart card (İstanbulkart) usage from 2013 to 2023 for rail transport systems operated by the Istanbul Metropolitan Municipality and the Turkish State Railways Directorate General (IBB, 2023b). The statistical average of ridership for the second week of April was used for 2013, 2015, 2017, 2019, 2021, and 2023 to calculate both the ridership change variable and the ridership levels variable.

The study uses both quantitative and descriptive data for analysis. Station characteristics were categorized as shown in Table 1. Additionally, quantitative data was utilized to assess ridership changes over the five studied phases at the station level, this relationship between variables and ridership changes was assessed using non-parametric statistical analysis due to the data's non-normal distribution.

Table 1

Categorization of Station Characteristics for Ridership Change Analysis (2013-2023)

variables	*categorical*	*2013-2015*	*2015-2017*	*2017-2019*	*2019-2021*	*2021-2023*
Location	Asia	19	38	60	60	77
	Europe	107	109	121	147	156
Line type	Metro	67	88	89	103	129
	Tram	54	54	54	66	66
	Train	5	5	38	38	38
Ridership levels	Very low (< 5000)	35	36	60	120	70
	Low (5000-10000)	30	33	46	52	64
	Medium (10000-15000)	20	33	29	14	46
	High (15000-20000)	14	15	19	7	23
	Very high (20000 <)	27	30	27	11	30
Opening date	Before 2013	100	100	100	100	100
	2013-2015	24	24	25	25	25
	2015-2017	2[A]	7	7	7	7
	2017-2019	0	16[A]	16	16	16
	2019-2021	0	0	33[A]	47	48
	2021-2023	0	0	0	12[A]	37

*The numbers represent the count of stations classified by their characteristics across the studied periods.

Note: Stations marked with ([A]) were opened from the start of the following period until April of the first year.

Statistical Analysis

In this analysis, we chose to use two non-parametric tests, the Mann-Whitney U Test and the Kruskal-Wallis Test, because these tests do not require the data to be normally distributed. These tests will help analyze differences in ridership changes at the stations based on the station's categorical characteristics for each studied phase.

The Mann-Whitney U and Kruskal-Wallis tests are nonparametric statistical tests for comparing variables between groups (McClenaghan, 2022). The Mann-Whitney U test compares two independent groups, while the Kruskal-Wallis test handles multiple groups (McClenaghan, 2023). Both tests using Eq. (1) establish the null hypothesis (H_0), which assumes similar average values across groups, and the alternative hypothesis (H_1), which assumes differences in these averages.

$$\begin{cases} H_0 : \mu_1 = \mu_1 = \ldots = \mu_n \\ H_1 : \mu_i \neq \mu_j , i \neq j \end{cases} \tag{1}$$

The Mann-Whitney U test statistic is calculated using Eq. (2) based on group sizes (n_1, n_2) and rank sums (R_1, R_2) (Mann & Whitney, 1947). In contrast, the Kruskal-Wallis test statistic is calculated using Eq. (3), where N is the total number of observations, n_i is the size of the i category, C is the total number of categories, and R_i is the sum of ranks for the i category (Kruskal & Wallis, 1952). The critical values for these tests are based on reliability levels, typically set at 0.95. If the P-value is less than 0.05, the null hypothesis is rejected, indicating significant differences between groups.

$$U = \text{Min}\left(R_1 - \frac{n_1(n_1+1)}{2}, R_2 - \frac{n_2(n_2+1)}{2}\right) \quad (2)$$

$$H = \frac{12}{N(N+1)}\sum_{i=1}^{c}\frac{R_i^2}{n_i} - 3(N+1) \quad (3)$$

After using the Kruskal-Wallis test to rank categories, the Mann-Whitney U statistical test must be used to determine whether there are significant differences between adjacent categories in the initial ranking (Washington et al., 2020). These tests, commonly used in research, were conducted in this study via SPSS.

RESULTS

Analysis of Ridership Changes by Station Location

The results of the Mann-Whitney U tests, as shown in Table 2, provide insights into the ridership changes between European and Asian stations in Istanbul over five periods, from 2013 to 2023. In the first period (2013-2015), the analysis reveals a significant difference between the two sides, with Asian stations experiencing substantially higher ridership changes than their European counterparts. This is evident from the mean rank values, where Asian stations had a mean rank of 88.05 compared to 59.14 for European stations. The U-value of 550 and the significant p-value of 0.001 support this conclusion, indicating that ridership changes in Asia were much more pronounced during this time.

