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PAPER

Impact of increased subway station density on air quality in the Yangtze River Delta

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Abstract

This study uses empirical methods to explore the relationship between subway system development and air quality in the Yangtze River Delta. We propose a new variable to measure subway development, 'subway station density value,' which can more accurately describe subway development than the traditional 'line opening' variable. It eliminates the effects of differences in subway line length, layout, and size of the local subway system. Using this variable, we find that subway development has a significant positive impact on air quality improvement; that is, an increase in the density of subway stations is significantly associated with improved air quality. This finding provides a scientific basis for the relevant authorities to formulate the development and layout of public transport facilities. It strongly responds to previous debates on the relationship between subways and air quality. In addition, we find that urban population size, economic development level, and subway system size play moderating roles in the relationship between subways and air quality. Increasing the availability of subways can significantly improve the air quality in cities with high population sizes and economic development levels. However, as the size of a subway system increases, its effect on air quality improvement may weaken, suggesting that the development of subway systems should not be unthinkingly expanded either. Although our study has valuable findings, we must discuss several limitations further. These include restrictions in the selection of the study population, data availability, and potentially oversimplified criteria for considering the impact of urban differences. Overall, this study not only provides new theoretical and empirical perspectives for understanding and explaining how subway development affects air quality but also indicates the direction for further exploration in future studies.

1. Introduction

Air pollution poses a significant threat to human health and is becoming more severe in the context of accelerated urbanization (Wei *et al* 2021). In developing countries, such as China, motor vehicle emissions have become a significant source of air pollution, and there is an urgent need to study how to effectively reduce and improve urban air quality. This suggests that a clean transport infrastructure can help to reduce vehicle emissions (Abulude *et al* 2022).

Studies have shown that public transport facilities, especially subways, can significantly improve air quality (Sun *et al* 2019b). Unlike motor vehicles, which emit large amounts of pollutants owing to incomplete fuel combustion, subways consume less energy and emit fewer pollutants (Zhao *et al* 2021). Subways also have high efficiency and do not occupy too much space on urban roads (Joen and Amekudzi 2005). Most importantly, subways can be a quality alternative to motor vehicle travel by expanding the choice of travel modes, optimizing the transport structure, and inducing travelers to change their travel habits, thereby reducing motor vehicle use and contributing to improved air quality (Wang *et al* 2022).

Although subways are widely recognized as an effective means of improving air quality, there is no consensus in the academic field on the impact of subways on air quality. In previous studies, scholars have often used the 'opening of a new subway line' as an explanatory variable, that is, using the date of the 'opening of a new subway line' as the origin and applying breakpoint regression analyses to compare the changes in air quality before and after the date of the line's opening. Some studies have shown that air quality improves after opening a new subway line (Liang and Xi 2016, Guo and Chen 2019, Sun *et al* 2022), while others have revealed that opening a new subway line leads to the deterioration of air quality (Wang *et al* 2020, Jiao *et al* 2022).

By analyzing the relevant studies, we suggest that the inconsistency in the 'new line opening' impact on air quality between studies may be attributed to three key factors: first, differences in the length and location of the new lines may have different effects. Second, heterogeneity in the size of the subway system in which the new lines are located may also affect the results. Finally, variability between sample cities, such as climate, population, and economic level, may similarly contribute to impact variability. Together, these factors contribute to the inconsistency in the impacts of 'new line openings' on air quality.

We believe that 'opening of new lines' as an explanatory variable cannot accurately reflect the impact of the subway on air quality because it cannot distinguish between the length and location of new lines nor can it reflect the size of the subway system in which the strings are located. To more accurately reflect the impact of the subway on air quality, the explanatory variable should be optimized to reflect the length and location of the new lines. Moreover, based on the optimization of the explanatory variable, the manner in which the size of the subway system and the variability of the sample cities play a role in the optimized explanatory variable and the relationship between air quality should be further clarified.

In light of these issues, this study aims to explore the following research questions: first, we need to find or design a new explanatory variable that integrates the length of the new lines, their layout location, and the size of the subway system in which they are located to more accurately measure the impact of the subway on air quality. Second, if such a variable exists, we will test the effect of changes in this new variable on air quality. Thereafter, we will also appraise how the impact of the new variable on air quality is moderated by the size of the subway system in which it is located. Finally, we will compare the variability in the impact of this new variable on air quality across population densities and levels of economic development.

After a literature review, we selected the formula for measuring the density of urban facilities proposed by Ewing and Cervero (2010). We used this formula to calculate the subway station density, that is, the density of the distribution of subway stations at the location of a given air quality monitoring station; this density value is our new explanatory variable. According to this formula, the density of subway stations increases as the number of stations (i.e., the length of the line) increases with the addition of new lines and as the distance of the new line from the air quality monitoring station decreases. Simultaneously, this density value increases with the size of the subway system (i.e., the number of lines).

Having established the use of subway station density as a new explanatory variable for the present study, we explore the relationship between station density and air quality. We selected nine cities in the Yangtze River Delta with subway lines for this study. We collected panel data on the density values of all subway stations and air quality in these cities from 2013 to 2021. After controlling for other factors that might affect air quality, we applied multiple regression analysis to investigate the relationship between subway station density and air quality.

We further examine how the effect of subway station density on air quality is moderated by the size of the subway system and sample differences. First, we take the median of all station densities as the benchmark, classify subway systems below the median as 'small' subway sizes and subway systems above the median as 'large' subway sizes, and then conduct independent multiple regression analyses on the two sets of data to determine whether the relationship between subway station density and air quality varies according to the size of subway systems. The two sets of data were then subjected to independent multiple regression analyses to determine whether the relationship between subway station density and air quality varied according to the size of the subway system. Next, the median population density of the cities was used as a benchmark, and cities below the median were categorized as the low population density group. In contrast, cities above the median were ranked as the high population density group. Multiple regression analyses were then conducted independently on these two data groups to investigate whether population density moderated the relationship between subway station density and air quality. Finally, we used the median per capita gross domestic product (GDP) of the cities as a criterion and categorized cities below the median as the low economic development level group and cities above the median as the high economic development level group. We then independently performed multiple regression analyses on these two groups of data to explore whether the level of economic development moderated the relationship between the density of subway stops and air quality.

