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Rail transit and travel satisfaction: Evidence from a natural experiment in Wuhan

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ABSTRACT

The impact of rail transit infrastructure on residents' travel satisfaction and subjective well-being has gained increasing attention among researchers and policymakers. However, few studies have used longitudinal data to analyze the causal effects of rail transit systems on travel satisfaction and its underlying mechanisms. This study employed a natural experiment approach, using two waves of survey data (2020 & 2021) from 422 participants in Wuhan, China, to assess the effects of a newly opened subway line on travel satisfaction. Applying a mixed-effects difference-in-differences (DID) method, we found that the new subway line significantly improved residents' travel satisfaction after accounting for socio-demographic and travel attitude covariates. Mediation analysis revealed that this improvement was primarily driven by increased perceived accessibility to downtown and transit stops or stations, as well as a reduction in the number of out-of-home activities on weekends. Heterogeneous analysis indicated that the subway's benefits are more pronounced among females, individuals under 60 years old, and those from middle-income households. These findings provide new causal evidence on the link between rail transit infrastructure and travel satisfaction, deepening our understanding of this complex relationship and offering practical insights for formulating strategies to improve urban residents' quality of life.

1. Introduction

Rapid urbanization and increasing traffic congestion in major cities often lead to longer commuting time, decreased travel satisfaction, and diminished overall well-being (De Vos et al., 2013; Mokhtarian & Pendyala, 2018). In response, rail transit, a sustainable transportation mode, has been widely adopted to alleviate traffic congestion and enhance quality of life (Cao, 2013; Yin et al., 2021). Travel satisfaction, a key component of subjective well-being, not only shapes residents' travel experience and mode choices but also influences their overall quality of life (Mao et al., 2022; Ye & Titheridge, 2017). Therefore, understanding the influence of rail transit on residents' travel satisfaction is crucial, as it helps urban planners and policy makers evaluate the social value of rail transit, guide public transportation improvements, and promote sustainable urban development (Wu, 2013, 2015). Moreover, this issue resonates with the United Nations Sustainable Development Goals (SDG). By improving accessibility and livability, rail transit development contributes to Sustainable Cities and Communities (SDG 11), which highlights the need for inclusive, safe, and sustainable transport systems (Assembly, 2015).

Travel satisfaction refers to individuals' overall cognitive evaluation of their travel experiences and is widely used as a measure of travel-related subjective well-being (SWB) (Wang & Gao, 2022). Traditional transportation research has often relied on decision utility outcomes (derived from observed travel mode choices) to assess travel behavior, but this may not reflect travelers' actual perception and preference because choices are frequently constrained. To better capture the actual feelings and perceptions of travelers, scholars have proposed focusing on experienced utility, which in psychology is operationalized as SWB (De Vos et al., 2016; Ettema et al., 2011). Within the transportation domain, travel-related SWB (also referred to as travel happiness) (Chen et al., 2019) includes both cognitive judgments (e.g., overall travel satisfaction) and affective reactions (positive and negative emotions during travel) (Mokhtarian & Pendyala, 2018). Hence, improving travel satisfaction has increasingly become a key goal for transport policy and urban planning, as well as a focal point of current academic research (De

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Vos et al., 2013).

Previous studies have shown that improved rail transit accessibility positively influences travel satisfaction (Li et al., 2018; Zhai et al., 2021). However, there are two major limitations in the existing research. First, most studies rely on cross-sectional research designs, which significantly limits causal inference between rail transit accessibility and travel satisfaction (Wang et al., 2020). Second, the mediating mechanisms through which rail transit affects travel satisfaction remain unclear. While the pathways via changes in perceived built environment features have been examined (Cao, 2013; Yin et al., 2021), other pathways, particularly those involving travel behavior, are often overlooked. Given that travel behavior, e.g., travel time and mode, significantly affect travel satisfaction (De Vos et al., 2013; Majumdar et al., 2021; Ye & Titheridge, 2017), and that rail transit accessibility significantly shapes residents' travel behavior (Dai et al., 2020; Sun et al., 2020). Thus, investigating the role of changing travel behavior as a potential mediator is essential to advancing this research field.

To fill these gaps, this study exploited the opportunity of the opening of a new rail line in Wuhan, China, as a natural experiment. Using the natural experiment design, we collected data in two waves from 422 participants across 40 neighborhoods before and after the subway line's opening, capturing changes in travel behavior, perceptions of the built environment, and travel satisfaction. A mixed-effects difference-in-differences (DID) regression model was used to estimate the impact of subway line's opening on travel satisfaction, while controlling socio-demographic factors and travel attitudes. Additionally, we conducted mediation analysis to explore the potential mechanisms linking rail transit to travel satisfaction, using perceived built environment features and travel behavior as mediators. Finally, we examined the heterogeneous effects of the new subway line on travel satisfaction across different participant subgroups.

This study contributes to existing literature in two ways. First, it is one of the first studies using a natural experiment approach to assess the causal impact of a new subway line on travel satisfaction, providing rigorous empirical evidence. Second, it develops a comprehensive framework linking rail transit, the built environment, travel behavior, and travel satisfaction, offering deeper insights into the mechanisms through which rail transit affects travel satisfaction.

2. Literature review

2.1. Rail transit and travel satisfaction

Many studies have explored the relationship between rail transit and travel satisfaction (Cao, 2013; Pani et al., 2023; Wu, 2013, 2015; Yin et al., 2021; Zhai et al., 2021). Most studies employ cross-sectional designs to compare travel satisfaction among residents in areas with and without rail transit stations. For example, Cao (2013) explored the impact of light rail in Hiawatha Corridor, Minnesota, USA, by comparing it to two similar urban corridors without light rail. The study found a positive association between rail transit and travel satisfaction as well as life satisfaction. Similarly, Yin et al. (2021) used data from Xi'an in 2014 to compare travel satisfaction between residents near Subway Line 2, which was operational, and those near Subway Line 4, which had not yet opened, finding that subway systems are linked to higher travel satisfaction in developing countries. Additionally, Zhai et al. (2021) examined the relationship between rail transit accessibility change and travel satisfaction using survey data conducted in Beijing in 2013. This study confirmed that improved rail transit accessibility was positively associated with residents' travel satisfaction.

However, cross-sectional studies primarily demonstrate the association between rail transit and travel satisfaction, without establishing causality due to the lack of temporal precedence and insufficient control of unmeasured confounders (Craig et al., 2017). Areas with and without rail transit may differ in both observable and unobservable ways (Wu, 2015). Longitudinal studies, particularly those using natural experiment designs, offer a more robust approach for addressing these limitations of cross-sectional research. Although a few studies have used longitudinal data to examine changes in travel satisfaction (Pineda & Lira, 2019; Wang et al., 2020), they neither adopted natural experiment designs nor focused on the effects of new rail transit. For example, Wang et al. (2020) analyzed two rounds of survey data from Beijing (2011 & 2013) to assess the impact of residential relocation on travel satisfaction. This study found that residential relocation could improve travel satisfaction, primarily through improved neighborhood environments. To date, there is no natural experiment investigating the causal impacts of new rail transit on travel satisfaction.