A similar pattern persists in the second period (2015-2017), where Asian stations again show a significant increase in ridership compared to European stations. The mean rank for Asian stations rose to 103.50, while European stations had a mean rank of 63.72, indicating that Asian stations continued to lead in ridership change. The U-value of 950 and the highly significant p-value of 0.000 confirm that the difference between the two regions remained statistically significant during this period.

However, the third period (2017-2019) marks a shift in ridership trends. For the first time, European stations showed greater ridership changes than Asian stations, with mean ranks of 97.79 and 77.32, respectively. Although the difference between the two groups is not as stark as in previous periods, the U-value of 2809 and the p-value of 0.013 still point to a statistically significant difference. This shift may reflect changing patterns in network expansion or population growth on the European side of the city.

In the fourth period (2019-2021), Asian stations once again outpaced European stations in ridership changes, with a mean rank of 120.03 compared to 97.46 for European stations. The U-value of 3448 and a p-value of 0.014 indicate a moderate yet significant difference. This resurgence in Asian ridership may correspond to new station openings or increased transit demand in Asia during this time frame.

Finally, in the fifth and most recent period (2021-2023), the differences between European and Asian stations in terms of ridership change appear to have diminished significantly. The mean ranks for European and Asian stations were 119.10 and 112.75, respectively, indicating a nearly equal level of ridership change. The high U-value of 5679 and the non-significant p-value of 0.499 demonstrate that there was no significant difference between the two regions during this period. This suggests that, by 2023, ridership changes have stabilized across both sides of the city, possibly due to an overall maturation of the rail network or other external factors affecting ridership across Istanbul equally.

Table 2
Mann-Whitney U Test Results for Ridership Changes by Location (Europe vs. Asia, 2013-2023)

	CH_13_15		CH_15_17		CH_17_19		CH_19_21		CH_21_23	
Location	**Europe**	**Asia**	**Europe**	**Asia**	**Europe**	**Asia**	**Europe**	**Asia**	**Europe**	**Asia**
Mean Rank	59.14	88.05	63.72	103.50	97.79	77.32	97.46	120.03	119.10	112.75
Sum of Ranks	6328	1673	6945	3933	11832	4639	14326	7202	18579	8682
Mann-Whitney U	550.000		950.000		2809.000		3448.000		5679.000	
Wilcoxon W	6328.000		6945.000		4639.000		14326.000		8682.000	
Z	-3.180		-4.960		-2.474		-2.460		-.676	
P-value	.001		.000		.013		.014		.499	

In summary, the analysis reveals dynamic shifts in ridership patterns between the European and Asian sides of Istanbul, with Asian stations generally experiencing greater changes in earlier periods, while European stations saw more growth during the 2017-2019 phase. By the final period, ridership changes became more balanced across the city.

Analysis of Ridership Changes by Line Type

The Kruskal-Wallis Test results in Table 3 provide an overview of ridership changes by line type across different time periods (2013-2023). The mean rank values for each line type provide insights into which types experienced more remarkable ridership changes, while the Chi-Square values indicate the statistical significance of these differences. From 2013 to 2015 (CH_13_15), the Chi-Square value of 60.581 and P-value of .000 shows that ridership changes differed significantly across Metro, Tram, and Train lines, with the Train line having the highest mean rank (121), followed by Metro (81.70) and Tram (35.59). Similar trends are observed for CH_15_17 and CH_17_19, where the P-values of .003 and .000, respectively, confirm that these differences persisted in ridership patterns across line types, with fluctuations in the ranking order. However, the results for the period CH_19_21 show no statistically significant differences (P = .203), indicating more uniform ridership changes among the different line types during this time. In contrast, the P-value for CH_21_23 returns to .000, again confirming significant differences in ridership changes, with Train lines experiencing the highest mean rank (145.37).

