

The effects of high-speed rail, bullet trains, and commuter rail on commuting flows across administrative boundaries: Implications for integrated transportation planning in China

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Abstract: While the development of high-speed rail (HSR), bullet trains, and commuter rail has played an important role in shaping coordinated megaregional development, few empirical studies have compared the effects of different types of rail transport infrastructure on the number of commuters across administrative boundaries. Using big data from multiple sources, this study employs a cross-classified multilevel model to estimate three planning strategies that affect commuting across administrative boundaries at the sub-district/community scale in the Pearl River Delta (PRD) region, including (1) the facilitation of rail infrastructure, (2) the impedance of administrative boundaries, and (3) land-use settings in both residential and workplace destinations. The results suggest that HSR and commuter rail connectivity are positively associated with commuting across administrative boundaries, with a larger estimated coefficient for HSR, whereas bullet train connectivity is not significant. City and district boundaries are negatively associated with commuting across administrative boundaries and weaken its association with intercity rail connectivity. Positive interaction effects are also found between HSR connectivity and residential density in home communities and job density in work communities. These findings can help policymakers determine the priority of various railway infrastructures in the PRD region, also suggesting their incorporation into regional governance and land-use strategies.

Keywords: intercity rail; land-use contexts; commuting across boundaries; cross-classified multilevel model; China Greater Bay Area

1 Introduction

Promoting regional integration and intercity commuting are the most important visions of megaregional planning (Chen & Haynes, 2015; Heuermann & Schmieder, 2019; Ross & Woo, 2011). Globally, many established megaregions have high rates of intercity commuting. In 2020, an estimated 27% of daily commuters in the San Francisco Bay Area crossed city boundaries, compared to roughly 20% in the New York metropolitan area in 2019 (Bay Area Council Economic Institute, 2021; New York City Department of City Planning, 2019). However, in Guangzhou and Shenzhen, two megacities in the Pearl River Delta (PRD) region, only 14% of commuters did so in 2020 (Beike Research Institute, 2020). To encourage commuting across administrative boundaries (CAB), it is essential to facilitate regional transportation integration and coordinated development in the PRD region.

Existing research has identified three types of factors that may influence CAB (Azaria et al., 2013; Guirao et al., 2018). First, the travel cost is a critical factor in determining CAB, as it is largely associated with the travel distance and transport facilities, such as highways, airlines, and railways (Guirao et al., 2018; Limtanakool et al., 2006). Second, administrative boundaries play an important role in impeding CAB due to local governments' autonomous management of education, healthcare, and housing (Cavallaro & Dianin, 2019, 2020; Karácsony et al., 2021; Medeiros et al., 2021). Third, different activity contexts, such as home and workplace, as well as their built environments, may also influence CAB by providing housing and employment opportunities (Heuermann & Schmieder, 2019; Wang et al., 2019). However, few studies have examined the combined effects of all three factors on CAB, with limited attention to the impact of different regional railway systems.

The construction of high-speed railway networks has emerged as a major infrastructure strategy for pursuing integrated regional development in China (see Chinese State Council, 2004). In 2019, the recent Intercity Railway Construction Plan (2020–2030) specifies targets for railroad construction for enhancing intercity commuting and linkages, aiming to ensure that major large cities in the PRD region can be reached within one hour of travel and medium-sized cities within two hours (National Development and Reform Commission, 2020). This plan also emphasizes the hierarchical roles of three types of intercity rail systems. High-speed rail (HSR) links major cities at speeds above 250 km/hour. Bullet trains connect major and medium-sized cities at speeds of 200–250 km/hour. Commuter rail supports daily travel between major city centers and surrounding small or fringe cities at speeds of 160–200 km/hour. More importantly, these three intercity railways not only improve public transit for CAB but also shape three types of home-work structures in the PRD region, including large city to large city models supported by HSR, medium-sized city to large city models by bullet train, and fringe city to large city models by commuter rail. However, few empirical studies have assessed the distinct impacts of HSR, bullet trains, and commuter rail on CAB. In practice, comparing these intercity railways can assist policymakers in prioritizing and assessing the benefits of regional railway infrastructure planning.