This study is both theoretically and practically significant. Through empirical analyses, this study provides a new perspective and methodology for understanding and measuring the impact of subways on air quality, which is made more comprehensive and precise by considering the lengths of new lines, layout locations, and sizes of subway systems. We explored the impact of subway station density on air quality, as well as whether the impact was moderated by the size of the subway system, population density, and level of economic development, among others. This composite perspective helps us understand the subway's impact on the urban environment more comprehensively. Our study results can serve as a reference for urban planners in designing public transport systems that meet travel needs, while effectively improving the urban environment, as well as for environmental authorities in formulating air quality improvement strategies. Moreover, our research methodology is replicable and can be applied to other cities or public facilities (e.g., public transport systems and bicycle paths) to further expand and deepen our understanding of the impact of public facilities on the urban environment.

The remainder of this paper is organized as follows: section 2 presents a literature review, section 3 describes the research methodology, section 4 reports the empirical results and discusses the results, section 5 summarizes the paper.

2. Literature review

2.1. Controversy over the impact of 'new line opening' on air quality

There have been numerous studies on the impact of subways on air quality, mainly focusing on the correlation between 'opening of new lines' and 'air quality.' In previous studies, researchers usually used 'opening of new lines' as an explanatory variable, that is, the day the line went into operation as a benchmark, and used breakpoint regression analysis to analyze the air quality changes before and after that date.

However, related studies do not agree with these conclusions. Several studies have found that air quality improves after the opening of subway lines, and they argue that the presence of subways increases the public's travel choices, which in turn reduces the reliance on motor vehicles as a way to improve air quality; for example, Chen and Whalley (2012) and Zheng *et al* (2019) found that carbon monoxide (CO) emissions were significantly reduced after the opening of subway lines in Taipei and Changsha. In addition, Sun *et al* (2022) found that concentrations of PM2.5 and other pollutants were significantly reduced after the opening of subway lines in cities such as Wuhan and Nanjing.

However, another group of studies has come to a contrary conclusion, finding that opening subway lines may worsen air quality. They argue that although the operation of subways may lead to a reduction in motor vehicle use, thereby improving road traffic, which in turn may stimulate new transport demand and increase the number of motor vehicles, and subsequently increases tailpipe emissions and leads to a deterioration in air quality. For example, neither Zhang *et al* (2015) found no evidence that the subway led to a reduction in the use of small cars by commuters. Wang *et al* (2020) found that opening subway lines instead increased PM2.5 concentrations.

2.2. Factors affecting the relationship between 'line opening' and air quality

Regardless of whichever viewpoint is taken, the literature has shed some light on the mechanisms by which the opening of subway lines affects air quality; however, in combing through the literature, we have also identified several key factors that may influence the relationship between the opening of subway lines and air quality, namely, the length and layout of the new line, the size of the railway system in which the new line is located, and the differences between the cities in which the new line is situated.

Differences in the lengths and layouts of new lines may affect the relationship between the opening of subway lines and air quality. On the one hand, longer subway lines tend to have more stops, and more subway stops mean that the line has a larger catchment area and, therefore, may attract more people to choose the subway instead of private cars, thus effectively improving air quality. This view is supported by Zheng *et al* (2019), who finds that areas with subway lines have better air quality than those without. On the other hand, the location of the subway line is also an influential factor, as Zhang *et al* (2015) confirms that neighborhoods closer to subway stations have lower motor vehicle ownership rates than those farther away from subway stations.

The size of the railway system in which a new line is located may affect the relationship between the opening of a subway line and air quality. In other words, the impact of subway line opening on air quality can be moderated by the size of the subway system. As noted by Feng and Li (2019), in the same city, the effect of opening the seventh subway line on the improvement of air quality was much lower than when the third line was opened. This may be because the subway system has reached a larger scale when the seventh line opens. This scale expansion extends the city's spatial structure, which induces a new travel demand and may lead to a rebound in motor vehicle use, thus weakening the subway's effect on air quality improvement.

The differences between the sample cities in which the new lines are located also influence the relationship between the opening of the lines and air quality. Chen and Whalley (2012) and Zhang and Yang (2022) empirically demonstrated the effects of the first subway line on air quality in Taipei and Chongqing, respectively. Chen and Whalley (2012) found that the first subway line in Taipei significantly reduced airborne CO concentration, while Zhang and Yang (2022) also found that the first subway line in Taipei significantly reduced airborne CO concentration. However, Zhang and Yang (2022) found that the first line opened in Chongqing did not significantly improve CO concentration. There are significant differences in critical factors such as climate, population size, and economic level between Taipei and Chongqing, and these differences may contribute to the heterogeneity of the effect of 'line opening' on air quality. These three factors may jointly or independently affect air quality.

2.3. Proposing an alternative explanatory variable to 'line opening'

The explanatory variable 'new line opening' in the previous literature only represents a benchmark for measuring whether a subway line is open or not; it cannot distinguish between the length and layout of the line, let alone reflect the size of the subway system where the line is located. Hence, it is unconvincing to test the impact of the subway on air quality. Therefore, it may be impossible to accurately interpret the relationship between subways and air quality. The test of differences in the size of the subway system and even the moderating effect of sample differences on the relationship between the subway and air quality may not be accurately interpreted.

To explore the impact of the subway on air quality more accurately, it is necessary to construct an explanatory variable that reflects the length of the subway line, its layout location, and the size of the subway system in which it is located. In the established research literature, some scholars have analyzed the impact of subways on air quality by considering the number of subway stations or the mileage of operations as explanatory variables. However, although these explanatory variables can represent line lengths to a certain extent and can even initially reveal the size of the subway system, they do not fully reflect the layout characteristics of subway lines.

We found that Reid and Robert (2010) proposed a formula for measuring the density of urban facilities in their urban research literature. This formula fully satisfies our need for an explanatory variable, and the 'subway station density value' calculated therewith can effectively reflect not only the length and location of the subway line but also the size of the local subway system, so this new explanatory variable is better than the 'new line opening' in the previous literature. Subway station density can also be considered an indicator of the accessibility of urban public transport. A high density of subway stations means that the public can more easily access and use the subway, which may reduce reliance on private cars. This is essential for our goal of exploring the impact of public transport on air quality.

