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Understanding post-pandemic metro commuting ridership by considering the built environment: A quasi-natural experiment in Wuhan, China

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ABSTRACT

The COVID-19 pandemic has had a significant impact on metro commuting ridership. However, the exact magnitude and spatial and temporal characteristics of the impact remain unclear. In this study, we explored the impact of the COVID-19 outbreak on metro commuting ridership in Wuhan, where the novel virus was first reported. The results of interrupted time-series (ITS) analysis showed that metro commuting ridership sharply dropped in the short term under the impact of the outbreak in the epicenter, rebounded rapidly as the pandemic eased, and returned to pre-pandemic levels in six months. Furthermore, there was a noticeable spatial heterogeneity in the rebound. Urban centers, especially job-rich areas, recovered faster than other areas. In addition, the number of residents, number of bus stops, number of enterprises around a metro station, and being a transfer station had a positive effect on metro ridership, while street length, number of restaurants, and number of metro exits had a negative effect. These findings may help local governments and metro managers develop sustainable metro operations and infection prevention policies to better cope with the impact of the pandemic and beyond.

1. Introduction

The COVID-19 pandemic has led to a serious disruption in metro transportation worldwide (Basu & Ferreira, 2021; Tirachini & Cats, 2020). First, strict policies of lockdown, quarantine, and social distancing directly limited metro use (Chang, Lee, Yang, & Liou, 2021). For example, Wuhan stopped all metro services from January 24 to March 28, 2020. Moreover, even when the metro system resumed operations as the outbreak eased, metro ridership remained low due to the perceived infection risk in crowded train cars (H. H. Chang et al., 2021; Kim & Kwan, 2021). The decline in metro ridership has exacerbated financial pressures on metro operators, and it may lead them to reduce metro service levels, which can result in the further decline of ridership.

There is a noticeable disparity in the metro ridership decline for trips with different purposes. A major decline was observed among trips for leisure and entertainment purposes, while trips for commuting purposes witnessed a milder decline (Pan & He, 2022). Commuting trips are essential for some people. For example, some commuters have no alternative means of travel, and the nature of some jobs (e.g., front-line workers) ruled out the work-at-home option. Hence, many commuters still use the metro as their primary mode of travel (Basu & Ferreira, 2021; Pan & He, 2022). Therefore, a fine-grained analysis of the impact of the pandemic on metro commuting behavior is important to mitigate the potential disruption of ridership.

The built environment features have proven to affect residents' metro travel during the non-pandemic era (Ewing & Cervero, 2001, 2010). However, we know little about such an effect in the post-pandemic era. As the current pandemic persists, it has the potential to permanently change people's work and living habits (Balbontin et al., 2021; Thomas, Charlton, Lewis, & Nandavar, 2021). Responding to the pandemic, people's short-distance trips to parks and recreational and commercial destinations around their residences have increased, and long-distance trips for non-commuting activities have decreased (Schlosser et al., 2020; Zhou, Wu, & Ma, 2021). A study in Taiwan showed a significant decrease in metro ridership near night markets, shopping centers, and schools (H. H. Chang et al., 2021). In addition, changes in economic activities such as work-from-home, online shopping, online education, and online entertainment driven by the

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pandemic are reshaping the built environment of cities by adjusting the spatial and distance preferences of businesses and residents and changing the distribution of services such as retail, cultural, and entertainment venues (Balbontin et al., 2021; D. A. Hensher, Balbontin, Beck, & Wei, 2022; B. P. Y. Loo & Huang, 2022). Changes in the built environment have also led to a redefinition of the impact of the built environment on residential metro travel in the post-pandemic era. Hence, we need to re-examine the associations between built environment characteristics and metro travel behaviors after the pandemic.

Several studies have enriched our knowledge of the impact of the pandemic on metro commuting behavior during the COVID-19 outbreak (Basu & Ferreira, 2021; S. Chang et al., 2021; de Palma, Vosough, & Liao, 2022), but few have explored the changes in metro commuting behavior when the pandemic was fully under control. In addition, it is unclear how built environment characteristics affect people's commuting trips in the post-pandemic era. These critical knowledge gaps may limit our ability to provide sustainable and efficient metro operations in the post-pandemic era.

To address these important research gaps, we examined the temporal trends in metro commuting ridership and the role of station-level built environment characteristics on the changes in metro commuting ridership after full control of the pandemic in Wuhan, China. Wuhan was the first city to have a COVID-19 outbreak and the first city to recover from the pandemic. We extracted big data on metro commuting ridership immediately before the outbreak (from April 2019 to January 2020) and immediately after the lockdown measures were lifted (from April 2020 to April 2021). During the period between April 2020 to April 2021, there were no new COVID-19 cases in Wuhan, and full resumption of work and production was achieved.

In the following section, a comprehensive literature review was conducted to explore the effects of the epidemic on the commuting behavior of residents and the relationship between the built environment and metro commuting behavior. Then, the study area, data sources, and methodology were presented. In the results section, we first depicted the spatial and temporal patterns of metro commuting ridership before and after the epidemic. We then investigated the influence of key factors on metro commuting ridership by employing an interrupted time-series analysis. Finally, a summary of the key findings and their implications were provided.

2. Literature review

2.1. The impact of the pandemic and residents' commuting behavior

The impact of the pandemic on commuting behavior has attracted widespread attention from scholars worldwide (S. Chang et al., 2021; Kim & Kwan, 2021; Liu et al., 2021; J. Wang et al., 2022). As a result of the pandemic, commuters generally reduced travel frequency and changed travel mode choices (Currie, Jain, & Aston, 2021; Palm et al., 2021).