Table 3
Kruskal Wallis Test Results for Ridership Changes by Line type (2013-2023)

	CH_13_15			CH_15_17			CH_17_19			CH_19_21			CH_21_23		
**Line type ª*	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
Mean Rank	81.70	35.59	121	83.79	59.51	58.20	66.67	92.98	145.16	96.60	110.21	113.26	124.26	86.47	145.37
Chi-Square	60.581			11.595			59.871			3.190			21.769		
P-value	.000			.003			.000			.203			.000		

*1=Metro, 2=Tram, and 3=Train. a = Kruskal Wallis Test

Meanwhile, Table 4 offers further insights into these changes by conducting a Mann-Whitney U Test, which compares ridership changes between two line types at a time and offers more granular details. During CH_13_15, the comparison between Metro and Tram reveals a significant difference in ridership changes, with Metro having a higher mean rank (81.48) than Tram (35.59), as indicated by the P-value of .000. Similarly, Metro shows significant differences when compared to Train during the same period (P = .001), with Train lines experiencing a more pronounced increase. Likewise, Tram and Train lines also show a significant difference (P = .000), where Train had a much higher rank, indicating a substantial rise in ridership compared to Tramlines.

In CH_15_17, the Metro and Tram comparison continues to show significant differences (P = .001), although the difference between Metro and Train and Tram and Train becomes non-significant (P = .214, P = .870). During CH_17_19, however, significant differences are observed across all comparisons, with Tramlines experiencing the biggest ridership changes, as reflected by their mean rank of 88.98. Finally, in CH_21_23, significant differences are again noted between Metro and Tram (P = .000) and between Tram and Train (P = .000), although Metro and Train show no significant difference (P = .113). This pattern suggests that ridership changes fluctuate between the line types over time, with train and metro lines often seeing more significant increases than tram lines.

Table 4

Mann-Whitney U Test Results for Ridership Changes by Line type (2013-2023)

	*Line type**	*Mean Rank*	*Sum of Ranks*	*Mann-Whitney U*	*Z*	*P-value*
CH_13_15	Metro	81.48	5459.00	437.000	-7.154	.000
	Tram	35.59	1922.00			
	Metro	34.22	2293.00	15.000	-3.378	.001
	Train	67.00	335.00			
	Tram	27.50	1485.00	.000	-3.674	.000
	Train	57.00	285.00			
CH_15_17	Metro	80.46	7080.50	1587.500	-3.314	.001
	Tram	56.90	3072.50			
	Metro	47.83	4209.00	147.000	-1.243	.214
	Train	32.40	162.00			
	Tram	30.11	1626.00	129.000	-.163	.870
	Train	28.80	144.00			
CH_17_19	Metro	61.70	5491.00	1486.000	-3.819	.000
	Tram	88.98	4805.00			
	Metro	49.98	4448.00	443.000	-6.571	.000
	Train	96.84	3680.00			
	Tram	31.50	1701.00	216.000	-6.426	.000
	Train	67.82	2577.00			
CH_21_23	Metro	108.48	13994.00	2905.000	-3.626	.000
	Tram	77.52	5116.00			
	Metro	80.78	10421.00	2036.000	-1.584	.113
	Train	94.92	3607.00			
	Tram	42.45	2802.00	591.000	-4.476	.000
	Train	69.95	2658.00			

Analysis of Ridership Changes by Ridership Levels

The Kruskal-Wallis Test (Table 5) shows significant differences in ridership changes for certain periods. For the period 2013-2015, there is a statistically significant difference in ridership changes across different ridership levels, as indicated by the Chi-Square value (31.862) and a P-value of 0.000. The mean ranks show that stations with very high ridership levels had the highest increases, while stations with very low ridership experienced the least change. However, for the 2015-2017 and 2017-2019 periods, no statistically significant differences were observed, suggesting that ridership levels during these intervals did not significantly affect ridership changes. The 2019-2021 period shows a strong significance (Chi-Square = 27.844, P = 0.000), with very low and high ridership levels experiencing notable changes. Similarly, in the 2021-2023 period, ridership changes differ significantly across ridership levels, as indicated by a high Chi-Square value of 93.785 and a P-value of 0.000, showing increased ridership for stations with higher ridership levels.