2.2. Pathways through which rail transit affect travel satisfaction

According to the existing literature, the determinants of travel satisfaction can be classified into four categories: individual socio-demographic factors (e.g., age, gender, education, income, health, car ownership) (Ye & Titheridge, 2017; Zhu & Fan, 2018), travel attributes (e.g., travel mode, travel time, travel frequency) (Mao et al., 2022; Wang et al., 2020), the built environment (e.g., accessibility, walkability) (Cao & Ettema, 2014; Ettema et al., 2011; Jayakumar et al., 2022; Majumdar et al., 2021), and travel attitudes (e.g., preferences for certain travel modes) (De Vos & Witlox, 2017; Ye & Titheridge, 2017). Some studies have examined the mediating role of the built environment in the rail transit–travel satisfaction relationship. For instance, Cao (2013) examined the impact of the Hiawatha Line in Minneapolis, finding that light rail transit was associated with higher travel satisfaction, largely through improved perceptions of transit access, service quality, and accessibility to different destinations. Yin et al. (2021) assessed the Xi'an subway lines, extending Cao's findings (Cao, 2013), and showed that the associations between subway systems and greater travel satisfaction were mediated not only by improved transit service quality and perceived accessibility but also by enhanced perceived walkability in nearby neighborhoods.

To our knowledge, only few studies have examined the mediating role of travel behavior between rail transit and travel satisfaction. Pineda and Lira (2019), for example, examined the impact of the newly opened Santiago Metro Line 6 in Chile on travel satisfaction. Using smart card data, they found that although the new line reduced passengers' travel time, perceived time savings were not associated with greater travel satisfaction, as passengers considered shorter travel times of new line an expected benefit. However, this study only examined travel time, without considering other key aspects of travel behavior, e.g., travel frequency or mode choice. Given that rail transit influences multiple dimensions of travel behavior, including travel time, frequency, mode, and activity participation (Dai et al., 2020; Sun et al., 2020; Wang et al., 2023), all of which can, in turn, affect travel satisfaction (Mao et al., 2022; Wang et al., 2020). Therefore, to gain a comprehensive understanding of the underlying mechanisms between rail transit and travel satisfaction, it is necessary to consider multiple dimensions of travel behavior as the potential mediators.

2.3. Research gaps

In summary, there are two major research gaps. First, few studies have explored the temporal dynamics of the relationship between rail transit and travel satisfaction. Most studies are cross-sectional providing snapshots of the associations. It remains hard to infer causal inference because cross-sectional studies often suffer from temporal ambiguity and uncontrolled covariates (Leatherdale, 2019). In contrast, longitudinal analysis, particularly natural experiments utilizing panel data, offers a more robust approach. This approach allows researchers to determine causal relationships by comparing treatment and control groups before and after interventions, thereby providing stronger inferences about the causal impact of rail transit on travel satisfaction (Craig et al., 2017). Therefore, this study addresses this gap by employing a natural experiment with panel data to assess how a newly introduced rail transit system influences travel satisfaction.

Second, the mechanisms underlying the relationship between rail transit and travel satisfaction are not well understood. Although previous studies have analyzed how rail transit systems affect travel satisfaction through changes in perceived built environment attributes, few have explored the role of changes in travel behavior. Existing research suggested that new rail transit systems can significantly influence the travel behavior of nearby residents (Wang et al., 2023). These changes in travel behavior, in turn, are likely to impact travel satisfaction (Ettema et al., 2011; Guan et al., 2023). Therefore, investigating how rail transit influences travel behavior and, consequently, travel satisfaction, is a critical effort to advance the research field.

3. Conceptual framework

Based on the literature and identified research gaps, we have developed a conceptual model to elucidate the mechanisms through which rail transit impacts travel satisfaction (Fig. 1). We hypothesize that the construction of new subway lines will lead to changes in the perceived built environment attributes and travel behavior, which in turn will result in changes in travel satisfaction. Factors such as travel attitudes and socio-demographic characteristics, which also influence travel satisfaction, will be controlled in the model.

Specifically, regarding the perceived built environments, the construction of new subway stations may change residents' perceptions of the surrounding built environment. Existing literature indicated that new subway systems may enhance travel satisfaction by improving perceived transit accessibility, walkability, and destination accessibility (Cao, 2013; Yin et al., 2021). Thus, we considered these three perceived built environment attributes as potential mediators in our analysis.

Regarding travel characteristics, on one hand, rail transit systems may induce notable changes in residents' travel behavior, including travel mode choice, travel time, frequency, and activity participation. Evidence suggested that new subway lines can significantly influence travel modes, such as increasing subway usage, reducing car dependence, and changing travel time and travel frequency (Sun et al., 2020; Wang et al., 2023). In addition, the introduction of subway lines can increase the range of travel opportunities and activity participation for nearby residents (Næss, 2006). On the other hand, according to travel theory, travel can influence travel satisfaction in at least two ways (De Vos et al., 2013; Mokhtarian & Pendyala, 2018). First, the travel experience itself—factors like travel mode choice (e.g., active and car travel) (Ettema et al., 2011; Olsson et al., 2013), travel conditions (e.g., public transport service quality) (Sukhov et al., 2021; van Lierop et al., 2018), and travel time, distance, and cost (Ettema et al., 2012; Wang et al., 2020)—affects travel satisfaction. The presence of companions also plays a role (Guan et al., 2023). Second, travel facilitates activity participation, enhancing satisfaction (Ettema et al., 2010). For example, a Swedish survey of 1,330 respondents found that travel satisfaction was primarily linked to participation in activities (Bergstad et al., 2011). Hence, we hypothesized travel characteristics as another mediating pathway. Due to the data limitation, we chose three variables to assess travel characteristics, including travel time, travel frequency, and number of out-of-home activities.

4. Methodology

4.1. Study design

The study area is in Wuhan, China, which has undergone rapid urbanization in recent years. This study designs a natural experiment based on the opening of Wuhan Subway Line 8 (Phase 2) in January 2021 to assess its impact on the changes of nearby residents' travel satisfaction (Fig. 2). The line spans 17.6 km and comprise 12 stations, representing a significant enhancement to the public transport network at the central area of Wuhan. We selected four stations of this line—Hongshan Road, Mafangshan, Wenzhi Street, and Hubei Academy of Agricultural Sciences stations (Fig. 2), because these stations are far away from other metro lines, minimizing potential confounding influences.