First, various social distancing measures directly decreased commuting trips. Wuhan was the first city in the world to experience the COVID-19 outbreak and also the first to successfully control the pandemic through stringent citywide lockdown measures. Such measures were followed by many cities around the world, which drastically reduced commuting trips (de Haas, Faber, & Hamersma, 2020; Schlosser et al., 2020). The outbreak led to a significant decrease in the working population. For example, during the pandemic, the working population in Beijing decreased by approximately 60%, and commuting trips decreased accordingly (Liu et al., 2021). In addition, the impact of various restrictions in response to the pandemic resulted in unprecedented levels of work-at-home practices (Balbontin et al., 2021; D. A. Hensher et al., 2022; Sam Engle, 2020). Such changes in work mode significantly reduced the need for commuting, and the impact was greater in the morning peak than in the evening peak (B. P. Y. Loo & Huang, 2022).

Second, the outbreak also led to a shift in travel mode choice, especially from public transportation to private vehicles, walking, and bicycling, due to the potential infection risks associated with public transportation (Abdullah, Dias, Muley, & Shahin, 2020). The results of a Boston-based survey show that the pandemic increased the willingness of car-free households to purchase private cars, with 18% of car-free households planning to purchase private cars due to the pandemic (Basu & Ferreira, 2021). In addition, low-income populations had a relatively lower willingness to reduce commuting trip frequency or use cars than did high-income populations (Abdullah et al., 2020; He, Rowangould, Karner, Palm, & LaRue, 2022).

With the gradual ease of the pandemic and the lifting of lockdown measures in some cities, commuter ridership rebounded. One study conducted in the United States showed that the amount of commuter ridership dropped significantly from March to April 2020 and began to recover gradually after June 2020 (Kim & Kwan, 2021). Because of the advantages of low cost, mass capacity and punctuality, many people still chose metro travel after the pandemic stabilized, especially low-income individuals. As a result, metro ridership may show a U-shaped rebound (Schlosser et al., 2020). However, some researchers concluded that demand for metros in the post-pandemic era may never return to the previous norm for two reasons (de Haas et al., 2020; Hsieh & Hsia, 2022). First, because metros are thought to carry a higher risk of infection, some residents may shift from public transportation to private cars (Hu & Chen, 2021; Lu, Zhao, Wu, & Lo, 2021; Pan & He, 2022). Second, the significant increase in mandatory work-from-home orders during the pandemic may be replaced by voluntary choices after the pandemic, which will also bring about a reduction in metro ridership (Balbontin et al., 2021; David A. Hensher, Beck, & Wei, 2021; Sam Engle, 2020). Considering that most of the studies focus on the data during the COVID-19 pandemic, less is known about the potential rebound of metro commuting trips when the pandemic was fully under control.

2.2. Built environment and metro commuting behavior

The built environment characteristics have long been recognized as important factors in metro travel behavior (Ewing & Cervero, 2001, 2010). Specifically, density (including population density and building density) may induce more travel demands, including metro ridership. A study based on nine low- to medium-density cities in the United States showed that population density had a significant positive effect on ridership (Kuby, Barranda, & Upchurch, 2004). In high-density cities such as Seoul and Beijing, population density and metro ridership showed similar associations (Jun, Choi, Jeong, Kwon, & Kim, 2015; P. Zhao, 2013). A study based in Nanjing showed a significant positive effect of commercial/office floor area in the station area and metro ridership (J. Zhao, Deng, Song, & Zhu, 2013), and similar findings were reported in Hong Kong and New York City (Becky P. Y. Loo, Chen, & Chan, 2010).

A higher level of land use mixture is more likely to boost metro ridership. A higher land use mixture indicates more and mixed types of facilities and destinations within the area, thus leading to more metro ridership (Ding, Cao, & Liu, 2019). However, some studies have also found that the effect of land use mixtures on metro ridership was insignificant (Cervero, 2006). These discrepancies require further research.

At the urban design level, street network connectivity, safety, and road network structure, all have an impact on metro ridership (Durning & Townsend, 2015). Many studies have shown that street network connectivity, such as street intersection density and street length in a station's surrounding area, has a significant positive effect on metro ridership (Ding et al., 2019; Durning & Townsend, 2015; Shao, Zhang, Cao, Yang, & Yin, 2020). However, some studies have also found that intersection density and metro passenger flow sometimes have a negative effect (An, Tong, Liu, & Chan, 2019; Yang et al., 2022).

Destination accessibility is another important factor influencing residents' metro ridership. The number of potential destinations around metro stations, such as companies, restaurants, and amenities, which are closely related to residents' work and daily life, has a positive impact on metro ridership (An et al., 2019; Gan, Yang, Feng, & Timmermans, 2020). Some researchers have used the distance to the Central Business District from a station to measure city-level accessibility, but the results are mixed. Studies based in Shenzhen and Nanjing, China, suggest that ridership at subway stations located in CBD areas was higher than at other stations (Shao et al., 2020; J. Zhao et al., 2013). However, the studies in Washington DC, and Shanghai, China, suggest a nonsignificant relationship (An et al., 2019; Ding et al., 2019).

The availability of other public transportation services, especially buses, may also promote metro ridership (Cervero, 2006). The number of bus stops within a reasonable walking distance of a metro station attracts residents to use the metro for long-distance trips while using the bus to reach the metro station from home (Wong, Szeto, Yang, Li, & Wong, 2018).