Table 5

Kruskal Wallis Test Results for Ridership Changes by Ridership Levels (2013-2023)

	Ridership levels	*Mean Rank*	*Chi-Square*	*P-value*
	Very low	39.54		
	Low	62.77		
CH_13_15	Medium	59.50	31.862	.000
	High	81.64		
	Very high	88.93		
	Very low	62.68		
	Low	70.77		
CH_15_17	Medium	81.85	5.356	.253
	High	72.13		
	Very high	83.43		
	Very low	95.53		
	Low	86.98		
CH_17_19	Medium	79.02	2.841	.585
	High	94.29		
	Very high	98.33		
	Very low	118.02		
	Low	67.44		
CH_19_21	Medium	88.93	27.844	.000
	High	116.71		
	Very high	107.18		
	Very low	60.76		
	Low	112.19		
CH_21_23	Medium	144.39	93.785	.000
	High	169.57		
	Very high	176.20		

The Mann-Whitney U Test (Table 6) provides more detailed pairwise comparisons of ridership changes between different ridership levels. During the 2013-2015 period, the very low ridership category consistently showed significantly more minor changes in ridership compared to the higher ridership categories, indicating notable differences between very low and other levels. Similarly, low ridership levels also showed significant differences compared to higher categories, particularly in very high ridership. However, differences between medium and high ridership levels were less pronounced.

During the 2019-2021 period, the differences between stations with very low and low ridership levels remain pronounced ($p = 0.000$), indicating that the stations with very low ridership experienced significantly different changes compared to those with higher ridership levels. However, the differences are less consistent across other ridership categories in this period, as shown by p-values above 0.05 in several comparisons, suggesting some convergence in ridership changes between these stations.

In the period 2021-2023, the ridership changes between different station categories are starkly different, especially between very low and higher ridership stations. This period reflects the most significant divergence, as the p-values consistently show substantial differences in ridership growth patterns across nearly all ridership level comparisons .

The findings suggest a growing disparity in ridership changes between low and high-performing stations over time, with the gap most pronounced in the 2021-2023 period. Instead of all stations growing at a similar pace, high-performing stations are pulling further ahead, while low-performing stations are stagnating or growing much more slowly. This widening gap could be driven by factors such as the expansion of the transportation network, evolving urban development around certain stations, or shifts in travel patterns that favor specific parts of the network.

Table 6

Mann-Whitney U Test Results for Ridership Changes by Ridership Levels (2013-2023)

	Ridership levels	Mean Rank	Sum of Ranks	Mann-Whitney U	Z	P-value
CH_13_15	Very low	25.63	897.00	267.000	3.395	.001
	Low	41.60	1248.00			
	Very low	24.60	861.00	231.000	2.082	.037
	Medium	33.95	679.00			
	Very low	20.31	711.00	81.000	3.630	.000
	High	36.71	514.00			
	Very low	23.00	805.00	175.000	4.224	.000
	Very high	42.52	1148.00			
	Low	26.07	782.00	283.000	.337	.736
	Medium	24.65	493.00			
	Low	19.60	588.00	123.000	2.192	.028
	High	28.71	402.00			
	Low	22.00	660.00	195.000	3.356	.001
	Very high	36.78	993.00			
	Medium	14.80	296.00	86.000	1.890	.059
	High	21.36	299.00			
	Medium	17.60	352.00	142.000	-2.754	.006
	Very high	28.74	776.00			
	High	17.36	243.00	138.000	-1.402	.161
	Very high	22.89	618.00			
CH_19_21	Very low	101.48	12178.00	1322.000	-5.995	.000
	Low	51.92	2700.00			
	Very low	68.82	8258.00	682.000	-1.149	.250
	Medium	56.21	787.00			
	Very low	63.62	7634.00	374.000	-.486	.627
	High	70.57	494.00			
	Very low	65.60	7872.00	612.000	-.398	.690
	Very high	70.36	774.00			
	Low	33.85	1760.00	346.000	-.282	.778
	Medium	32.21	451.00			
	Low	29.35	1526.00	148.000	-.797	.425
	High	34.86	244.00			
	Low	31.83	1655.00	277.000	.163	871
	Very high	32.82	361.00			
	Medium	9.93	139.00	34.000	1.119	263
	High	13.14	92.00			
	Medium	13.07	183.00	76.000	.055	956
	Very high	12.91	142.00			
	High	10.14	71.00	34.000	.408	684
	Very high	9.09	100.00			
CH_21_23	Very low	45.90	3213.00	728.000	6.735	000
	Low	91.13	5832.00			
	Very low	41.41	2899.00	414.000	6.750	000
	Medium	84.50	3887.00			
	Very low	38.50	2695.00	210.000	5.298	000
	High	72.87	1676.00			