Before applying this formula, we select urban air quality monitoring stations as starting points and record their geographical locations. Whenever a new subway line opens in a city, we obtain the locations of all the stations from the official website and calculate their distances from the monitoring station. We then substituted these data into the formula to derive a value that reflects the density of subway stations at the location of the monitoring station. This value is affected by the number of new stations added and the distance from each station to the monitoring station; therefore, it accurately reflects the length and layout of the line. We retained the old line station data, and the total station data from the opening of the new lines were used to calculate the new subway station densities, thus reflecting the overall size of the subway system. However, herein, we only consider the increase in the number of lines and stations and not other factors, such as the distance between stations and frequency of operation.

2.4. Selection of air quality indicators

After selecting 'subway station density' as the explanatory variable, we next select 'air quality' as the explanatory variable. The air quality index (AQI) is often used as an explanatory variable to measure the impact of subways on air quality in related studies (Xiao 2019, Sun *et al* 2019a, Zhang and Yang 2022) to investigate whether opening subway lines can help improve air quality. Meanwhile, pollutants emitted by motor vehicles, such as PM2.5, PM10, and CO, are often used as explanatory variables (Chen and Whalley 2012, Xiao *et al* 2020). If these pollutants decreased after the subway's opening, then it could be inferred that the opening of the subway line reduced the public's reliance on motor vehicles. In addition, the relationship between nitrogen dioxide (NO_2) and sulfur dioxide (SO_2), which are the primary sources of acid rain and PM2.5, and the subway is controversial. For example, Sun *et al* (2019a) study showed that NO_2 was significantly reduced after the opening of the subway. However, Zhang and Yang (2022) found that opening subway lines did not substantially affect NO_2 and SO_2 emissions. Overall, AQI, PM2.5, PM10, CO, NO_2, and SO_2 are related to motor vehicle emissions (Filonchyk and Yan 2018). Therefore, it is essential to explore the effects of changes in 'subway station density' on AQI, PM2.5, PM10, CO, NO_2, and SO_2.

2.5. Exploring the moderating roles of subway scale and sample differences

After evaluating the impact of 'new line openings' on air quality, some past studies have further explored the role of subway system size and sample city differences (e.g., differences in city population and level of economic development) on this impact but have not reached a consistent conclusion. Liang and Xi (2016) found that the larger the size of the subway system, the more significant the contribution of the subway line opening to air quality improvement, while Feng and Li (2019) argued that the smaller the size of the subway system, the more significant the contribution of the subway line opening to air quality improvement. Practically, Feng and Li (2019) asserts that smaller subway systems significantly affect air quality improvement. In terms of the population size of the sample city, Liang and Xi (2016) reports that subway lines have a better effect on air quality improvement when the population size of the sample city is more significant. However, Wang *et al* (2020) findings show the opposite trend. Regarding economic level, Gao *et al* (2018) states that the higher a city's financial status, the stronger the impact of subway lines on air quality improvement, while Jiao *et al* (2022) findings challenge this view. However, Gendron-Carrier *et al* (2022) argues that the size of the subway system, population size of the city, and economic level do not significantly affect the relationship between the opening of subway lines and air quality.

Therefore, after identifying the explanatory variable, that is, subway station density, and the explanatory variables, namely, AQI, PM2.5, PM10, CO, NO_2, and SO_2, in our study, we will further explore the possible moderating effects of subway system size and sample differences (e.g., differences in urban population and economic development level) on the relationship between subway station density and air quality.

In the previous literature, the effect of the subway on air quality has been controversial, mainly due to the limitations of the variable itself, the difference in the size of the subway system, the difference in the sample cities where the subway is located, and so on. In our study, by introducing the new explanatory variable—density of subway stations—we aim to reveal the effect of the subway on air quality in a more accurate way. By introducing the new explanatory variable 'subway station density,' our study aims to reveal the effect of subways on air quality more accurately, and we will further explore the moderating effect of subway system size and city differences on this relationship. The importance of this study lies in the fact that it provides a unique theoretical and empirical perspective on the global issues of public transport optimization and urban environmental improvement, and the results provide evidence for new thinking in urban planning and policymaking.

3. Methodology

3.1. Study area and study period

Nine cities located in the Yangtze River Delta in eastern China (Shanghai, Nanjing, Suzhou, Wuxi, Changzhou, and Xuzhou in Jiangsu Province; and Hangzhou, Ningbo, and Wenzhou in Zhejiang Province) were selected as the study area. The study period spans from 2013 to 2021. Starting from 2013, with the continuous expansion of the built-up areas of the cities (Zhang *et al* 2022), the subway development in these cities has become increasingly rapid, with a total of 53 lines added over 8 years, accounting for 84% of the total number of lines in the nine cities (www.rail-transit.com/). The air quality in the abovementioned cities has gradually improved after 2013. There is a trend of gradual improvement in air quality; however, improving air quality remains an urgent issue for these cities (Wang *et al* 2022). Therefore, the rapid subway development and air quality improvement trends in these cities provide an ideal environment for an in-depth exploration of the potential relationship between the increase in the density of subway stops and air quality improvement. With an increase in the number of subway lines, the size of the subway systems in these nine cities has expanded, providing an empirical basis for investigating how the size of subway systems moderates the relationship between subway station density and air quality. Meanwhile, these nine cities still have significant differences in population size and degree of economic development, which provide the necessary empirical background for us to study how inter-city differences play a role in the effect of station density on air quality. The results of this study will provide a vital reference for subway construction as well as urban planning and environmental policymaking in other parts of China and even in other developing countries worldwide.

3.2. Measurement models and variables

This study measures the correlation between subway station density and air quality using the following econometric model:

$$\mathrm{Ln}\,Air_{it} = \partial_1 + \partial_2 Density_{it} + \partial_3 X_{it} + \mu_t + \mu_i + \varepsilon_{it} \tag{1}$$

where i denotes air quality monitoring stations in the nine cities; t denotes the date; and Air_{it} are the explanatory variables, including the daily AQI, PM2.5 (μg m^{-3}), PM10 (μg m^{-3}), NO_2 (μg m^{-3}), CO (mg m^{-3}), and SO_2 (μg m^{-3}), as detected by the monitoring stations.