Metro ridership is influenced not only by the built environment but also by the characteristics of metro stations (Jun et al., 2015; keemin Sohn, 2010). Compared to non-transfer stations, transfer stations have higher network connectivity and therefore higher ridership (Kuby et al., 2004). Terminal stations have a larger catchment area than non-terminal stations, and thus have significantly higher ridership than non-terminal stations (J. Zhao et al., 2013). In addition, some studies have shown that the number of exits at metro stations also has a significant positive effect on the number of passengers at metro stations (Yang et al., 2023).

However, the pandemic may change the impact of built environment characteristics on metro travel behaviors. Some studies have found that higher population density and spatial density were strongly associated with COVID-19 infection (Viezzer & Biondi, 2021). As a result, many commuters chose to stay away from crowded areas and the metro out of concern for personal safety and health (Choe et al., 2021). A Chicago-based study showed that metro stations experienced an average 72.4% drop in ridership due to the pandemic (Hu & Chen, 2021). The ridership declines were greater in business districts and zones with higher percentages of white, highly-educated, and high-income people (Hu & Chen, 2021). In addition, urban spatial restructuring and residential demand changes driven by the pandemic may have a long-lasting impact on the relationship between the built environment and residential metro travel behavior (Zhou et al., 2021). On the one hand, the impact of COVID-19 has made city centers less attractive and reduced the value of central areas, and the decline in the value of businesses around metro stations has been even more dramatic and slow to recover (Rosenthal, Strange, & Urrego, 2022). On the other hand, surveys based on multiple regions show that even with the lifting of COVID-19 restrictions, there is significant support for future work-from-home behavior, and some companies are adapting to this "new normal", which could result in significant changes in metro commuting (Balbontin et al., 2021; Osorio, Liu, & Ouyang, 2022; Thomas et al., 2021). Therefore, an in-depth investigation of the impact of the built environment on metro commuting behavior in the post-pandemic era is necessary.

2.3. Research gap and contribution

Existing studies have confirmed that the COVID-19 pandemic has a significant impact on metro commuting ridership, and the impact may vary during different phases of the pandemic (Kim & Kwan, 2021; Tirachini & Cats, 2020). However, there are two major research gaps. First, most studies are conducted based on data from the early or different stages of the pandemic, and the changes in metro ridership after the pandemic is fully controlled are not yet clear. Second, we still know little about the role of the built environment characteristics around metro stations on the change in metro commuting behavior during the post-pandemic era. The absence of such knowledge may hinder our effort to improve urban resilience through land planning strategies when facing future pandemic outbreaks.

To address these gaps, we estimate the effects of the COVID-19 outbreak on metro commuting behavior using data both before the pandemic and immediately after its full control. In addition, we examined the impact of the built environment characteristics on metro ridership after full control of the pandemic. This study is significant in two aspects. First, it studied the spatial and temporal characteristics of metro ridership before and after the pandemic, which enabled us to understand the impact of the pandemic on metro ridership and provided evidence-based guidance for post-pandemic metro operations, it is also essential to prepare for the challenges of future global pandemics. Second, this study also examined the impact of the station-level built environment and metro station characteristics on ridership, which can help us develop urban planning policies to provide sustainable metro services in the post-pandemic era.

3. Method

3.1. Study area

This study was conducted in Wuhan, China, where the new strain of coronavirus was first reported. The city, which has 11 million residents and is the largest city in Central China, quickly became the epicenter for the disease.

Fig. 1 shows the layout of Wuhan, which can be divided into distant suburbs, the urban area and the core. The urban area has been built up since the 1990s, and all the metro lines are located there. The core is the urban center of Wuhan and contains the city's major population, major business and enterprise districts. The core is located in the center of the urban area and bounded by the city's Third Ring Roads.

To contain the virus, the government immediately imposed a strict lockdown in Wuhan, shutting down all public transportation (e.g., metro, bus, ferry, train, air flight), closing nonessential businesses, and issuing stay-at-home orders on January 23, 2020. The outbreak was quickly brought under control in the following two months. Hence, the lockdown measures were gradually lifted. On March 28, 2020, the city resumed the operation of metro lines 1, 2, 3, 4, 6, and 7. On April 22, 2020, all metro lines resumed normal operation. In addition, on April 26, 2020, the Wuhan government allowed commercial enterprises and restaurants to resume operations. Since the absence of any new COVID-19 local cases in Wuhan over the subsequent year, the city's residents gradually returned to their pre-pandemic work and life routines during this period.

3.2. Data

The dependent variable was the average daily commuting ridership for all weekdays in a month. The unit of analysis was a metro station. The time unit was a month, representing the frequency with which observations were taken. To make the data comparable, we removed the new metro lines opened in 2020 and 2021 and retained 189 stations from the nine metros that operated before the outbreak. Metro stations were used as units of analysis in this study.

The dependent variable was the average daily ridership on weekdays in a specific week at a metro station each month. The metro smartcard data is provided by the Wuhan Institute of Strategic Transport Development, which contains information regarding the desensitized card number of the cardholder, the station numbers at which the card was swiped upon entry and exit, and the precise time of such entries and exits. Referring to existing studies (Huang, Levinson, Wang, Zhou, & Wang, 2018), a metro commuter was identified with the following algorithm.