The treatment group consists of residents living within the 800-meter street-network buffer of the four subway stations, and the control group includes residents living farther away from the stations (within 800–2400 m). An 800-meter distance threshold is commonly used in urban rail transit studies and is considered as the walking catchment

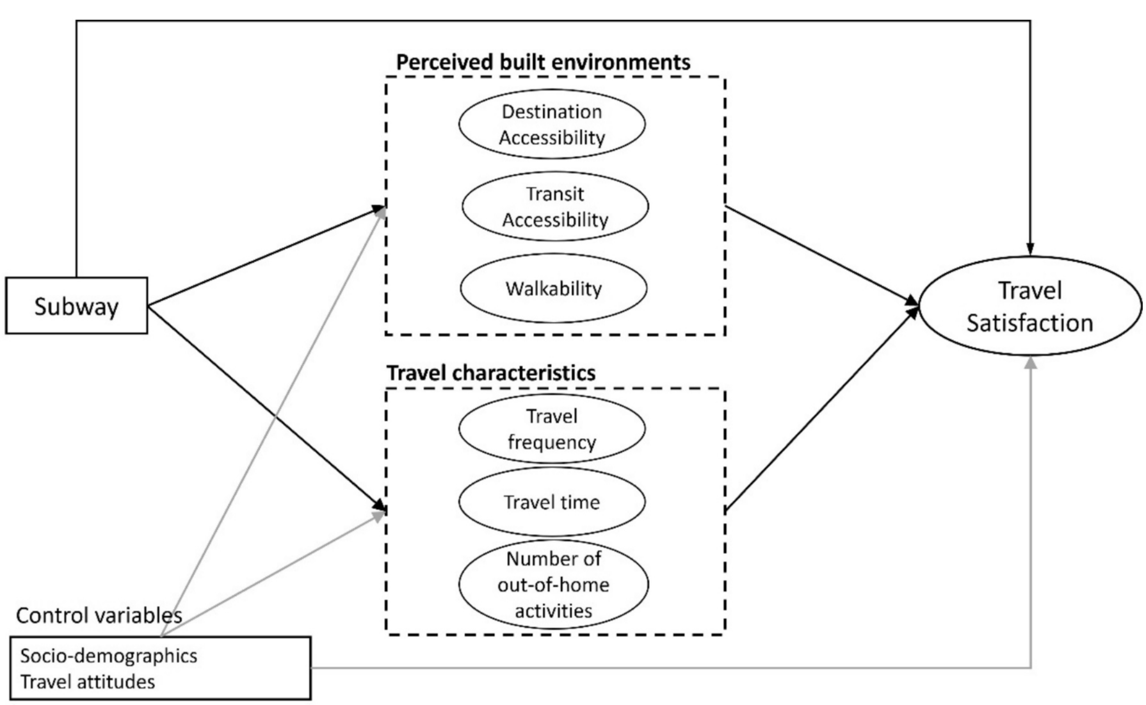

Fig. 1. Conceptual model.

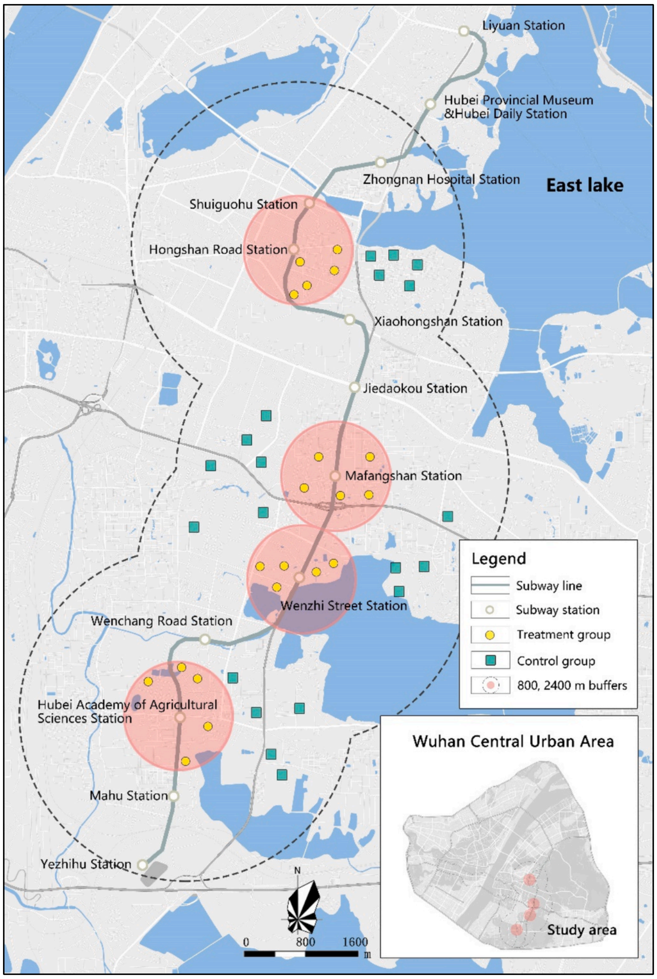

Fig. 2. The Wuhan Subway Line 8 study area and the distribution of treatment and control groups. Note: The buffers are calculated based on street network distances. They are simplified for graphical display.

area for subway stations in China (Boarnet et al., 2017; Zacharias & Zhao, 2018). The control group was defined as residents living between 800–2400 m from new stations, which is beyond the typical comfortable walking distance and therefore less directly affected by the new line.

4.2. Sampling procedure

To ensure a representative sample, we employed a multi-stage stratified sampling method, with detailed descriptions in this study (Wang et al., 2024). First, we systematically selected ten neighborhoods (*Xiaoqu* in Chinese) for each station, with five in the treatment group and five in the control group. Using complete neighborhood lists from local administrative records, we determined a fixed sampling interval and selected neighborhoods systematically according to this interval. Second, within each selected neighborhood, we used the same systematic approach to select 20–25 households from lists ordered by building and unit numbers, ensuring spatial representativeness. If a household declined to participate, the next one in sequence was approached. Within each household, one participant was chosen by the Kish grid method (McBurney, 1988). Participants were required to meet the following inclusion criteria: (1) aged 19 or older, (2) living in the selected neighborhoods for at least one year (to control for potential residential self-selection bias) (Cao et al., 2009; Heinen et al., 2018), and (3) able to walk independently for at least 15 min. Participants who completed the baseline and follow-up surveys were financially awarded (gift cards worth RMB 30 and 70 respectively) to encourage participation.