[3] $Density_{it}$ is the core explanatory variable that indicates the daily density of subway stops. The specific formula is presented as follows:

$$Density_{it} = \sum_{j \in N_t} \frac{1}{Distance_{ij}^2}.$$

This calculation method is equivalent to measuring the density of subway stations operating in an area centered on a specific monitoring station, and the larger the calculated value, the greater the number of subway stations at the site or the closer they are to the monitoring station. In this formula, i represents an air quality monitoring station, j represents a subway station point, *Distance* represents the distance between air quality monitoring station i and subway station point j, t represents the date, and N_t represents the set of subway stations that are in operation on date t. The density of subway stations at the location of air quality monitoring station i within the city on a particular date t is defined as the sum of the reciprocal of the square of the distances of all subway stations operating on date t concerning air quality monitoring station i.

According to the calculation rules of the formula, the magnitude of change in subway station density reflects the length and layout location of the newly opened line. The increase in subway station density is more significant when a new line opens in a city, and the more stations there are on the line, the shorter the total distance of all stations from an air quality testing station (i.e., the station is closer to the testing station).

According to the calculation rules of the above-given equations, as the number of subway lines increases, the density of subway stations also increases, implying that the density of subway stations reflects the size of the subway system. Specifically, suppose that at date $t1$, there is an air quality monitoring station and several subway stations in a city. At this point, the subway station density is represented by the sum of the inverse of the squares of the distances from each subway station to that monitoring station. Then, at date $t2$ ($t2 > t1$), if the number of subway sites increases, the sum of the inverse of the square of the distance from each newly added site to the monitoring station and subway site density at date $t1$ constitutes the subway site density at date $t2$. The more lines are opened in a city, the larger its subway system (Feng and Li 2019).

In this study, we adhered to the following process to obtain subway station density values for the air quality monitoring stations in the study area. First, we obtained latitude and longitude information as of 1 January 2013, for all urban subway and air quality monitoring stations. We then calculated the distance between each air quality monitoring station and each subway station, and based on these distances, we applied the subway station density formula in Excel to obtain the subway station density of all monitoring stations in each city before the start of the study period. We then updated these density values based on the new subway lines that opened in each city between 2 January 2013 and 31 December 2021. Specifically, the density values of the new subway lines opened on a given day were added to the city's total subway station density values such that the total subway station density values gradually increased as more subway lines were added.

X_it represents the meteorological conditions of the control variables, including total daily precipitation (0.1 mm), average daily relative humidity (1%), average daily temperature (0.1 °C), and average daily wind speed (0.1 m s^{-1}). Meteorological conditions are chosen as control variables because they significantly affect air pollution (Zhao *et al* 2013). Precipitation can remove air pollution via deposition (Akinwumiju *et al* 2021). Changes in humidity can affect the chemical reactions and transformations of pollutants, and high temperatures can accelerate the dispersion of pollutants and reduce their ground-level concentrations. Wind speed also affects pollutant dispersion (Filonchyk and Yan 2018). μ_t and μ_i are time and monitoring station (individual) fixed effects, respectively. ε_it is a random error term.

3.3. Data sources

We obtained air quality data, including AQI, PM2.5 (μg m^{-3}), PM10 (μg m^{-3}), NO_2 (μg m^{-3}), CO (mg m^{-3}), and SO_2 (μg m^{-3}) from the official website of the Ministry of Environmental Protection of China. We ensured that the data covered all the air quality monitoring stations in the nine cities within the study area.

The opening date of the subway line is used to calculate the density of the subway station, and the latitude and longitude of the subway station site are obtained from the official website of each city's subway system (shown in table 1). The distance between the subway station and the air quality testing station was obtained using geographic information system software calculations.

Table 1. Sources of subway-related data.

No.	Municipalities	The official name of the subway system	Data sources used in this study (website names)	Link (on a website)
1	Shanghai	Shanghai Subway	Shanghai Subway Official Website	http://service.shsubway.com/yxxlt/index.htm
2	Nanjing	Nanjing Subway	Nanjing Subway Official Website	www.njsubway.com.cn/
3	Suzhou	Suzhou Rail Transit	Rail network	www.rail-transit.com/
4	Wuxi	Wuxi Subway	Wuxi Subway Official Website	www.wxsubway.net/
5	Changzhou	Changzhou Subway	Changzhou Subway Official Website	www.changzhou.gov.cn/
6	Xuzhou	Xuzhou Subway	Xuzhou Subway Official Website	www.xzdtjt.com/
7	Hangzhou	Hangzhou Subway	Hangzhou Subway Official Website	www.hzsubway.com/
8	Ningbo	Ningbo Rail Transit	Rail network	www.rail-transit.com/
9	Wenzhou	Wenzhou Rail Transit	Rail network	www.rail-transit.com/

Note: According to government documents, the subway networks in Suzhou, Ningbo, and Wenzhou also include other rail transport modes (including light rail, tram, and maglev), using the name 'rail transport system.' In terms of cumulative mileage, the subway has the highest share (above 95% in all three cities).

In addition, the daily meteorological data collected for this study were obtained from Weather Subway.com. Data on the population density and GDP per capita of the cities were obtained from the China Urban Statistical Yearbook.

3.4. Analysis process

First, we correlate the density of subway stations with the AQI, PM2.5 (μg m^{-3}), PM10 (μg m^{-3}), NO_2 (μg m^{-3}), CO (mg m^{-3}), and SO_2 (μg m^{-3}), which are air quality indicators, at all air quality monitoring stations in the nine cities from 2013 to 2021.

Then, using the median density of all subway stations, 2.618, as the benchmark, we classified subway systems below the median as the 'small' subway size group and those above the median as the 'large' subway size group, and then conducted independent correlation analyses between these two groups of data and air quality. Separate correlation analyses between subway station density and air quality were then performed on these two groups of data to determine whether the relationship between subway station density and air quality varied according to the size of the subway system.

Next, we took the median population density of 1000 people km^{-2} obtained from the 2013–2021 censuses of nine cities as the benchmark and categorized cities below the median as the low population size group and cities above the median as the high population size group. We then independently carried out correlation analyses between the density of subway stations and air quality on these two groups of data to investigate whether population size moderates subway stations and the relationship between station density and air quality.