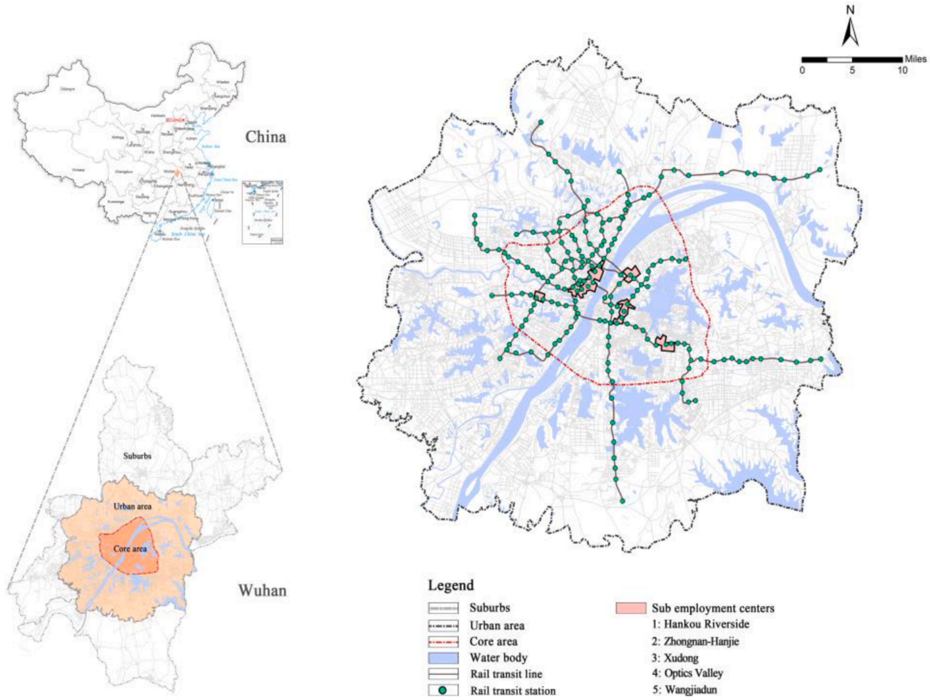

Fig. 1. Schematic diagram of the study area.

1) Constructing the daily passenger origin-destination (OD) travel chain based on the desensitized card number, which is formatted as the following information for each trip: unique card number, entry station ID, entry time, exit station ID, exit time.
2) For passengers with only two trips in a 24-hour period: If an individual travel from metro station A to station B in the morning and returns from station B to station A in the afternoon/ evening, with a time interval between the two trips exceeding 6 hours, then such an individual can be identified as a commuter who resides near station A and works near station B.
3) The following criterion is applied to passengers who make more than two trips within a 24-hour period. If an individual departs from station A in the morning and returns to station A in the afternoon/ evening, with a time interval between departure and return exceeding six hours, and determine the longest stay occurring at station B. This allows us to identify potential commuters who reside near station A and work near station B. The longest stay occurring at station B is calculated by determining the time interval between the two entries into the metro station at station B.
4) Using the OD travel chains for all weekdays in a week, an individual is identified as a commuter who resides near station A and works near station B, if the same pattern is observed for at least three weekdays per week.

According to the above rules, 32,670,742 commuters were identified in this study, accounting for 16.45% of all metro passengers.

In addition, the independent variables included the built environment characteristics around a metro station and the metro station characteristics (Table 1). Following previous studies (Bivina, Gupta, & Parida, 2020; El-Geneidy, Grimsrud, Wasfi, Tétreault, & Surprenant-Legault, 2013; Guo, Yang, Lu, & Zhao, 2021), we created an 800 m circular buffer around each metro station to measure built environment characteristics.

We selected the 5Ds framework to measure the built environment characteristics (Ewing & Cervero, 2010). Density included resident population density and building volume ratio in the buffer; diversity was measured by land use mixture; pedestrian-oriented design was measured by street intersection density and total street length; and transit accessibility was measured by number of bus stops. The accessibility of destinations was expressed in terms of the number of companies, dining facilities, living services, and distance to CBD. Considering that Wuhan is a multicenter city, the distance to the subcenter was added to measure the accessibility of the area.

We selected the number of exits, being a transfer station, and being a terminal station, which proved to affect metro commuters' ridership (Jun et al., 2015; keemin Sohn, 2010; Kuby et al., 2004; Sung et al., 2014). Being a transfer stations and being a terminal station were treated as dummy variables.

Furthermore, socio-economic attributes are recognized as influencing factors in metro commuting ridership (van de Coevering, Maat, & van Wee, 2018). To capture this influence, the study employs the average housing price around rail stations as a proxy variable, because real estate is the key component of household wealth among urban residents (Xie, Lu, Wu, & An, 2021). This data is obtained from one Chinese real-estate brokerage company (LianJia), and the transactional details include price per m^2, total price, transaction time, and location of the traded properties. The average price per m^2 during the study period within each station's coverage area was utilized.

3.3. Data analysis

The purpose of this study is to investigate the impact of the COVID-19 outbreak on metro commuting ridership and the moderating effect of the station-level built environment on commuting trips in the post-pandemic era. Because the lockdown measures (e.g., closing all metro stations) had a significant impact on metro ridership, interrupted time-series (ITS) analysis is used. ITS is a quasi-natural experimental analysis commonly used in the fields of social studies, public health, and environmental science to explore the effects of interventions, e.g., new policies or naturally occurring events (Bernal, Cummins, & Gasparrini, 2017; Latchmore et al., 2022). ITS is useful when a randomized control trial is infeasible or too costly. The advantage of ITS is that it uses pre- and post-intervention comparisons, and a parallel control is optional. Thus, without a valid control group, ITS designs can yield robust estimates (Rafael Pinto, 2022). The ITS model with the addition of built environment variables can be expressed as:

Table 1
Description of the variables.