To fill these research gaps, we collected multiple sources of big data, including cellphone-based big data that measures the finer-grained commuting flows of over 7 million users, a travel cost dataset between 609 urban/rural communities obtained from an online map platform, and big data on housing transactions. Based on these datasets, we introduced a cross-classified multilevel model (CCMM) to estimate the number of commuters between 609 communities. The CCMM allows for multilevel analysis to isolate the impact of flow-based factors between communities (e.g., rail connectivity, boundary restrictions, and driving time) from area-based factors in the origin and/or destination areas (e.g., land use and socioeconomic attributes). In this case, commuting flows are cross-classified according to home and work communities; thus, this methodology allows for the differentiation of the impacts of factors in both the home and workplace communities, as well as the flow factors between them. In summary, we investigate two research questions: (1) What are the different roles of HSR, bullet trains, and commuter rail in facilitating CAB in the PRD region? (2) How do these intercity railway connectivity levels moderate the effects of administrative boundaries and land-use disparities on CAB?

This study contributes twofold to the literature. First, it is among the first to compare the impacts of various intercity rail systems on CAB. Second, this research explores the added value of improving the three types of railway connectivity in promoting CAB by assessing the moderation effects of administrative boundaries and land-use contexts. These moderation effects can provide policy implications for regional coordinated

development by suggesting a combined policy package of incorporating rail transport and land-use planning, as well as incorporating regional infrastructure and governance strategies.

The rest of the paper is organized as follows. Section 2 reviews the related literature on CAB. Section 3 introduces the research area and data. Section 4 presents the CCMM method. Section 5 determines the optimal station buffer size. Section 6 presents the findings. The final section discusses and concludes.

2 Literature review

Existing literature has widely investigated the factors that affect the number of commuters, primarily focusing on two perspectives (Kanakoglou et al., 2015; Ma & Banister, 2006; Rahman & Akther, 2022). Some studies have examined area-based factors, such as socioeconomic attributes and land-use features in different geography contexts (Bai et al., 2020; Bergantino & Madio, 2019; Maoh & Tang, 2012), while others have emphasized flow-based factors, such as physical distance, administrative boundary, and transit connectivity (Bergantino & Madio, 2019; Ganning, 2018; Wang et al., 2020). However, few studies have simultaneously considered both area-based factors and flow-based factors, especially in the context of long-distance commuting across administrative boundaries (CAB).

2.1 Effects of intercity rails on CAB

Intercity rail infrastructure, as a key mode of transportation connecting communities across megaregional scales, plays a critical role in the emergence of CAB (Rahman & Akther, 2022). By reducing commuting time and costs, intercity rail increases the acceptable home-work distance for commuters, thereby facilitating CAB. Moreover, intercity rail has unique advantages compared to other commuting modes. Unlike subways or bus rapid transit, which primarily serve intra-city commuting, intercity rail systems are not confined by city boundaries and facilitate long-distance CAB (Deng & Nelson, 2011; Ingvardson & Nielsen, 2018). Compared to private car, intercity rail systems significantly reduce travel costs and avoid the impact of traffic congestion (Diao et al., 2017; Garmendia et al., 2011).

A growing body of research links intercity rail systems, such as high-speed rail (HSR), bullet trains, and commuter rail, and CAB (Cummings & Mahmassani, 2022; Diao et al., 2017; Ghimire & Lancelin, 2019; Wang et al., 2019). The impact of these rail systems on CAB varies, not only due to differences in speed and cost but also because of the scale of the cities they connect. Studies consistently show that intercity rail connections between large and smaller cities drive CAB. For example, Heuermann and Schmieder (2019) found that a 1% reduction in commute time due to HSR resulted in a 0.25% increase in commuter numbers between counties in Germany. Many workers relocate to smaller cities while maintaining their residences in larger cities, and HSR enables this separation of home and workplace. Similarly, Guirao et al. (2018) observed that HSR reshaped inter-provincial commuting flows in Spain. The uneven distribution of population and employment across cities of different sizes fuels the demand for cross-boundary commuting.