We collected two waves of data: a baseline survey in October 2020, three months before the line's opening, and a follow-up survey in October 2021, nine months after the subway line opening. In the baseline survey, we gathered 908 valid responses. In the follow-up survey, 422 participants of the initial sample participated again in the follow-up survey, leading to a retention rate of 46.5 %. We found no significant demographic or travel attitude differences between participants who completed both surveys and those who dropped out (Wang et al., 2024), as shown in the appendix (Table A). This indicates that our final sample remains representative despite the observed attrition rate. Notably, during both survey periods, the COVID-19 pandemic in Wuhan had been mostly controlled and residents' travel behaviors had largely returned to near pre-pandemic norms (Yang et al., 2023), minimizing direct disruptions. Moreover, our difference-in-differences design accounts for common shocks, so any residual pandemic-related influences would affect both groups similarly and thus be differenced out.

4.3. Measures

4.3.1. Travel satisfaction data

Travel satisfaction was measured by using the Satisfaction with Travel Scale (STS) developed by Bergstad et al. (2011), which has been widely used in the research (Cao, 2013; Wang et al., 2020; Yin et al., 2021). This scale includes five statements: "I am completely satisfied with my daily travel"; "My travel facilitates my daily life"; "When I think of my daily travel the positive aspects outweigh the negative"; "I do not want to change anything regarding my daily travel"; and "My daily travel makes me feel good". Participants were asked to rate the statements on five-point Likert scales (from 1 = strongly disagree to 5 = strongly agree) in the two waves of surveys. The Cronbach's alpha of this scale was 0.88 in the baseline survey and 0.83 in the follow-up survey, which are both higher than 0.7, demonstrating good internal consistency and suitability for this context. Finally, the STS was calculated by taking the average of the ratings for each statement (Bergstad et al., 2011; De Vos, 2019).

4.3.2. Perceived built environment attributes data

The perceived built environment attributes were adapted from previous studies (Cao, 2013; Wang et al., 2024; Yin et al., 2021). We selected 11 variables to measure three attributes of perceived built environment: destination accessibility, transit accessibility, and walkability (Table 1). Participants were asked to assess these statements by using a five-point Likert scale (from 1 = not at all true to 5 = entirely true).

4.3.3. Travel characteristics data

Travel behavior included travel frequency, travel time and number of out-of-home activities. Travel frequency asks participants to specify the number of days they used each travel mode on weekdays and weekends in the previous month. Travel modes include rail, bus, car, e-

Table 1
Measurements of perceived built environment attributes.

Perceived built environment attributes	Variables
Destination Accessibility	Easy access to downtown
	Civic buildings (e.g., library) nearby
	Easy access to a regional shopping mall
	Shopping areas within walking distance
	Easy access to parks and open spaces
	Easy access to workplace
Transit Accessibility	Easy access to transit stops or stations
	Extensive public transportation routes
Walkability	Good street lighting
	Safe neighborhood for walking
	Quiet neighborhood

bike, bicycle, and walking. Statements of travel frequency are categorized into six groups and converted to average monthly usage times in the model: (1) "never" =0; (2) "less than once a month" = 0.5 times; (3) "one to three times a month" = 2 times; (4) "once a week" = 4.3 times; (5) "two to three times a week" = 10.75 times; (6) "four to five times a week" = 19.35 times.

In both waves of the survey, participants were asked to provide travel diaries for one weekday and one weekend, which record all activities and travel modes during a 24-hour period, along with the time spent on each activity and trip. Both travel time and the number of out-of-home activities (measured by the total number of different destinations visited) are obtained from the travel diaries for weekdays and weekends. We excluded repeated activities with the same purpose at the same location (Allen & Farber, 2020). Notably, the questionnaire was piloted with 30 residents, and refinements were made to improve clarity and validity.

4.3.4. *Control variables*

During the surveys, we also collected detailed socio-demographic and travel attitude data, which impacts travel satisfaction (Ye & Titheridge, 2017; Zhu & Fan, 2018). For example, studies have shown that people who enjoy driving tend to have higher travel satisfaction when traveling by car (De Vos et al., 2016). Older adults may have higher travel satisfaction compared to younger people (Ye & Titheridge, 2017).

Socio-demographic variables include gender, age, education level, monthly household income, household size (number of family members), and household car ownership. Education level was classified into six categories, from "primary school or below" to "postgraduate or above", while monthly household income was categorized into eleven categories, ranging from "CNY 1,500 or less" to "CNY 40,000 or more". Travel attitude variables are measured by assessing participants' preferences towards each travel mode (e.g., subway, bus, car, e-bike, bicycle, and walking). Preferences for each travel mode were rated on a five-point scale, ranging from 1 = "least preferred" to 5 = "most preferred".

4.4. *Statistical analysis*

The analysis comprises three steps. First, a difference-in-differences (DID) method was employed to assess the causal impact of the new subway line on participants' travel satisfaction. The DID method is reliable to obtain the causal effects of interventions by comparing pre- and post-intervention changes in the treatment group to those in the control group (Dai et al., 2020; Spears et al., 2016; Wu, 2015). Socio-demographics, travel attitudes are controlled in the model for potential confounding bias. Random intercepts for subjects and neighborhoods were incorporated in the model to account for the clustering data structure. The mixed-effects DID regression model is as follows (1).

$$Y_{ijt} = \beta_0 + \beta_1 Treatment_{ij} + \beta_2 Time_t + \beta_3 Treatment_{ij} \times Time_t + \beta_4 X_{ij} + \alpha_i + \mu_j + \varepsilon_{ijt} \tag{1}$$

where Y_{ijt} is the travel satisfaction of participant i in neighborhood j and time t. $Treatment_{ij}$ is a dummy variable (1 = treatment group, 0 = control group). $Time_t$ is also a dummy variable with a value of 1 for the after-opening period and 0 for the before-opening period. $Treatment_{ij} \times Time_t$ is an interaction term that estimates the effect of the new subway line on the change of travel satisfaction for participants living nearby compared to those living far away. X_{ij} is the vector of covariates, including socio-demographics, and travel attitude variables. α_i and μ_j refer to the random intercepts for subject i and neighborhood j. $\beta_1, \beta_2, \beta_3, \beta_4$ are the estimated parameters. β_0 is the overall intercept and ε_{ijt} is the error term.