Very low	41.44	2901.00	416.000	4.769	000
Very high	71.63	2149.00			
Low	43.92	2811.00	731.000	4.490	000
Medium	71.61	3294.00			
Low	36.13	2312.00	232.000	4.851	000
High	65.91	1516.00			
Low	38.52	2465.00	385.000	4.664	000
Very high	66.67	2000.00			
Medium	28.98	1333.00	252.000	3.526	000
High	47.04	1082.00			
Medium	29.80	1371.00	290.000	4.251	000
Very high	51.83	1555.00			
High	19.74	454.00	178.000	2.997	003
Very high	32.57	977.00			

Analysis of Ridership Changes by Station Opening Date

The Kruskal-Wallis test results (Table 7) show significant differences in ridership changes based on station opening dates across various periods. A detailed examination of each period reveals that station opening dates strongly influence ridership patterns.

Period 1 (2013-2015): Stations opened before 2013 have significantly lower ridership changes (Mean Rank = 55.32) than those opened between 2013 and 2015 (Mean Rank = 101.67). However, stations opened until April 2015 (2015-2017) show the lowest ridership change (Mean Rank = 14.50), suggesting that newer stations during this period had less impact on ridership growth.

Period 2 (2015-2017): The ridership change pattern evolves over time, with stations opened before 2013 continuing to have a moderate impact (Mean Rank = 61.40), while newer stations opened between 2015-2017 and until April 2017 (2017-2019) (Mean Ranks = 124.29 and 132.88) see increasingly greater ridership changes. This indicates a growing contribution from newly opened stations in this period.

Period 3 (2017-2019): A more complex pattern emerges. Stations opened before 2013 and between 2013 and 2015 exhibit higher ridership changes (Mean Ranks = 84.66 and 93.16), but stations from 2015 to 2017 experienced a notable decline in ridership growth (Mean Rank = 59.71). Conversely, stations opened until April 2019 (2019-2021) show the highest growth (Mean Rank = 150.61), suggesting these newer stations significantly influenced ridership increases during this period.

Period 4 (2019-2021): The period from 2017-2019 shows the most significant jump in ridership changes (Mean Rank = 198.19), followed by stations from 2019-2021 (Mean Rank = 144.36) and until April 2021 (2021-2023) (Mean Rank = 164.58). This suggests that the most recent expansions (2017-April 2021) have driven substantial ridership growth, particularly for stations opened in the latest years.

Period 5 (2021-2023): In the final period, stations opened between 2017-2019 experience the lowest ridership changes (Mean Rank = 22.88), whereas stations opened before 2013 and between 2013-2021 show higher ridership changes (Mean Ranks ranging from 127.11 to 143.76). This result indicates that ridership changes tend to stabilize for newer stations as they mature, with the most recent stations (2019-2023) seeing a gradual increase in ridership, though less than earlier expansions.

Table 7

Kruskal Wallis Test Results for Ridership Changes by Opening date (2013-2023)

	Opening date	Mean Rank	Chi-Square	P-value
CH_13_15	Before 2013	55.32	34.836	.000
	2013-2015	101.67		
	2015-2017	14.50		
CH_15_17	Before 2013	61.40	49.137	.000
	2013-2015	72.58		
	2015-2017	124.29		
	2017-2019	132.88		
CH_17_19	Before 2013	84.66	77.782	.000
	2013-2015	93.16		
	2015-2017	59.71		
	2017-2019	18.00		
	2019-2021	150.61		
CH_19_21	Before 2013	73.34	109.424	.000
	2013-2015	68.40		
	2015-2017	79.00		
	2017-2019	198.19		
	2019-2021	144.36		
	2021-2023	164.58		
CH_21_23	Before 2013	127.11	55.293	.000
	2013-2015	143.76		
	2015-2017	112.00		
	2017-2019	22.88		
	2019-2021	142.46		
	2021-2023	80.22		

The results of the Mann-Whitney U Test (Table 8) conducted on ridership data from 2013 to 2023 reveal substantial differences in ridership changes across various station opening periods. Specifically, stations that opened in the more recent periods of 2017 to 2023 demonstrate significantly higher ridership levels than those established before 2013. The analysis indicates extreme disparities for stations inaugurated between 2019-2021 and those opened in 2021-2023. This trend highlights the rapid growth and increasing demand for public transportation within Istanbul's expanding rail network. Statistical significance ($p < .05$) is evident across most comparisons, indicating meaningful differences in ridership associated with the age of the stations. This suggests that the newer stations are attracting more passengers and playing a critical role in shaping the overall ridership landscape in Istanbul.