Moreover, several studies have explored the positive impact of intercity rail connections between large cities on CAB (Chung et al., 2020; Lin et al., 2018; Liu et al., 2019; Tang et al., 2020). On one hand, high-paying, specialized jobs in large cities often drive individuals to commute from surrounding areas, even when these opportunities are geographically concentrated. At the same time, improvements in transportation infrastructure have made intercity rail commuting increasingly efficient, sometimes

matching or surpassing the effectiveness of intra-city commuting, particularly in the face of congestion in urban cores. For example, Wang et al. (2019) show that integrating HSR and bullet trains enhances connectivity between large cities, boosting commuting flows by reducing travel time and promoting regional mobility. This integration strengthens economic ties and labor market connectivity across major urban centers. Lin et al. (2018) shows a positive correlation between HSR and cross-city commuting, demonstrating that HSR improves connectivity, reduces travel time, and boosts commuting flows between large metropolitan areas.

The findings above suggest that intercity railways facilitate CAB between cities of varying sizes. However, the existing literature rarely differentiates between large cities or the dynamics between large and smaller cities in this context.

2.2 Effects of administrative boundary and land use on CAB

Administrative boundaries are another important flow-based factor influencing CAB (Bergantino & Madio, 2019; Heuermann & Schmieder, 2019; Karácsony et al., 2021). In general, local governments have varying degrees of independent administrative authority over education, healthcare, or housing purchases. When commuters choose to live and work in different administrative regions, they may face potential restrictions, particularly in remote areas (Faludi & Waterhout, 2002; Zhang et al., 2020). It is worth noting that most past studies have shown that city boundaries negatively impact CAB, while overlooking the role of district/county boundaries (Azaria et al., 2013; Comerio et al., 2021).

Moreover, boundary effects on cross-border commuting can be mitigated by developing public transport (e.g., Cavallaro & Dianin, 2019; Medeiros et al., 2021). For example, Cavallaro and Dianin (2020) as well as Medeiros et al. (2021) have reported that the implementation of cross-border public transport, such as the construction and provision of railway services, can alleviate the negative effects of national boundaries on transnational commuting in central Europe. Unfortunately, few studies have quantitatively examined this moderating effect of intercity rail on the impedance posed by administrative boundaries and CAB. Understanding the moderating effect of intercity railways is essential for incorporating effective rail transport planning and governance strategies.

In addition, some area-based factors in both residence and workplace may also influence CAB (Bergantino & Madio, 2019; Guirao et al., 2017; Niebuhr et al., 2012). In general, individuals who reside in communities with low incomes, low housing prices, high residential density, and low job density tend to work in other communities (Bai et al., 2020; Bergantino & Madio, 2019; Maoh & Tang, 2012). Low incomes may drive residents to seek higher-paying jobs in other communities (e.g., those in city centers), even if it means facing long-distance CAB (Guirao et al., 2018). Communities with low housing prices are typically situated in suburban areas distant from urban employment centers, compelling commuters who reside there to engage in longer-distance CAB. Communities with high residential density and low job density offer limited employment opportunities, thus encouraging residents to work in other communities. For example, Mitra and Saphores (2019) found that the job-housing ratio in residential areas is negatively associated with the likelihood of family members engaging in long-distance commuting. Cui et al. (2021) used social network location data and found that high average wages in residential areas are negatively associated with intercity travel flow, while high housing prices are positively associated with it on weekdays.