Finally, we take the median average per capita GDP of cities from 2013 to 2021, RMB 140 000, and categorize cities below the median as the low economic development level group and cities above the median as the high economic development level group. Then, we independently conduct correlation analyses between subway station density and air quality for these two groups of data to explore whether the level of economic development moderates the correlation between the density of subway stops and air quality.

3.5. Research hypothesis

Against this backdrop, we formulate four hypotheses. The first hypothesis is that, in general, as the density of Mass Transit Railway (MTR) stations increases, the AQI and concentrations of all air pollutants decrease.

Our second hypothesis is as follows: when the size of the subway system is relatively small, an increase in station density will significantly affect air quality improvement more considerably than when the subway system is more extensive.

Our third hypothesis is that as the population density of a city increases, the effect of the increase in the density of subway stations on improving air quality will be more significant.

The fourth hypothesis is that the higher the GDP per capita, the more significant the effect of increasing the density of subway stations on air quality improvement.

Table 2. Descriptive statistics.

Variable	Obs.	Mean	Std. Dev.	Min	Max
Density	233 377	6.438	17.009	0	139.799
AQI	233 377	71.408	40.077	0	500
PM2.5	233 377	46.141	33.789	0	652
PM10	233 377	75.632	49.508	0	819
SO_2	233 377	15.022	13.96	1	925
NO_2	233 377	41.804	20.647	1	214
CO	233 377	0.857	0.409	0	8.558
PRE	233 377	38.766	117.028	0	3872
HUM	233 377	73.519	14.114	21	100
TEMP	233 377	175.528	88.969	−94	361
WNSP	233 377	21.829	9.442	0	85

Table 3. Effect of subway station density increases on AQI.

Variables	lnAQI	lnAQI	lnAQI	lnAQI
Density	-0.0002^{***}	0.0003^{***}	-0.032^{***}	-0.033^{***}
	(−3.005)	(5.236)	(−96.331)	(−103.174)
PRE		−0.000	−0.000	−0.000
		(−0.308)	(−0.202)	(−1.441)
HUM		-0.010^{***}	-0.009^{***}	-0.007^{***}
		(−140.687)	(−132.484)	(−115.770)
TEMP		-0.002^{***}	-0.002^{***}	0.001^{***}
		(−164.031)	(−165.810)	(56.389)
WNSP		-0.012^{***}	-0.013^{***}	-0.012^{***}
		(−115.799)	(−127.737)	(−126.480)
Constant	4.139^{***}	5.401^{***}	5.129^{***}	4.955^{***}
	(3601.374)	(932.089)	(497.665)	(480.885)
Watch station FE	N	N	Y	Y
Time FE	N	N	N	Y
Observations	221 040	220 304	220 304	220 304
R-squared	0.000	0.226	0.317	0.384
Adjusted R^2	0.383	0.383	0.383	0.383

t-statistics in parentheses, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

4. Results and discussion

4.1. Descriptive statistics

Table 2 reports the descriptive statistics of the data, with columns 1–6 reporting the variable's name, number of variables, mean, standard deviation, as well as minimum and maximum values, respectively.

4.2. Baseline regression analysis

In our study, we used subway station density as the primary explanatory variable and further analyzed its association with AQI, PM2.5 (μg m^{-3}), PM10 (μg m^{-3}), NO_2 (μg m^{-3}), CO (mg m^{-1}), and SO_2 (μg m^{-3}) air quality indicators. Please refer to tables 3 and 4 for the results.

Table 3 reveals that after controlling for meteorological conditions and introducing fixed effects, the AQI will significantly decrease by 3.3% at the 1% significance level for every standard deviation increase in subway station density. This result suggests that a significant improvement in air quality is expected when the number of subway stations increases, when stations are closer to air quality monitoring stations, or when the size of the subway system continues to expand, that is, when the distribution of subway stations is denser. This phenomenon may stem from the fact that the thicker the distribution of subway stations, the greater the supply capacity of the subway system and the greater the incentive for commuters to use the subway instead of private cars, thus reducing air pollution and optimizing air quality.

Table 4 demonstrates that for every 1 standard deviation increase in subway station density, the concentrations of PM2.5, PM10, SO_2, NO_2, and CO will decrease by 4.8%, 4%, 7.8%, and 2.5%, respectively, at the 1% significance level, after also controlling for meteorological conditions and introducing fixed effects. This result further indicates that increasing the density of subway stations can significantly reduce the concentrations of these pollutants. As these pollutants mainly originate from motor vehicle tailpipe

Table 4. Effects of subway station density increases on PM2.5, PM10, SO_2, NO_2, and CO.

	(1)	(2)	(3)	(4)	(5)
Variables	lnPM2.5	lnPM10	$\ln SO_2$	$\ln NO_2$	lnCO
Density	-0.048^{***}	-0.040^{***}	-0.078^{***}	-0.020^{***}	-0.025^{***}
	(−109.294)	(−105.419)	(−157.275)	(−63.016)	(−76.880)
PRE	−0.000	−0.000	-0.000^{**}	0.000	−0.000
	(−0.803)	(−1.033)	(−2.484)	(0.005)	(−0.220)
HUM	-0.004^{***}	-0.012^{***}	-0.014^{***}	-0.002^{***}	0.002^{***}
	(−47.900)	(−154.975)	(−138.132)	(−31.855)	(32.581)
TEMP	0.002^{***}	0.002^{***}	-0.001^{***}	0.000^{***}	0.000^{***}
	(44.294)	(60.640)	(−17.590)	(2.661)	(11.864)
WNSP	-0.019^{***}	-0.014^{***}	-0.008^{***}	-0.020^{***}	-0.009^{***}
	(−140.488)	(−125.378)	(−55.837)	(−216.058)	(−96.536)
Constant	4.451^{***}	5.280^{***}	3.912^{***}	0.041^{***}	−0.016

t-statistics in parentheses, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

emissions, we infer that the denser the distribution of subway stations, the more likely it is to reduce commuters' reliance on private cars, reduce motor vehicle use tailpipe emissions, and optimize air quality.

Our results provide a more precise measure of the impacts analyzed by the increased density of subway stations rather than simply the opening or non-opening of subway lines, and they refute past conclusions that subway development worsens air quality. For example, Wang *et al* (2020) showed that the air quality deteriorated significantly after the opening of subway lines in several Chinese cities. However, our study shows that an increased subway station density substantially improves air quality.