Table 8

Mann-Whitney U Test Results for Ridership Changes by Opening date (2013-2023)

	Ridership levels	Mean Rank	Sum of Ranks	Mann-Whitney U	Z	P-value
CH_13_15	Before 2013	53.58	5358.00	308.000	-5.642	.000
	2013-2015	99.67	2392.00			
	Before 2013	52.24	5224.00	26.000	-1.786	.074
	2015-2017	14.50	29.00			
	2013-2015	14.50	348.00	.000	-2.310	.021
	2015-2017	1.50	3.00			
CH_15_17	Before 2013	60.61	6061.00	1011.000	-1.195	.232
	2013-2015	70.38	1689.00			

	Before 2013	50.93	5093.00	43.000	-3.868	.000
	2015-2017	97.86	685.00			
	Before 2013	50.86	5086.00	36.000	-6.117	.000
	2017-2019	106.25	1700.00			
	2013-2015	13.50	324.00	24.000	-2.835	.005
	2015-2017	24.57	172.00			
	2013-2015	13.71	329.00	29.000	-4.500	.000
	2017-2019	30.69	491.00			
	2015-2017	9.86	69.00	41.000	-1.002	.316
	2017-2019	12.94	207.00			
CH_17_19	Before 2013	62.11	6211.00	1161.000	-.549	.583
	2013-2015	66.56	1664.00			
	Before 2013	55.23	5523.00	227.000	-1.550	.121
	2015-2017	36.43	255.00			
	Before 2013	65.49	6549.00	101.000	-5.598	.000
	2017-2019	14.81	237.00			
	Before 2013	53.33	5333.00	283.000	-7.122	.000
	2019-2021	108.42	3578.00			
	2013-2015	17.56	439.00	61.000	-1.208	.227
	2015-2017	12.71	89.00			
	2013-2015	27.36	684.00	41.000	-4.249	.000
	2017-2019	11.06	177.00			
	2013-2015	20.68	517.00	192.000	-3.462	.001
	2019-2021	36.18	1194.00			
	2015-2017	18.57	130.00	10.000	-3.074	.002
	2017-2019	9.13	146.00			
	2015-2017	4.00	28.00	.000	-4.111	.000
	2019-2021	24.00	792.00			
	2017-2019	8.50	136.00	.000	-5.628	.000
	2019-2021	33.00	1089.00			
CH_19_21	Before 2013	64.19	6419.00	1131.000	-.734	.463
	2013-2015	58.24	1456.00			
	Before 2013	53.47	5347.00	297.000	-.668	.504
	2015-2017	61.57	431.00			
	Before 2013	50.54	5054.00	4.000	-6.373	.000
	2017-2019	108.25	1732.00			
	Before 2013	55.79	5579.00	529.000	-7.563	.000
	2019-2021	112.74	5299.00			
	Before 2013	51.35	5135.00	85.000	-4.845	.000
	2021-2023	99.42	1193.00			
	2013-2015	16.00	400.00	75.000	-.570	.569
	2015-2017	18.29	128.00			
	2013-2015	13.00	325.00	.000	-5.345	.000
	2017-2019	33.50	536.00			
	2013-2015	20.16	504.00	179.000	-4.832	.000
	2019-2021	45.19	2124.00			
	2013-2015	13.00	325.00	.000	-4.867	.000
	2021-2023	31.50	378.00			
	2015-2017	4.00	28.00	.000	-3.742	.000