Besides, few studies have explored workplace contexts (Limtanakool et al., 2006; Wang et al., 2020). For example, Lee et al. (2011) found that work areas are more

significant than residential areas in explaining transit commuting ridership, and that job density in workplace neighborhoods is positively associated with transit commuting ridership. Chung et al. (2020) identified that the density of healthcare facilities and financial institutions in workplace cities is negatively associated with intercity commuting time, while the density of public transport facilities in workplace cities is not significantly associated with intercity commuting time. Thus, more studies are needed to investigate the influence of socioeconomic and land-use factors within workplace areas on CAB.

2.3 Research gaps

Overall, although existing studies have separately explored the impact of intercity rail systems, administrative boundaries, and land use on CAB, three prevailing research gaps deserve further investigation.

First, the existing literature lacks a comprehensive comparison of the effectiveness of HSR, bullet trains, and commuter rail in promoting CAB, as well as an analysis of the home-work structures they represent across large cities, large and medium-sized cities, and large and small cities within a megaregion. To compare the impacts of the three intercity rail systems in the PRD region, we utilize cellphone-based big data. This approach compensates for the traditional survey research's sample size limitations and enables research at a megaregion scale. Ignoring the differences between intercity rail systems may lead to confusion regarding their actual roles, thereby reducing the accuracy of transportation planning. Our study can assist policymakers in prioritizing the construction of HSR, bullet trains, and commuter rail for future intercity railway construction plans.

Second, existing research on intercity rail commuting has not fully explored the influence of city and district boundaries, nor their moderating effects. Although some studies have suggested that intercity rail connectivity can mitigate the inhibitory effects of administrative boundaries on CAB, few have quantified these moderating effects at the city and district levels (Cavallaro & Dianin, 2019, 2020; Medeiros et al., 2021). This approach is crucial for understanding the distinct impacts of city and district boundaries on CAB and their interaction with intercity rail. Thus, our study offers a quantitative assessment to help policymakers develop integrated policies that synergize intercity rail construction and regional integration to facilitate CAB.

Third, CAB research has paid limited attention to the influence of different land-use contexts, particularly in work communities, let alone their moderating effects with intercity rail. For example, some studies have found that differences in residential density and employment opportunities between home and work locations can significantly impact the number of cross-regional commuters (Guirao et al., 2018; Lee et al., 2011; Wang et al., 2020). These findings imply that both home and work contexts influence individuals' commuting choices. More importantly, intercity rail may further moderate the contextual density effects by reducing commuting costs and time. Comprehending this moderating effect is crucial for aligning intercity rail development with land-use strategies to improve CAB.

3 Research area and data

This study focuses on the PRD megaregion, adjacent to Hong Kong and forming the mainland part of China's Greater Bay Area. The PRD region has been committed to coordinated development and regional integration through the construction of intercity railways for a long time. As of 2020, the length of the intercity rail systems in the PRD megaregion had reached about 4,000 km. As Figure 1 shows, HSR mainly connects Hong

Kong, Shenzhen, Dongguan, and Guangzhou. Bullet train services mainly connect Guangzhou with Jiangmen, Zhongshan, and Zhuhai. Commuter rail has the widest regional coverage and links Guangzhou with Foshan, Zhaoqing, Dongguan, Huizhou, and Shenzhen.