Second, we applied mediation analysis to explore the potential pathways through which the new subway affected travel satisfaction. Mediation analysis is a robust method used to understand mechanism underlying associations and is well-suited for longitudinal data (VanderWeele, 2016). The relationships among variables in these two mediating pathways are complex. For instance, among the three perceived built environment attributes, transit accessibility may influence walkability, as rail transit development often improves the surrounding pedestrian environment (Wang et al., 2020). Moreover, the relationship between destination accessibility and transit accessibility is likely bidirectional: enhanced perceived transit accessibility may facilitate greater destination accessibility, while areas with high destination accessibility—typically featured by high density and mixed land use—may, in turn, enhance perceived transit accessibility (Yin et al., 2021). Given these complex interrelationships, we opted to examine each mediator separately (Fig. 1). The mediation analysis models are shown in equation (2).

$$\begin{aligned} Subway_{ijt} &= \beta_0 + \beta_1 Treatment_{ij} + \beta_2 Time_t + \beta_3 Treatment_{ij} \times Time_t \\ &\quad + \beta_4 X_{ij} + \alpha_i + \mu_j + \varepsilon_{ijt} \\ Mediator_{ijt} &= \beta_0 + \beta_1 Treatment_{ij} + \beta_2 Time_t + \beta_3 Treatment_{ij} \times Time_t \\ &\quad + \beta_4 X_{ij} + \alpha_i + \mu_j + \varepsilon_{ijt} \\ Subway_{ijt} &= \beta_0 + \beta_1 Treatment_{ij} + \beta_2 Time_t + \beta_3 Treatment_{ij} \times Time_t \\ &\quad + \beta_4 Mediator_{ijt} + \beta_5 X_{ij} + \alpha_i + \mu_j + \varepsilon_{ijt} \end{aligned} \tag{2}$$

where $Mediator_{ijt}$ are the variables in the perceived built environment and travel characteristics of participant i in neighborhood j in time t.

Third, we examined the heterogeneous impact of the new subway on travel satisfaction of different participant subgroups, using mixed-effects DID regression models (Model 1). Specifically, we investigated the varying effects based on gender (male or female), age (<60 or ≥60), car ownership (with or without), and household income (low, middle, high).

5. Results

5.1. *Descriptive analysis*

Table 2 presents the socio-demographic characteristics, travel attitudes, and average Satisfaction with Travel Scale (STS) scores for the 422 participants who completed two waves of surveys. In both the treatment and control groups, females slightly outnumbered males, which is in line with the gender ratio in Wuhan. Participants had an average age of approximately 47 years and an education level around junior college. Compared to the control group, participants in the treatment group had lower monthly household incomes, roughly between CNY 10,001 and 15,001. Both groups had an average household size of more than three members. Additionally, the treatment group had a slightly higher car ownership rate than the control group (0.85 vs. 0.72). Among the travel attitude variables, only the preference for walking showed a significant difference between the two groups. Overall, Table 2 shows no significant differences between the treatment and control groups, suggesting that both groups share similar demographic characteristics.

Before the new line opened, the average STS scores showed no significant difference between the treatment and control groups. However, after the opening of the new subway line, the treatment group experienced a significant increase of 0.77 in STS scores, whereas the control group showed a smaller, insignificant increase of 0.48. Moreover, the difference in these changes was statistically significant ($p < 0.05$), indicating that the new subway line likely enhanced travel satisfaction for the treatment group but not for the control group.

5.2. *DID results*

Table 3 presents the DID model results for travel satisfaction. The interaction term (Treatment × Time) captures the impact of the new subway line on changes of travel satisfaction. In Model 1, this interaction term is positively associated with travel satisfaction and statistically significant, suggesting that the new subway line has significantly

Table 2
Descriptive statistics of samples (N = 422).

Variables	Treatment group Mean (SD) or %	Control group Mean (SD) or %	p-value
Socio-demographics			
Gender (% Male)	45.76 %	49.46 %	0.593
Age	46.96 (14.86)	46.18 (14.92)	0.594
Education level	3.81 (1.41)	4.02 (1.30)	0.148
Household income	5.72 (1.68)	5.92 (1.97)	0.452
Household size	3.26 (1.30)	3.11 (1.36)	0.235
Car ownership	0.85 (0.68)	0.72 (0.62)	0.148
Travel attitude			
Preference for subway	3.96 (1.26)	4.10 (1.12)	0.401
Preference for bus	3.38 (1.32)	3.44 (1.22)	0.798
Preference for car	3.17 (1.41)	2.97 (1.46)	0.158
Preference for e-bike	2.56 (1.57)	2.54 (1.50)	0.894
Preference for bicycle	2.53 (1.51)	2.64 (1.49)	0.397
Preference for walking	4.15 (1.15)	3.69 (1.36)	<0.001***
Average STS scores			
Average STS scores at baseline	2.75 (1.23)	2.97 (1.22)	0.157
Average STS scores at follow-up	3.52 (0.95)	3.45 (0.93)	0.451
Changes in average STS scores	0.77***	0.48	0.015*
Number of participants	236 (55.92 %)	186 (44.08 %)	

Notes:
(a) Education level: 1 = primary school or below, 2 = middle school, 3 = secondary school including vocational school, 4 = junior college, 5 = bachelor's degree, 6 = postgraduate or above.
(b) Household income: 1 = ¥1,500 or less, 2 = ¥1,501–3,000, 3 = ¥3,001–5,000, 4 = ¥5,001–8,000, 5 = ¥8,001–10,000, 6 = ¥10,001–15,000, 7 = ¥ 15,001–20,000, 8 = ¥ 20,001–25,000, 9 = ¥ 25,001–30,000, 10 = ¥ 30,001–40,000, 11 = ¥ 40,000 or more.
(c) Household size was calculated by the number of family members.
(d) Car ownership was measured by the number of cars at the household level.
(e) Travel attitude: 1 = least preferred, 5 = most preferred.
(f) The participants' socio-demographic characteristics and travel attitudes were gathered at the baseline survey. Independent samples *t*-test and Mann-Whitney *U* test were used to assess the differences between two groups and paired *t*-test were conducted for the difference between average STS scores at baseline and follow-up period. Significance level: $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***).

Table 3
Mixed-effects DID regression models of travel satisfaction.

Variables	Model 1 β (SE)	Model 2 β (SE)	Model 3 β (SE)
Treatment	−0.085 (0.059)	−0.091 (0.059)	−0.105 (0.064)
Time	0.207*** (0.040)	0.209*** (0.040)	0.165*** (0.047)
Treatment × Time	0.117* (0.048)	0.114* (0.049)	0.138** (0.048)
Socio-demographics			
Gender (Ref. Male)		0.012 (0.038)	−0.015 (0.039)
Age		0.033 (0.043)	−0.002 (0.044)
Education level		−0.069 (0.045)	−0.055 (0.045)
Household income		−0.038 (0.045)	−0.031 (0.045)
Household size		0.023 (0.042)	0.022 (0.042)
Car ownership		−0.039 (0.037)	−0.047 (0.039)
Travel attitude			
Preference for subway			0.030 (0.034)
Preference for bus			0.149*** (0.035)
Preference for car			0.057 (0.035)
Preference for e-bike			0.043 (0.036)
Preference for bicycle			−0.089* (0.035)
Preference for walking			0.093** (0.034)
Observations	844	844	844
R^2	0.397	0.405	0.434

Note: β is Standardized Beta. Significance level: $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***).

enhanced travel satisfaction for nearby residents. Models 2 to 3 sequentially consider additional control variables, yet the interaction term remains stable and significant across all models, reinforcing the robustness of the findings. Several travel attitude variables are significantly correlated with travel satisfaction, indicating that travel attitudes play an important role in travel satisfaction, consistent with previous studies (Cao & Ettema, 2014; Ye & Titheridge, 2017).