Variable	Variable Description	Mean	St. dev.
Dependent variable			
Ridership of commuters	Average daily metro ridership on weekdays of commuters	7625.66	6671.07
Built environment features			
Resident population	Population of residents in the station area of the metro station (in ten thousands)	19.19	1.74
Plot ratio	The plot ratio of the area around the metro station is calculated from the building vector data	0.81	0.69
Land use mixture	$Landuse = -\sum_{i=1}^{k} P_{ki}\ln(P_{ki})/\ln k$ Where k is the number of land use types in the area around site i. P_{ki} is the proportion of the area of the kth type of land use in the area. A larger Landuse value indicates a higher land use mixture, while a smaller one indicates a lower land use mixture.	0.65	0.20
Street intersection Density	The overall length of road within the catchment area of the metro station	18.99	10.52
Length of street network	The overall length of road within the catchment area of the metro station(km)	1.597	2.55
Number of bus stops	Number of bus stops in the area of the metro station	7.57	5.46
Number of enterprises	Number of enterprises in the area of the metro station	99.05	97.17
Number of restaurants	Number of restaurants in the area of the metro station	123.93	122.28
Number of service facilities	Number of service facilities in the area of the metro station	57.98	61.26
Distance from the city center	Euclidean distance between the metro station and the city center (km)	11.80	6.59
2Distance from the sub-city center	Euclidean distance between the metro station and the nearest sub city center (km)	7.10	5.61
Metro station features			
Transfer station	Dummy variables, where 1 means the station is a transfer station and 0 means the station is not	0.14	0.34
Terminal station	Dummy variables, where 1 means the station is the terminal and 0 means the station is not	0.10	0.29
Exit quantity	Number of exits of the metro station	5.26	3.27
Demographics			
Housing price	The average of house prices surrounding the station (10,000 RMB)	1.83	0.43

$$Y_t = \beta_0 + \beta_1 Time_t + \beta_2 Outbreak + \beta_3 Time * Outbreak + \beta_4 Other_t + \varepsilon_t \quad (1)$$

where Y_t is the commuter's ridership of metro stations and $Time_t$ is the equal time interval (month). *Outbreak* is a binary variable representing the pre-pandemic period (coded as 0) or post-pandemic period (coded as 1). β_1 refers to the pre-pandemic slope of metro ridership, β_2 refers to the change in the level of metro ridership at the time of interruption, and the significance of β_3 shows changes in the slope of metro ridership in the post-pandemic period. $Other_t$ represents the potential covariates representing built environment features, metro station features, and socio-economic attributes. β_4 estimates the effect of $Other_t$ on commuting ridership. ε_t is the residual term. All analyses were performed in RStudio 4.1.3.

4. Results

4.1. Descriptive analyses

(1) The changes in ridership for the metro system

Fig. 2 shows the average daily commuting ridership on weekdays of each month from March 2019 to April 2021. Commuter ridership was relatively stable, with approximately 1.5 million passengers weekly before the outbreak (March 2019 to January 2020), and it was not subject to seasonal fluctuations. After the lockdown period of January to March 2020, instantaneous ridership dropped by approximately 76% in April 2020 compared to the pre-pandemic average. Then, commuter ridership showed a smooth and rapid recovery and returned to the pre-pandemic level in six months. Ridership in Wuhan briefly decreased in February 2021 due to the Chinese New Year holiday but quickly bounced back and reached the highest ridership in March.

(1) Changes in ridership at the station level

We compared the commuter ridership of metro stations before and after the COVID-19 outbreak and observed the changes in ridership at each station across the two periods. Fig. 3 shows that before the outbreak, the ridership at metro stations in the core area was significantly higher than that in other urban areas. After the pandemic began, Wuhan metro ridership showed a similar trend. Furthermore, by comparing the changes in the average ridership at each station before and after the outbreak, we find that when the metro resumed operation in March 2022, the vast majority of metro stations showed a downward trend in ridership, with the largest decline reaching 70.28%. However, 24 metro stations had increased ridership, with the largest increase reaching 68.80%. Regarding spatial distribution, the areas where metro ridership rose were concentrated in the eastern part of Wuhan. This region is an agglomeration of emerging strategic industries in Wuhan and ranks highest in terms of total GDP, fixed asset investment, and total funds available for investment in recent years. The growth rate of industrial sector is also the highest in the city. The substantial and rapid industrial development has led to an influx of employers, resulting in a significant increase in commuting trips within the region after the relaxation of epidemic control measures, even surpassing the pre-epidemic level.

4.2. The associations of the station-level built environment and metro commuter ridership

Before we conducted the ITS analysis, a VIF test was conducted. All variables had a VIF $<$ 5, indicating that multicollinearity was not a problem. Table 2 shows the results of the ITS analysis and Fig. 4 visualized the ITS trend of the ridership immediately after the lockdown measures were lifted. The monthly ridership declined by 10,800 passengers due to the outbreak ($p<0.001$), and commuter ridership increased by 512 monthly in the post-pandemic period compared with that in the pre-pandemic period.

In terms of the built environment, population density, the number of bus stops, and the number of enterprises showed a significant positive effect on commuter ridership, while land use mixture road length was negative, and the number of restaurants was also inversely correlated. Other variables (e.g., plot ratio) were statistically insignificant. At the level of metro station characteristics, ridership was significantly higher at transfer stations than at non-transfer stations, while metro traffic was significantly lower at terminals than at non-terminals. In addition, the number of exits also showed a significant negative effect on ridership. In terms of socio-economic attribute characteristics, house prices have a significant positive impact on metro commuting ridership.