Our findings also address the historical academic controversy over whether subway openings reduce pollutants. For example, Zheng *et al* (2019) found that CO concentrations decreased but PM2.5 did not change significantly after the opening of the subway line. Chen and Whalley (2012) noted that CO concentrations decreased, but NO_2 concentrations did not significantly reduce after the opening of the subway line. Zhang and Yang (2022) found that after the opening of the subway line, the concentrations of PM2.5 and PM10 decreased significantly, but those of NO_2, SO_2, and CO did not change significantly. However, according to our results, the concentrations of PM2.5, PM10, SO_2, NO_2, and CO decreased substantially with increasing subway station density.

4.3. Analysis of heterogeneity in the scale of the subway system

Having conclusively demonstrated the impact of increased subway station density on air quality improvement, we proceeded a step further. We explored the moderating effect of heterogeneity in subway system size on the relationship between increased subway station density and air quality. Table 5 reports the correlations between improved subway station density and AQI, PM2.5, PM10, SO_2, NO_2, and CO at both small and large subway system sizes in descending order, where an increase of 1 standard deviation in subway station density at the small subway system size reduces AQI, PM2.5, PM10, SO_2, NO_2, and CO at the 1% significance level by 28.3%, 42.8%, 32.1%, 72.3%, 18.4%, and 29.3%, respectively. At the large subway system scale, an increase in subway station density by 1 standard deviation decreases AQI, PM2.5, PM10, SO_2, NO_2, and CO by 7.4%, 11.5%, 9.6%, 17.4%, 5.1%, and 4.5%, respectively, at the 1% significance level.

The results in table 5 show that for both small and large subway systems, each standard deviation increase in subway station density significantly reduces the concentrations of all the AQIs, thus further corroborating the findings in tables 3 and 4 that subway station density has a significant effect on air quality improvement.

Comparing the reductions in each of the AQIs in rows 3 and 4 of table 5, we observe that the improvement in air quality per standard deviation increase in subway station density is more pronounced in smaller subway systems. This result implies that the subway system size has a moderating effect on the relationship between subway station density and air quality. The larger the subway system size, the weaker the improvement in air quality per standard deviation increase in subway station density.

The mechanism of this phenomenon may be that the subway system mainly serves to divert road traffic in the initial development stage, when the increased density of subway stations can effectively guide commuters to reduce the use of motor vehicles, thus effectively improving air quality. However, with further expansion of the subway system, the increase in urban development space may generate new travel demand, leading to a rebound in road traffic and an increase in motor vehicle emissions, thus weakening the air quality improvement effect of the increased subway station density.

The results in table 5 also provide new perspectives on previous studies on the effect of subway system size on the relationship between subways and air quality. Liang and Xi (2016) found that the larger the

Table 5. Effects of increases in subway station density on air quality at different rail transit scales.

	(1)	(2)	(3)	(4)	(5)	(6)
Variables	lnAQI	lnPM2.5	lnPM10	$\ln SO_2$	$\ln NO_2$	lnCO
Density (low density of rail stations)	-0.283^{***} (−89.224)	-0.428^{***} (−99.966)	-0.321^{***} (−85.244)	-0.723^{***} (−152.413)	-0.184^{***} (−55.999)	-0.293^{***} (−93.353)
Density (high density of rail stations)	-0.074^{***} (−100.383)	-0.115^{***} (−109.750)	-0.096^{***} (−108.006)	-0.174^{***} (−161.075)	-0.051^{***} (−72.046)	-0.045^{***} (−58.997)

t-statistics in parentheses, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 6. Effects of increases in subway station density on air quality in cities with different population densities.

	(1)	(2)	(3)	(4)	(5)	(6)
Variables	lnAQI	lnPM2.5	lnPM10	$\ln SO_2$	$\ln NO_2$	lnCO
Density (∼1000 people km^{-2})	-0.025^{***} (−57.143)	-0.035^{***} (−59.530)	-0.030^{***} (−57.069)	-0.057^{***} (−86.011)	-0.017^{***} (−37.754)	-0.020^{***} (−49.775)
Density (1000∼ people km^{-2})	-0.032^{***} (−73.359)	-0.046^{***} (−79.141)	-0.038^{***} (−75.681)	-0.077^{***} (−112.722)	-0.019^{***} (−46.263)	-0.021^{***} (−49.248)

t-statistics in parentheses, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

subway system size, the better the effect of subway line opening on air quality improvement; however, Feng and Li (2019) asserted that the larger the subway system size, the worse the impact of the subway system on air quality improvement. However, our study, using subway station density as an explanatory variable, found that the effect of increasing subway station density on air quality improvement was relatively weaker as the size of the subway system increased.

4.4. Analysis of heterogeneity in urban population size

Table 6 shows the correlation between subway station density and AQI, PM2.5, PM10, SO_2, NO_2, and CO for scenarios in which the city's population density is below the median of 1000 people km^{-2} and above the median, from top to bottom. A 1-standard-deviation increase in subway station density in cities with low population sizes reduces AQI, PM2.5, PM10, SO_2, NO_2, and CO by 2.5%, 3.5%, 3.0%, 5.7%, 1.7%, and 2.0%, respectively, at the 1% significance level. A 1-standard-deviation increase in subway station density in cities with high population sizes reduces AQI, PM2.5, PM10, SO_2, NO_2, and CO; at the 1% significance level, PM2.5, PM10, SO_2, NO_2, and CO decrease by 3.2%, 4.6%, 3.8%,7.7%, 1.9%, and 2.1%, respectively. These results are consistent with our baseline regression analyses (see tables 3 and 4), that is, each standard deviation increase in subway station density significantly reduces the concentrations of all AQIs, regardless of whether the population size is large or small.

From the results in table 6, it can be observed that there is a significant difference between the population density of the city and the effect of subway station density on air quality. For every standard deviation increase in subway station density in more densely populated cities, AQI, PM2.5, PM10, SO_2, NO_2, and CO decrease more than those in less densely populated cities. This seemingly implies that subway station density has an increasingly significant effect on improving air quality as population density increases.