5.3. Robustness tests

5.3.1. PSM-DID method

To further verify the robustness of our results, we employed the propensity score matching and difference-in-difference (PSM-DID) approach. While the DID method can control both observable and unobservable differences between the treatment and control groups, sample selection bias may still exist since participants were not randomly assigned. To mitigate this issue, we applied the PSM-DID method (Fan & Zhang, 2021; Xu et al., 2018). Following Wang et al. (2024), we used socio-demographic variables to match participants in the treatment and control groups. The matched sample was then used in Equation (1) for analysis.

Table 4 presents the results of PSM-DID models (Model 4-6). The coefficients for the interaction term (Treatment × Time) remained significantly positive across all these PSM-DID models after controlling the covariates, which was consistent with the primary DID analysis. It revealed that the effect of the new subway line on improving travel satisfaction was relatively robust after matching samples.

5.3.2. Sensitivity analysis

We conducted sensitivity analysis to assess the impact of the new subway line on travel satisfaction, with two additional distance thresholds: 700 m and 900 m (Table 5). The estimated coefficients for the interaction term (Treatment × Time) remained significant across both models. These results align with the previous analysis, confirming the robustness of our findings.

5.4. Mediation analysis

We hypothesized that the new subway line may improve travel satisfaction through changing perceived built environment characteristics and travel behavior of nearby residents (Fig. 1), and these hypotheses were tested with mediation analysis.

5.4.1. Perceived built environment attributes

Table 6 presents the results of the mediation analysis regarding the perceived built environment. Among the mediators tested, only "easy access to downtown" and "easy access to transit stops or stations" significantly mediated the relationship between the new subway line and travel satisfaction ($p < 0.01$). This indicates that the new subway

Table 4
PSM-DID regression model results.

Variables	Model 4 β (SE)	Model 5 β (SE)	Model 6 β (SE)
Treatment	−0.131 (0.066)	−0.123 (0.067)	−0.122 (0.069)
Time	0.181** (0.063)	0.186** (0.063)	0.154* (0.072)
Treatment × Time	0.153* (0.072)	0.147* (0.071)	0.177* (0.071)
Control variables:			
Socio-demographics	No	Yes	Yes
Travel attitude	No	No	Yes
Observations	512	512	512
R^2	0.414	0.425	0.458

Note: β is Standardized Beta. Significance level: $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***). The control variables of socio-demographics and travel attitude were the same as those in Table 3.

Table 5
Sensitivity testing.

	Treatment: 700 *m* Control: 700–2400 *m*	Treatment: 900 *m* Control: 900–2400 *m*
Variables	β (SE)	β (SE)
Treatment	−0.083 (0.059)	−0.075 (0.068)
Time	0.178*** (0.040)	0.152** (0.052)
Treatment × Time	0.119* (0.047)	0.138** (0.053)
Control variables:		
Socio-demographics	Yes	Yes
Travel attitude	Yes	Yes
Observations	844	844
R^2	0.431	0.439

Note: β is Standardized Beta. Significance level: $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***). The control variables of socio-demographics and travel attitude were the same as those in Table 3.

line improved travel satisfaction by providing better perceived accessibility to downtown and transit stops or stations, which are similar to those findings in previous studies (Cao, 2013; Yin et al., 2021). However, none of the variables from perceived walkability were significant in the mediation test (p > 0.10), suggesting that these factors did not play a mediation role.

5.4.2. Travel characteristics

Table 7 presents the results of the mediation analysis focusing on travel characteristics. Among the examined mediators, only the variable, number of out-of-home activities on weekends, significantly mediated the relationship between the new subway and travel satisfaction. Notably, the coefficient between the new subway and this mediator was negative, indicating that the subway's opening may have reduced the number of out-of-home activities on weekends, ultimately leading to increased travel satisfaction. This may be due to the development of several large shopping malls in the areas surrounding new subway stations, which allow people to conveniently access shopping, dining, and entertainment in a single location without the need to travel to multiple destinations. This change enhanced the overall travel experience, thereby improving travel satisfaction. Additionally, we observed that the new subway line increased rail use and reduced car use, and travel time was negatively associated with travel satisfaction. However, the mediation tests for travel frequency and travel time are statistically insignificant.

5.5. Heterogeneity analysis

Table 8 presents the results of heterogeneity analysis. It revealed the heterogeneous effect of the new subway line for different participant subgroups. Specifically, the impact of the new subway line on improving travel satisfaction is more significant for females, individuals under 60 years old, and those from middle-income households. However, the new subway line does not have a significant effect on the travel satisfaction of either car owners or non-car owners.

6. Discussion

The construction of rail transit systems has been widely regarded as a crucial strategy to reduce traffic congestion, improve travel satisfaction, and enhance quality of life for urban residents. However, research on the impact of rail transit on travel satisfaction remains limited, especially studies based on panel dataset, which make it difficult to infer causal relationships. In addition, the specific mechanisms through which rail transit affects travel satisfaction are not well understood. To address these gaps, we employed a natural experiment approach, using two waves of survey data collected from 422 participants in Wuhan, China, to assess the causal impact of a newly opened subway line on travel satisfaction and underlying mechanisms. There are three major findings.

6.1. Main findings

First, the DID results indicated that travel satisfaction of residents living close to the newly opened subway stations significantly enhanced, compared with that of those living far away. The result remains valid to various robust tests. This finding is not only aligned with previous

Table 7
Mechanism analysis of travel characteristics.