4.3. Robustness test

To ensure the robustness of the results on the impact of the epidemic on metro commuting ridership, in the robustness analysis (Table 3), we removed the built environment variables, which are known to influence metro travel behavior. The results indicated that the association between the epidemic and metro ridership remained stable, with only

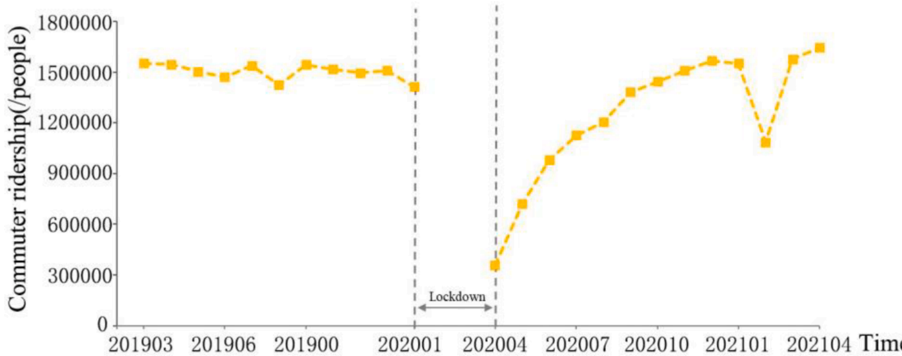

Fig. 2. Wuhan metro commuting ridership immediately before the outbreak (from April 2019 to January 2020) and immediately after the lockdown measures were lifted (from April 2020 to April 2021). Metro service was suspended the citywide lockdown (from January 2020 to April 2020).

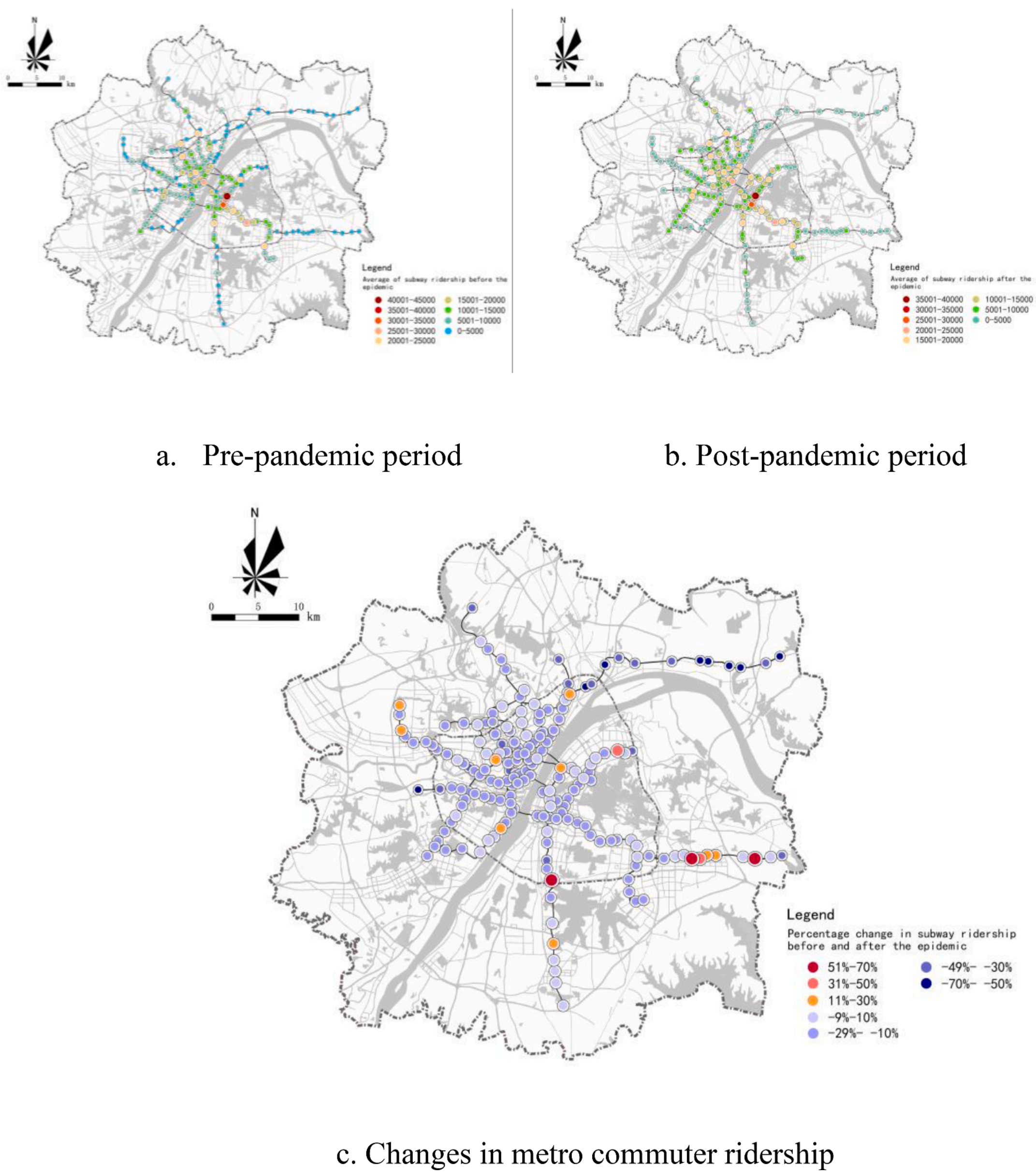

Fig. 3. Changes in metro commuter ridership before and after the COVID-19 outbreak

Table 2
Results of ITS of metro ridership.