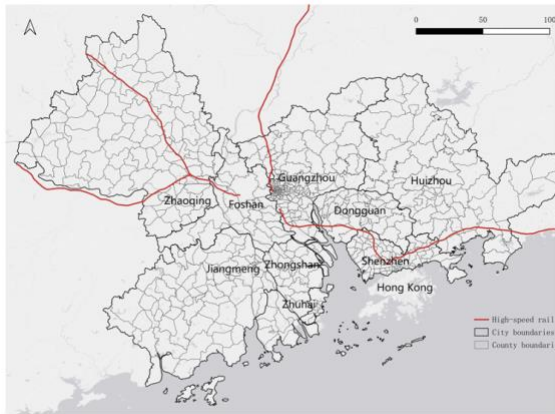


Figure 1a. High-speed rail network



Figure 1b. Bullet-train network

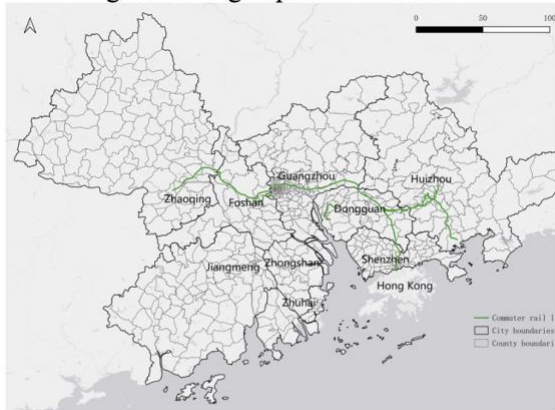


Figure 1c. Commuter-rail network

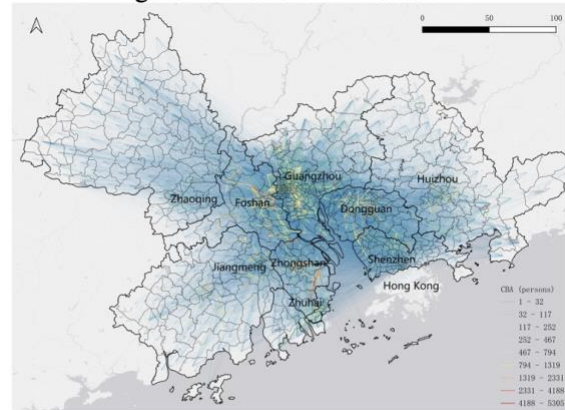


Figure 1d. CAB commuting flows

Figure 1. Commuting flows and intercity railways in the PRD region

This study employs several sources of big data to conduct the analysis. The dependent variable is the number of commuters traveling between communities within the PRD region. We collected commuting data from a 2018 mobile phone signaling dataset obtained from China Telecom, one of the three major telecommunication carriers in China. Here, we focus on the fine-grained community scale, which represents the lowest level (street or town) of the four administrative divisions in China (i.e., province, city, district/county, street/town). The calculation of commuting data involves three steps. First, we identify the residential and workplace locations for residences. Using mobile phone trajectory data from April 2018, we identified users' residential and workplace locations by pinpointing the longest stop points between 9 pm and 8 am, and 7 am and 7 pm, respectively. This dataset includes 3,824,967 individuals living and working in 609 urban or township/village communities in the PRD region. Second, we identify the effective range of the intercity rail station. Based on the results of a nonlinear analysis (refer to Section 5), we determined that the maximum effective influence of an intercity rail station is approximately 20 km. Then, we assess whether each community lies within the effective service range of HSR, bullet trains, and commuter rail by determining if the

distance from the community center to the nearest station is under 20 km. Third, we select the research CAB flows. Since both the residential origins and workplace destinations of some commuting flows fall within the same intercity rail station's service area, we excluded these shorter commuting flows from the analysis to avoid confounding the results. Finally, we obtained 323,850 commuting flows between communities, involving 778,346 commuters.

The independent variables comprise both flow-based attributes and community-based attributes (Table 1). The flow-based attributes include three types of intercity rail connectivity variables, two cross-boundary variables, and driving time between communities. First, we estimated three intercity rail connectivity variables based on the effective service of intercity rail stations. For instance, if both the residential and employment communities are within the 20 km service range (see Section 5) of different HSR stations, the HSR connectivity for that commuting flow is assigned a value of 1; otherwise, it is 0. The same approach was used to calculate connectivity for bullet trains and commuter rail. Second, we defined two cross-boundary variables based on whether commuting flows crossed administrative boundaries. If the residential and employment areas belong to different cities, the cross-city variable is assigned a value of 1; otherwise, it is 0. The same method was used for cross-district. Administrative boundary data was sourced from the National Geomatics Center of China. Third, we estimated the driving times between communities with Baidu API. The Baidu API, similar to ArcMap, is an online road network platform. Using a Python crawler, we uploaded the coordinates of each community government to the Baidu API, which then estimated and returned driving times between communities, accounting for road grade and average congestion.