A possible explanation is that densely populated cities have a greater demand for transport and, therefore, a higher likelihood of an imbalance between transport supply and demand. Traffic congestion may be triggered when the need for transportation exceeds the supply, for example, when the capacity of public transport cannot meet the demand of all passengers or when the design capacity of roads cannot accommodate too many vehicles. Some studies have proven that traffic congestion increases motor vehicle exhaust emissions, which can exacerbate air pollution (Wang *et al* 2022). In densely populated cities, an increase in the density of subway stations implies an expansion of the coverage of public transport facilities and an increase in the supply of traffic, which is conducive to the diversion of road traffic, thus reducing motor vehicle emissions and contributing to the improvement of air quality.

The results in table 6 provide new perspectives on past studies on the effect of urban population size on the relationship between subways and air quality. Wang *et al* (2020) argues that the impact of subways on air quality shifts from improving air quality to significantly worsening air quality as the population increases. Feng and Li (2019) asserts that, regardless of changes in the people, the opening of subway lines consistently improves air quality and increases with population size. Our results are closer to Feng and Li (2019)

Table 7. Effect of subway station density increasing on air quality in cities with different per capita GDPs.

	(1)	(2)	(3)	(4)	(5)	(6)
Variables	lnAQI	lnPM2.5	lnPM10	$lnSO_2$	$lnNO_2$	lnCO
Density (low GDP per capita)	-0.019^{***} (−41.245)	-0.026^{***} (−42.839)	-0.023^{***} (−42.458)	-0.044^{***} (−64.205)	-0.013^{***} (−29.161)	-0.017^{***} (−38.521)
Density (high GDP per capita)	-0.046^{***} (−105.193)	-0.069^{***} (−112.580)	-0.056^{***} (−108.153)	-0.111^{***} (−158.992)	-0.026^{***} (−60.331)	-0.032^{***} (−70.205)

t-statistics in parentheses, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

argument that in cities with higher population densities, each standard deviation increase in the density of subway stations significantly improves air quality.

4.5. Analysis of heterogeneity in the level of urban economic development

Table 7 shows, in ascending order, the correlation between subway station density and AQI, PM2.5, PM10, SO_2, NO_2, and CO in urban environments with GDP per capita below the median (RMB 140 000) and above the median. A 1-standard-deviation increase in subway station density in cities with low economic levels was associated with a 1.9%, 2.6%, 2.3%, 4.4%, 1.3%, and 1.7% decrease in AQI, PM2.5, PM10, SO_2, NO_2, and CO, respectively, at the 1% level of significance. A 1-standard-deviation increase in subway station density in cities with high economic levels was associated with a 1.7% reduction in AQI, PM2.5, PM10, SO_2, NO_2, and CO, at the 1% level of significance, while AQI, PM2.5, PM10, SO_2, NO_2, and CO decrease by 4.6%, 6.9%, 5.6%, 11.1%, 2.6%, and 3.2%, respectively. This result is consistent with our baseline regression analyses (see tables 3 and 4), which indicate that each standard deviation increase in subway station density significantly reduces the concentrations of all air quality indicators, regardless of the city's economic development level.

Based on the data in table 7, we can find that a city's level of economic development significantly impacts the relationship between subway station density and air quality. In cities with a higher level of economic development, for every standard deviation increase in subway station density, the AQI, PM2.5, PM10, SO_2, NO_2, and CO are more reduced than in cities with a lower level of economic development. This indicates that the improvement effect of subway station density on air quality becomes more significant as the economic level increases.

The results in table 7 can be attributed to an underlying reason, that is, in cities with a high level of economic development, commercial activities are more active, and the transport demand is relatively higher. In this case, a higher density of subway station layout would provide more transport supply to meet the diversified travel needs, thereby reducing the pressure on road traffic, lowering motor vehicle emissions, and improving air quality.

Furthermore, the results presented in table 7 provide new perspectives on previous studies on the effect of a city's economic level on the relationship between subways and air quality. For example, on the one hand, Jiao *et al* (2022) shows that when a city's GDP per capita is less than RMB 140 000, the opening of new lines will significantly improve air quality. However, when a city's GDP per capita exceeds RMB 140 000, opening new lines may significantly deteriorate air quality. On the other hand, Gendron-Carrier *et al* (2022) concluded that a city's level of economic development did not influence the relationship between the opening of subway lines and air quality. Our study complements and extends the above by finding that the improvement in air quality is more significant for each standard deviation increase in subway station density in cities with a GDP per capita bounded by RMB 140 000 and above. Therefore, we conclude that the higher the level of economic development, the more significant the improvement effect on air quality for each standard deviation increase in the density of subway station layout.

After analyzing the results, we concluded that in our study area, the concentration levels of AQI, PM2.5, PM10, SO_2, NO_2, and CO improved significantly for each standard deviation increase in the density of subway stations between 2013 and 2021. This result reveals a positive correlation between the number of subway stations and air quality, that is, the higher the number and denser the distribution of subway stations, the more pronounced the improvement in air quality. Considering that PM2.5, PM10, SO_2, NO_2, and CO are often regarded as indicators of motor vehicle emissions, it is inferred that the increase in the density of subway stations may have guided commuters to reduce their reliance on motor vehicles in favor of public transport, such as the subway, thus contributing to a reduction in air pollution.

Furthermore, we explored the effects of the size of the subway system, the size of the city's population, and the level of economic development on the relationship between subway station density and air quality. Despite the differences in these three factors, an increase in subway station density positively affected air quality. However, we found that the larger the size of the subway system, the relatively weaker the effect of increased subway station density on air quality improvement, whereas the larger the size of the urban population or level of urban economic development, the more significant the effect of increased subway station density on air quality improvement. We speculate that this may be because an increase in the size of the subway system expands the development space of the city to a certain extent, thus stimulating new transport demand, which in turn may lead to an increase in the use of motor vehicles and a relatively weaker effect on the improvement of air quality. On the contrary, cities with large populations or high levels of economic development have higher transport demand. An increase in the density of subway stations is equivalent to a rise in transport supply, which diverts motor vehicle traffic and significantly affects air quality improvement.