Mediators		Path a (X → M)	Path b (M → Y)	Direct effect (X → Y)	Indirect effect (a × b)
	Rail	0.151**	0.002	0.138**	0.0003
	Bus	−0.041	−0.061	0.136**	0.002
	Car	−0.097*	−0.049	0.133**	0.005
	E-bike	−0.016	−0.161***	0.135**	0.003
	Bicycle	−0.053	0.015	0.139**	−0.001
	Walking	−0.045	−0.081*	0.134**	0.004
Travel time	Weekday travel time	−0.035	−0.147***	0.134**	0.005
	Weekend travel time	−0.074	−0.017	0.137**	0.001
	Total time	−0.074	−0.105**	0.131**	0.007
Number of out-of-home activities	Weekday activities	−0.004	0.009	0.138**	−0.0003
	Weekend activities	−0.119*	0.096**	0.150**	−0.011*
	Total activities	−0.062	0.073	0.143**	−0.005

Note: Significance level: $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***). X is the interaction term (Treatment × Time), indicating the opening of the new subway line. M is the list of mediators. Y represents travel satisfaction.

Table 6
Mechanism analysis of perceived built environment.

Mediators		Path a (X → M)	Path b (M → Y)	Direct effect (X → Y)	Indirect effect (a × b)
	Easy access to downtown	0.193***	0.189***	0.102*	0.036**
	Civic buildings (e.g., library) nearby	0.014	0.137***	0.136**	0.002
	Easy access to a regional shopping mall	0.081	0.143***	0.126**	0.011
	Shopping areas within walking distance	0.067	0.186***	0.125**	0.013
	Easy access to parks and open spaces	0.061	0.129***	0.131**	0.008
	Easy access to workplace	0.021	0.187***	0.135**	0.004
Transit Accessibility	Easy access to transit stops or stations	0.242***	0.205***	0.089*	0.049***
	Extensive public transportation routes	0.046	0.143***	0.131**	0.007
Walkability	Good street lighting	−0.094	0.114***	0.149**	−0.011
	Safe neighborhood for walking	−0.036	0.162***	0.143**	−0.005
	Quiet neighborhood	−0.046	0.078*	0.141**	−0.003

Note: Significance level: $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***). X is the interaction term (Treatment × Time), indicating the opening of the new subway line. M is the list of mediators. Y represents travel satisfaction.

Table 8
Heterogeneous effect of the new subway line on travel satisfaction.

Variables	Gender Male	Female	Age <60	≥60	Car ownership With	Without	Household income Low	Middle	High
Treatment × Time	0.066	0.187*	0.146*	0.170	0.131	0.114	0.092	0.183*	0.151
	(0.061)	(0.074)	(0.065)	(0.109)	(0.071)	(0.098)	(0.086)	(0.086)	(0.079)
Control variables:									
Socio-demographics	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Travel attitude	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	400	444	636	208	562	282	352	228	264
R^2	0.100	0.309	0.238	0.382	0.227	0.169	0.280	0.578	0.514

Note: Significance level: $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***). The figures in parentheses represent standard errors. The low, middle, and high-income households are classified based on the income levels of all the sampled households.

findings based on cross-sectional research design (Cao, 2013; Yin et al., 2021; Zhai et al., 2021) but also strengthens existing literature by adding more causal inference evidence based on a natural experiment research design.

Second, we identified mediating effects of both perceived built environment characteristics and travel behavior on the link between newly opened subway line and improved travel satisfaction. Regarding perceived built environment characteristics, perceived accessibility to downtown and transit stops or stations are significant variables. This suggests that investments in subway stations improved accessibility to transit stops and stations, as well as to the city center, thereby enhancing residents' travel satisfaction. This finding is consistent with previous studies (Cao, 2013; Yin et al., 2021). However, the variables of perceived walkability did not mediate this relationship, which differs from some prior research. This discrepancy may be explained by the timing of the second survey, conducted only nine months after the subway opening. Within this relatively short follow-up period, the built environment around the new stations may not have undergone substantial changes, and pedestrian-friendly infrastructure may not yet have been fully developed. Consequently, the potential effects of walkability on travel behavior and satisfaction could not be fully captured.

Regarding travel characteristics, the number of out-of-home activities on weekends significantly mediated the link between the new subway line and increased travel satisfaction. Interestingly, the coefficient between the subway opening and this mediator was negative, suggesting that the new line reduced the number of weekend out-of-home activities, which in turn enhanced travel satisfaction. First, fewer out-of-home activities were associated with higher travel satisfaction. This finding is consistent with existing evidence that a more streamlined itinerary, with fewer scheduled activities, often reduces time pressure and improves the overall travel experience, leading to higher travel satisfaction (Ettema et al., 2011). Second, the reduction in activity frequency following the subway opening seems to contradict earlier studies that emphasize the role of new rail transit in expanding travel opportunities and increasing activity participation (Allen & Farber, 2020). However, recent evidence from Shenzhen indicates that metro expansion can also reduce the total number of trips by consolidating daily activities and transforming multiple short, non-motorized trips into fewer, transit-based journeys (Zhou et al., 2024). In our study context, the construction of large shopping malls near newly opened subway stations likely played a crucial role. These malls offered residents a "one-stop" destinations for shopping, dining, and leisure, thereby reducing the need to visit multiple sites on weekends. Thus, the decline in number of out-of-home activities does not indicate reduced accessibility, but rather a reorganization of weekend travel patterns toward greater efficiency and convenience. This reorganization, enabled by the subway and co-located commercial development, ultimately contributed to higher travel satisfaction.

Moreover, the results showed that neither travel time nor travel frequency significantly mediate the relationship between the new subway line and travel satisfaction. Specifically, although our analysis confirmed that shorter travel time is associated with higher travel satisfaction, consistent with previous studies (De Vos et al., 2016; Ettema et al., 2011; Zhao & Li, 2019), the new subway line did not significantly change residents' travel time in our sample, either on weekdays or weekends. This could be because the line mainly affects residents' travel modes (such as shifting from buses or private cars to the subway) rather than substantially shortening travel duration. Furthermore, although subway use increased and private car use decreased, this modal shift did not directly enhance overall travel satisfaction. This may be because travel satisfaction depends on broader aspects of the travel experience (e.g., comfort, convenience, reliability, safety) beyond mode or time savings. For example, a study conducted in Delhi, India, found that a higher perceived level of night-time travel safety was positively associated with greater travel satisfaction (Majumdar et al., 2021).

Third, this study revealed significant heterogeneous effect of rail transit on travel satisfaction across different socio-demographic groups, particularly by age, gender, and household income. Women exhibited a more pronounced increase in travel satisfaction than men after the opening of the new subway line. Similarly, younger individuals experienced a greater increase in travel satisfaction than older adults. These results align with previous studies showing that older adults and men generally report lower travel satisfaction (Zhao & Li, 2019). One possible explanation for lower impact on older adults is their lower expectations and needs for public transport because they tend to have larger proportion of activities conducted within their residential vicinity (dell'Olio et al., 2011). Hence, they may be less responsive to external changes such as newly built rail transit. Compared with men, women are more sensitive to the travel environment, deriving greater comfort and satisfaction from the clean, orderly, and safe travel conditions offered by the subway system, which enhances their travel satisfaction (dell'Olio et al., 2011).