	2017-2019	15.50	248.00			
	2015-2017	7.14	50.00	22.000	-3.670	.000
	2019-2021	30.53	1435.00			
	2015-2017	4.00	28.00	.000	-3.550	.000
	2021-2023	13.50	162.00			
	2017-2019	54.44	871.00	17.000	-5.669	.000
	2019-2021	24.36	1145.00			
	2017-2019	20.50	328.00	.000	-4.457	.000
	2021-2023	6.50	78.00			
	2019-2021	27.53	1294.00	166.000	-2.184	.029
	2021-2023	39.67	476.00			
CH_21_23	Before 2013	61.02	6102.00	1052.000	-1.222	.222
	2013-2015	70.92	1773.00			
	Before 2013	54.63	5463.00	287.000	-.794	.427
	2015-2017	45.00	315.00			
	Before 2013	64.97	6497.00	153.000	-5.180	.000
	2017-2019	18.06	289.00			
	Before 2013	71.79	7179.00	2129.000	-1.110	.267
	2019-2021	80.15	3847.00			
	Before 2013	76.70	7670.00	1080.000	-3.733	.000
	2021-2023	48.19	1783.00			
	2013-2015	17.40	435.00	65.000	-1.026	.305
	2015-2017	13.29	93.00			
	2013-2015	28.56	714.00	11.000	-5.051	.000
	2017-2019	9.19	147.00			
	2013-2015	38.00	950.00	575.000	-.291	.771
	2019-2021	36.48	1751.00			
	2013-2015	40.88	1022.00	228.000	-3.365	.001
	2021-2023	25.16	931.00			
	2015-2017	19.29	135.00	5.000	-3.408	.001
	2017-2019	8.81	141.00			
	2015-2017	19.71	138.00	110.000	-1.465	.143
	2019-2021	29.21	1402.00			
	2015-2017	30.71	215.00	72.000	-1.845	.065
	2021-2023	20.95	775.00			
	2017-2019	10.00	160.00	24.000	-5.582	.000
	2019-2021	40.00	1920.00			
	2017-2019	10.81	173.00	37.000	-5.018	.000
	2021-2023	34.00	1258.00			
	2019-2021	54.63	2622.00	330.000	-4.946	.000
	2021-2023	27.92	1033.00			

The data indicates a clear dynamic shift in ridership growth over time, closely tied to the opening of new stations. Specifically, stations inaugurated after 2017 show the most substantial increases in ridership, reflecting a growing trend in public transportation usage that correlates with network expansion efforts. In contrast, older stations, particularly those established before 2013, continue to exhibit consistent, albeit moderate, growth in ridership.

CONCLUSION

This study demonstrates that the expansion of Istanbul's rail transit network from 2013 to 2023 has profoundly influenced ridership patterns across the city. By analyzing station characteristics—such as location, line type, ridership levels, and opening date—we uncovered critical insights into how these factors shape passenger flow.

Our findings highlight that station location plays a pivotal role, with European-side stations exhibiting higher ridership, especially in established economic and historical hubs. However, as the network expanded, particularly on the Asian side, we observed a narrowing of the gap in ridership changes, indicating the growing importance of newly developed suburban areas.

Moreover, the study highlights the influence of station age and line type on passenger volumes. Newly opened stations often displayed initial fluctuations in ridership, followed by stabilization as surrounding areas became better connected and developed. In contrast, older, more established stations exhibited consistent yet moderate ridership growth, underscoring their entrenched role within the network. The distinction between metro, tram, and commuter rail lines revealed varying ridership behaviors. Metro lines consistently attracted higher passenger volumes due to their speed, frequency, and connection to dense urban areas, while tram and commuter rail catered to localized and long-distance travel. Over time, ridership changes fluctuated between the line types, with metro and train lines often seeing more substantial increases than trams. The Marmaray line, which links the European and Asian sides, emerged as a critical network element despite its higher fares and lower frequency, further underscoring its strategic importance in the Istanbul rail network system.

Statistical evidence from our non-parametric analyses reinforces the conclusion that ridership changes are intrinsically linked to the evolving characteristics of stations and lines within the network. These findings have important implications for future urban transport planning in Istanbul. As the city continues to expand, further investment in rail infrastructure should focus on optimizing connectivity between existing and new stations, enhancing service reliability, and addressing the evolving needs of the city's diverse population.

In conclusion, this study underscores the dynamic nature of rail transit ridership in a rapidly growing metropolitan area. The insights gained here can guide policymakers and urban planners in making informed decisions about future network expansions, ensuring that Istanbul's rail transit system remains a vital tool for sustainable urban mobility.

Ethical Statement

This article is extracted from my master thesis entitled "SUPPORTING STATIONS AS THIRD PLACES IN EVOLVING RAIL TRANSIT SYSTEMS: THE CASE OF ISTANBUL" supervised by Prof. Dr. Metin Şenbil (Master's Thesis, Gazi University, Ankara, Türkiye, 2025).

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The authors declare no conflict of interest for the present study.

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