Variable	Estimate	Std. Error	P value
ITS key variables			
Intercept (β_0)	6000.000	1095.000	<0.001 ***
Time (β_1)	-59.570	12.850	0.008 **
Outbreak (β_2)	10800.000	243.100	<0.001 ***
Time*Outbreak (β_3)	512.100	17.800	<0.001 ***
Built environment features			
Resident population	217.000	64.620	<0.001 ***
Plot ratio	-88.230	196.600	0.327
The degree of land use mixture	-573.000	400.800	0.077 *
Density of intersection	-1.609	10.740	0.440
Length of road network	-86.690	45.620	0.029 **
Number of bus stops	33.470	15.830	0.018 **
Number of enterprises	1.501	0.753	0.024 **
Number of restaurant	-2.656	1.612	0.051 *
Number of service facilities	-1.705	2.920	0.280
Distance from the city center	15.480	22.650	0.248
Distance from the sub-city center	-17.790	25.170	0.240
Metro station features			
Transfer station	750.300	212.200	<0.001 ***
Terminal	-395.500	216.600	0.035 **
Exit quantity	-49.270	20.420	0.008 **
Demographics			
Average of house prices	1984.000	500.400	<0.001 ***

Note: *$p < 0.1$, ** $p < 0.05$, *** $p < 0.001$.

small changes observed.

5. Discussion

5.1. *Key findings*

The outbreak of the pandemic may have a long-lasting impact on metro commuters. Understanding the impact of the pandemic on metro ridership is important for the operations of metro systems and the need to prevent infections in the post-pandemic era. Hence, this topic has attracted wide attention from managers and researchers (H. H. Chang et al., 2021; Ibraeva, Van Wee, Correia, & Pais Antunes, 2021; Palm et al., 2021). However, the changes in commuter ridership in the post-pandemic era are unclear. In addition, the built environment has been considered an important factor in commuter ridership (Ewing & Cervero, 2001, 2010), but the impact of the built environment on ridership in the post-pandemic era is still unknown. We addressed these research gaps by using longitudinal data and ITS analysis, and we yielded five major findings.

First, the outbreak led to a sharp drop in metro commuter ridership but rebounded quickly in Wuhan. Ridership declined by 76% abruptly when the metro reopened in April 2020. This result echoes the 95% drop in metro ridership in Chicago (Hu & Chen, 2021). After the resumption of subway operations, ridership recovered rapidly, returning to its pre-outbreak normal by October 2020 in six months. This recovery trend was similar to the situation in Seoul after the MERS experience (Sung, 2016).

Second, there were also spatial disparities in terms of the change in ridership. Consistent with other findings, the pandemic caused a higher decline in the urban center of Wuhan than in other areas (H. H. Chang et al., 2021; Hu & Chen, 2021). With the lifting of COVID-19 travel restrictions, metro traffic quickly returned to most of its pre-pandemic levels (Osorio et al., 2022). The ridership of stations near employment centers recovered fastest, and metro stations in the urban core recovered faster than those in other urban areas. In addition, in some areas of the city where strategic emerging industry clusters are developing rapidly, post-pandemic commuter ridership even exceeded the average of the pre-pandemic period.

Third, we found that the built environment characteristics around metro stations and the features of metro stations had a significant effect on ridership. Consistent with the results of the pre-pandemic study, higher population density implies more demand for travel and thus has a significant positive effect on metro ridership (Ding et al., 2019; Ibraeva et al., 2021). The greater the number of bus stops around a station, the more conducive to multimodal transportation using the bus system, and the greater the increase in ridership (An et al., 2019). The more that corporations, as destinations for commuter trips, cluster near metro stations, the more likely individuals will use the metro (An et al., 2019). In addition, transfer stations tend to have better accessibility and tend to promote metro ridership (Kuby et al., 2004; Shao et al., 2020).

Furthermore, some findings about the built environment-ridership associations are inconsistent with previous findings conducted in the pre-pandemic era (Gan et al., 2020). For example, street length showed a significant negative effect on commuter ridership. We speculate that under the influence of the pandemic, commuters in areas with more streets are more likely to shift from metro to private cars. Wuhan's car sales soared to more than 300,000 vehicles after the city lifted precautions in April 2020 and continued to increase after April 2020 (Hong, 2021). Such a shift may further aggravate urban traffic congestion, energy consumption, and air pollution, which may hinder

Table 3
Robustness test results.

Variable	Estimate	Std. Error	P value
ITS key variables			
Intercept (β_0)	8733.56	449.84	<0.001 ***
Time (β_1)	-61.45	12.89	<0.001 ***
Outbreak (β_2)	-10801.75	243.88	<0.001 ***
Time*Outbreak (β_3)	513.36	17.86	<0.001 ***

Note: *$p < 0.1$, ** $p < 0.05$, *** $p < 0.001$.