Furthermore, the impact of the new subway on travel satisfaction was significant for participants from middle-income groups, but not for either low or high-income groups. This aligns with prior research indicating that middle-income residents experience higher travel satisfaction (Zhao & Li, 2019). High-income individual typically own private cars and have diverse travel options, making the new subway line less attractive for them (Brown & Werner, 2008). While low-income groups may benefit from the increased convenience of rail transit, other factors like high transportation costs may hinder their travel satisfaction improvements (Shi et al., 2022; Ye & Titheridge, 2019). In contrast, middle-income groups who usually use a combination of private and public transportation, experience the most significant gains in transport efficiency and quality of life due to the new subway line, thereby resulting in the largest increase in travel satisfaction.

6.2. Implications

First, this study shows that the primary mechanisms through which the newly opened subway enhances residents' travel satisfaction are by improving accessibility to downtown and transit stops or stations, as well as streamlined weekend activities. Therefore, enhancing accessibility to major destinations, such as central business districts, workplaces, commercial areas, and educational institutions, should be a key objective in rail transit planning (Cao, 2013; Wang et al., 2020). Furthermore, the integration of new subway stations and urban development in surrounding areas can reduce the required trips and enhance overall travel satisfaction.

Second, this study found that the increase in travel satisfaction attributed to the new subway was not significant for older adults and low-income individuals. This suggests that government officials should place greater emphasis on addressing the specific transportation needs of vulnerable groups (e.g., older adults and low-income people), thereby promoting transportation equity and social inclusiveness. For older adults, improving barrier-free facilities (e.g., elevators, escalators, handrails, ramps) and enhancing age-friendly design (e.g., more seating in waiting areas) may enhance comfort and travel satisfaction. For low-income people, providing subsidized subway fare may increase their subway ridership and overall travel satisfaction.

6.3. Limitations

This study has several limitations. First, this study measured overall travel satisfaction without distinguishing between travel satisfaction for commuting vs. non-commuting trips, and weekday vs. weekend trips. Future research should assess travel satisfaction across different dimensions. Second, the observed increase in travel satisfaction may partly reflect temporary externalities associated with the construction phase. For example, noise, dust, and traffic congestion during construction could have initially reduced travel satisfaction, and their removal after construction may partly explain the observed improvement in travel satisfaction. Therefore, the observed change may not fully reflect the net effect of rail transit on travel satisfaction (Wu, 2015). Third, due to the research design, this study only captures changes in travel satisfaction within one year, which may reflect short-term impacts. According to hedonic adaptation theory (Lyubomirsky, 2012), individual's happiness or satisfaction tends to return to its baseline after an initial adjustment (can be either increase or decrease) to environmental changes. In the context of rail transit improvements, residents may report higher satisfaction immediately due to enhanced accessibility and convenience, but this effect may diminish over time as they adapt. Therefore, to fully understand the long-term effects of rail transit on travel satisfaction, future studies should incorporate multiple follow-up surveys over an extended timeframe. Fourth, the simple mediation model used in this study effectively illustrates the role of different mediating variables; however, it cannot account for the complex interrelationships between variables, potentially overlooking more complex mediation effects (e.g., chained mediation). Future research should apply more sophisticated mediation analysis techniques to address this issue. Finally, although we collected both subjective travel attitudes and actual travel behavior, we did not explicitly test the consistency between the two (Pani et al., 2023). Future studies could further investigate the alignment between preferences and behavior and its implications for travel satisfaction.

7. Conclusion

This study employed a natural experiment approach to evaluate the impact of a new subway line on travel satisfaction in Wuhan, China. We have reached several conclusions. First, the Difference-in-Differences results demonstrated that the new subway line significantly enhanced travel satisfaction for residents living nearby. Second, mediation analysis revealed that the improvement in travel satisfaction was primarily driven by increased perceived accessibility to downtown and transit stops or stations, as well as a reduction in the number of out-of-home activities on weekends. Third, heterogeneous analysis highlighted that the effect of the new subway line on travel satisfaction was more pronounced among females, individuals under 60 years old, and those from middle-income households. Overall, our findings provide robust causal evidence linking rail transit infrastructure to travel satisfaction, thereby deepening our understanding of this complex relationship and offering valuable insights to enhance residents' travel satisfaction with rail transit infrastructure.

8. Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the authors used ChatGPT in order to polish language and grammar. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

CRediT authorship contribution statement

Zhenhua Li: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Yi Lu:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Jingjing Wang:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Yihao Wu:** Methodology, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table A
Characteristics for the follow-up and lost to follow-up samples.

Variables	Follow-up (n = 422) Mean (SD) or %	Lost to follow-up (n = 486) Mean (SD) or %	p-value
Socio-demographics			
Gender (% Male)	46.9 %	48.0 %	0.745
Age	46.618 (14.863)	45.525 (14.939)	0.271
Education level	3.905 (1.368)	3.605 (1.367)	0.080

(continued on next page)

Table A (*continued*)

Variables	Follow-up (n = 422) Mean (SD) or %	Lost to follow-up (n = 486) Mean (SD) or %	p-value
Household income	5.810 (1.817)	4.930 (1.889)	0.064
Household size	2.194 (1.324)	2.163 (1.347)	0.721
Car ownership	0.799 (0.674)	0.695 (0.677)	0.145
Travel attitude			
Preference for subway	4.026 (1.202)	3.917 (1.252)	0.184
Preference for bus	3.409 (1.278)	3.559 (1.282)	0.079
Preference for car	3.085 (1.431)	2.993 (1.490)	0.346
Preference for e-bike	2.556 (1.541)	2.580 (1.551)	0.820
Preference for bicycle	2.582 (1.499)	2.580 (1.464)	0.978
Preference for walking	3.952 (1.264)	3.884 (1.312)	0.428

Notes:

(a) Education level: 1 = primary school or below, 2 = middle school, 3 = secondary school including vocational school, 4 = junior college, 5 = bachelor's degree, 6 = postgraduate or above.
(b) Household income: 1 = ¥1,500 or less, 2 = ¥1,501–3,000, 3 = ¥3,001–5,000, 4 = ¥5,001–8,000, 5 = ¥8,001–10,000, 6 = ¥10,001–15,000, 7 = ¥ 15,001–20,000, 8 = ¥ 20,001–25,000, 9 = ¥ 25,001–30,000, 10 = ¥ 30,001–40,000, 11 = ¥ 40,000 or more.
(c) Travel attitude: 1 = least preferred, 5 = most preferred.
(d) Independent samples *t*-test and Mann-Whitney *U* test were conducted to assess differences between the two groups.
(e) $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***).

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