5. Conclusions

Against the backdrop of accelerated urbanization and the growing problem of air pollution caused by motor vehicle emissions, exploring alternative modes of travel to reduce motor vehicle emissions has become a key issue in improving urban environmental quality. As a high-capacity and high-efficiency public transport mode, the influence of the subway has attracted considerable attention, especially in connection to its impact on urban air quality. Although previous studies have debated the effect of subways on air quality, this is mainly due to ignoring factors such as differences in the length and layout of lines before and after their opening, differences in the size of the subway system, and differences in the cities in which they are located. Therefore, we propose the adoption of a new variable that reflects the length and layout of the lines and the size of the subway system to assess the impact of the subway on air quality more accurately.

In this study, we use the formula for measuring the density of urban facilities proposed by Reid and Robert (2010) to calculate subway station density values as a reflection of the density of subway stations in the area in which they are located relative to an air quality monitoring station. This approach allows for a more efficient normalization of line lengths and layout locations, as well as the size of the subway system in which they are located, thus revealing more precisely the impact of the level of subway development on air quality. This new metric provides a quality option and new research perspective for future subway-environment-related studies.

We selected nine cities in the Yangtze River Delta as the study area from 2013 to 2021 to empirically analyze the correlation between subway station density and air quality. For each standard deviation increase in subway station density, the concentrations of the AQI and pollutants related to motor vehicle emissions, namely, PM2.5, PM10, SO_2, NO_2, and CO, were significantly reduced. Subway station density may affect air quality for several possible reasons. First, the subway, as an efficient and high-capacity mode of public transport, is more likely to attract more people to choose the subway as a mode of travel when its network is denser, thus reducing reliance on private cars, which in turn reduces motor vehicle emissions and improves air quality.

Through our analysis, we also find that differences in the size of subway systems, the size of urban populations, and the level of urban economy do not diminish the positive impact of subway station density on air quality during the development of urbanization but do modulate the extent of this positive impact. At the primary stage, when the subway system is mainly responsible for diverting road traffic, increasing subway station density can effectively orient commuters to reduce their reliance on motorized vehicles, thus significantly improving air quality. However, with the gradual expansion of subway systems and the growth of urban development spaces, new travel demands may be generated, causing a rebound in road traffic volume and increasing motor vehicle emissions, thus weakening the positive effect of subway station density on air quality. In densely populated cities, the demand for transport is higher; hence, the risk of an imbalance between transport supply and demand is correspondingly higher. Traffic congestion may occur when demand outstrips supply, for example, when the capacity of public transport cannot meet the demand of all commuters or when the design capacity of a road cannot accommodate too many vehicles. Increased air pollution is a direct consequence of traffic congestion. Therefore, in densely populated cities, increasing the density of subway stations implies an expansion in the coverage of public transport facilities and an increase in the capacity of transport supply, thus effectively diverting road traffic and reducing traffic congestion, which are ultimately conducive to improving air quality. For cities with high levels of economic development, traffic demand tends to relatively increase because of commercial activities. Under such circumstances, increasing the density of MTR stations can provide a broader range of transport supply to meet diversified travel needs, thereby reducing the pressure on road traffic and lowering motor vehicle emissions, which will help further improve air quality.

Our findings provide a robust empirical basis for debating whether subways improve air quality. By using the term 'station density' instead of the traditional 'line opening,' we can precisely examine the impact of not only the opening of subway lines but also the increase in the coverage of subway services on air quality. This more refined perspective helps us better understand the mechanism of the subway's impact on air quality. In addition, we find that differences in the size of the subway system, size of the city population, and level of the economy have a stable impact on the relationship between subway station density and air quality. The aforementioned summarizes the findings of this study, which we hope will provide a reference for future urban planning and transport policymaking.

This study makes the following significant contributions: first, we introduce a new variable, 'subway station density value,' to more accurately describe and measure the development status of the subway. This measure can more accurately reflect the actual state of the subway system than the 'line opening' variable commonly used in previous studies, and its broad applicability can effectively eliminate the influence of the length of the subway lines as well as the layout and size of the subway system. This new measure provides a high-quality option and new research perspective for future subway-environmental studies.

Second, by analyzing the correlation between 'subway station density' and air quality, we conclude that subway development can effectively improve air quality. This result provides a solid response to the academic controversy regarding the relationship between subways and air quality. It provides a scientific basis and reference for policymakers planning the development and layout of subways and other public transport facilities.

Finally, we clarify the moderating roles of subway system size, city population size, and economic development level in the relationship between subways and air quality. The analysis results reveal that increasing the supply of subways in cities with large population sizes and high levels of economic development can effectively alleviate the air pollution problem. However, the subway system should not be expanded mindlessly because as the size of the subway system increases, its effect on air quality improvement may weaken. Thus, it needs to be coupled with other traffic management measures, such as setting up congestion charges and restricting private cars, to improve air quality.

Although our study has some valuable findings, several limitations must be discussed. First, there are limitations vis-à-vis the selection of the study population. The fact that this study is conducted in only nine cities in the Yangtze River Delta means that the findings may be influenced, to some extent, by that particular geographic region and may not be broadly applicable to other areas. Future studies should expand the sample to include more cities with more geographic and socioeconomic conditions to increase the comprehensiveness and applicability of the findings.

Second, data availability is also a fundamental limitation. As the Chinese government did not publish daily data on air quality indicators for prefecture-level cities before 2013, we could not empirically investigate the correlation between subway development and air quality before 2013. This limits our complete understanding of the long-term impacts of subway construction on air quality.

We have also mainly used the dimensions of population size and level of economic development for categorization when considering the impact of urban differences on the relationship between the subway and air quality. This may have overlooked other important urban conditions affecting the relationship between subways and air quality, such as traffic congestion, the number of motor vehicles in the city, as well as urban planning and public policies. Future studies need to adopt more diverse criteria for urban conditions to fully understand and reveal how these conditions affect the relationship between subways and air quality.

In the future, with further urbanization and increased awareness of environmental protection, more cities may consider expanding their subway networks to reduce motor vehicle emissions. However, the construction and operation of the subway will also generate specific environmental pressures, including dust and dirt during construction and noise and vibration during the process. Therefore, future studies should consider all the environmental effects of subways in an integrated manner to assess their actual ecological benefits.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

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Ethical statement

This research has adhered to all relevant ethical guidelines and has been approved by Kobe University.

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