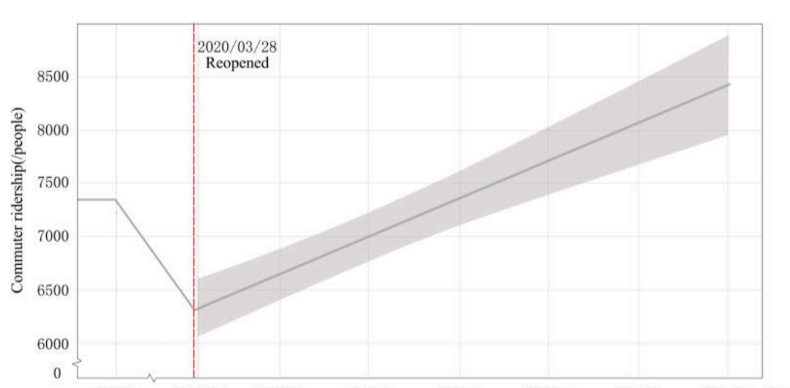

Fig. 4. The effect of lift of lockdown measures on the trend of metro commuting ridership from April 2020 to April 2021. The shaded areas represent the 95% confidence interval.

sustainable urban development (Pan & He, 2022). Furthermore, the degree of land use mix also has a negative effect on metro commuting ridership. This finding is inconsistent with the results of most pre-epidemic studies (Ewing & Cervero, 2010; Su, Zhao, Zhou, Li, & Kang, 2022), which emphasized the importance of mixed land use in TOD development. During epidemics, the risk of transmission is significantly higher in areas with mixed land use. Hence, mixed land use strategy may reduce the appeal of metro commuting trips during epidemics.

Finally, housing prices have a significant positive impact on metro commuting ridership, which is also inconsistent with the results of most studies (van de Coevering et al., 2018). This can be attributed to two reasons. First, housing prices in Wuhan exhibit a pattern of high prices in the central area and low prices in the periphery, which aligns with the spatial distribution of metro commuting ridership in Wuhan. Second, house prices in Wuhan showed an overall upward trend between March 2019 and April 2021, which matches the pattern of metro ridership during the same period.

5.2. Policy implications

By comparing the spatial and temporal distribution characteristics of metro ridership before and after the outbreak of COVID-19, ITS analysis helps explain the relationship between the built environment and ridership under the influence of the pandemic. These findings provide important policy recommendations for the organization of metro operations and the prevention and control of COVID-19 in the post-pandemic era. It also provides important insights into how we may better prepare for future global pandemics.

First, this post-pandemic recovery characteristic of metro ridership provides solid evidence for metro operations. Several studies have shown that the decline in metro traffic during the pandemic caused serious financial problems in metro operations (de Palma et al., 2022; Tirachini & Cats, 2020), and the problem may also arise in the event of future epidemics. To address this issue, we proposed two approaches to reduce metro operating costs based on the ridership pattern observed here. In the early stage of the pandemic, the frequency of metros can be reduced due to the significant decline in metro ridership. After the pandemic subsides, train frequency should be gradually increased. In terms of operating lines, priority will be given to restoring metro lines along employment centers, while delaying restoration of metro lines in suburban areas.

Furthermore, to prevent changes in people's transportation choices from metro to private cars, in the post-pandemic era, government agencies and metro companies should enhance the attractiveness of the metro by providing sanitary, convenient, and efficient metro transportation services (Basu & Ferreira, 2021; Hu & Chen, 2021).

In addition, we found that stations with some characteristics (e.g., high population density and more enterprises and transfer stations) were used more often than others in the post-pandemic era. These stations may become hotspots for virus spread in current and future virus outbreaks (D. Wang et al., 2021). Therefore, we suggest that social distancing and virus prevention measures (e.g., checking temperature, mandating mask wearing, maintaining social distancing) should be further strengthened at metro stations in the abovementioned areas to reduce the spread of virus.

Finally, we should reevaluate the existing urban planning strategies which promote mixed and compact urban development. Although them have been shown to increase metro commuting ridership (Ewing & Cervero, 2010), these strategies themselves may be inadequate contain the spread of epidemics. Since entering the 21st century, human society has already experienced several respiratory infectious diseases such as SARS, avian influenza and Middle East respiratory syndrome. Given that mixed and dense land use stimulates the spread of air-borne viruses, it is critical to incorporate epidemic control strategies, e.g., creating more parks and open spaces, and providing adequate healthcare facilities (Ghorbanzadeh, Kim, Erman Ozguven, & Horner, 2021; Isabella, Claudia, Giulia, Alessandro, & Alessandro, 2022), to create a sustainable and resilient urban environment.

5.3. Limitations

This study has several limitations. First, socioeconomic attributes such as individual income, education level, and household car ownership are also important factors influencing metro commuting ridership (He et al., 2022; Sun, Ermagun, & Dan, 2017). Future studies should also investigate the impact of residents' socioeconomic characteristics on metro commuting behavior in the post-pandemic era. Second, we collected data on metro commuting in the post-pandemic era for only one year, during which time there were no new COVID-19 cases in Wuhan. Future studies may need to investigate potential long-term changes in metro commuting in the post-pandemic era. Finally, this study was conducted in Wuhan, where the most stringent lockdown policies were adopted. The stringent level of lockdown policies may vary significantly across different cities. Evidence from other cities is needed to validate our findings.

6. Conclusion

We used an ITS research design to assess the impact of the COVID-19 outbreak on metro commuting ridership and the effect of the built environment on ridership during and after the outbreak. Our results show that COVID-19 caused an abrupt decline in commuter ridership in the short term but bounced back to normal within six months after the epidemic was effectively controlled. In addition, the built environment characteristics of the station and its surrounding area have a significant effect on commuter ridership. Based on the results of the study, we tentatively suggest adjusting metro spatial and temporal operation according to the changes in metro ridership. We also recommend that metro operators strengthen virus prevention measures at stations in densely populated areas and employment centers to reduce the infection risk and improve the attractiveness of metros. In addition, we propose reassessing the current mix and dense urban development model for transit-oriented development. To enhance urban resilience and cope with future infectious disease outbreaks, we may consider creating a porous urban structure with a network of parks, open space, and tree-lined walkways.

Declaration of Competing Interest

The authors declare that they have no competing interests.

Data availability

The authors do not have permission to share data.

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