Community-based attributes include four land-use variables: residential density, job density, subway accessibility, and proximity to the nearest city center, as well as five socioeconomic attributes: housing prices, GDP, gender ratio, child ratio, and aging population. First, we calculated the residential density and job density in each community based on the user's home and work locations. Second, we determined subway accessibility based on whether the community has a subway station. Third, we calculated the distance to the nearest city center on the Baidu API platform.

As for socioeconomic attributes, we collected second-hand housing prices as a proxy for community wealth due to the lack of personal income data. Using a Python crawler, we collected and estimated the average housing prices per square meter in 609 communities from Lianjia.com, China's largest second-hand housing website, in June 2019. Additionally, we collected GDP data from the 2019 Guangdong Statistical Yearbook, along with gender ratio, child ratio, and aging population figures from the Seventh National Census of China, conducted in 2020.

Table 1. Description of variables

Variables	Description	Mean	St. dev
<i>Dependent variables</i>			
CAB	Number of commuters across administrative boundaries in the flow between home and work communities (persons)	2.4	45.5
<i>Level-1 independent variables:</i>			
<i>flow-based variables</i>			
HSR	Whether home and work communities are connected by high-speed rail (1=Yes; 0=No)	0.28	0.45
Bullet-train	Whether home and work communities are connected by bullet trains (1=Yes; 0=No)	0.47	0.50
Commuter-rail	Whether home and work communities are connected by a commuter rail (1=Yes; 0=No)	0.45	0.50
Cross-city	Whether commuting routes cross city boundary (1=Yes; 0=No)	0.79	0.41

Variables	Description	Mean	St. dev
Cross-district	Whether commuting routes cross the district/county boundary (1=Yes; 0=No)	0.90	0.30
Driving time	Driving time from home to work communities (minutes)	93.10	45.80
<i>Level-2 independent variables: Land-use variables of home and work communities</i>			
Residential density	The average density of mobile phone users per square kilometer residing in communities (thousand persons/sq. km)	0.50	0.89
Job density	The average density of China Telecom users per square kilometer working in communities (thousand persons/sq. km)	0.74	1.52
Subway accessibility	Whether communities have at least one subway station (1=Yes; 0=No)	0.22	0.42
Distance to the nearest city center	Driving time from the location of the community government to the nearest city government (minutes)	25.30	23.85
<i>Level-2 independent variables: Socioeconomic attributes of home and work communities</i>			
Housing price	The average transaction price of second-hand housing (thousand yuan/sq. meter)	21.93	18.86
GDP	Gross domestic product (billion yuan)	1.81	1.92
Gender ratio	Ratios of male and female population	1.11	0.11
Children ratio	Percentage of residents under the age of 18 (%)	14.76	5.66
Aging population	Percentage of residents over the age of 65 (%)	7.23	3.77

Note: We measured all level-2 independent variables based on community boundaries and did not standardize them.

4 Methodology

This study employed a cross-classified multilevel model (CCMM) to investigate the impact of flow-based variables and community-based variables in both residential origin and workplace destination on CAB. Previous studies have used advanced statistical models, such as structural equation models or multilevel mixed-effects linear regression models, to examine the effects of land use in home and work areas on travel behavior (e.g., de Abreu e Silva et al., 2012; Guan & Wang, 2019). However, these statistical methods struggle to distinguish between the influences of home and work contexts.

In CCMM, the flow-based variables exhibit a cross-classified multilevel structure, in which each commuting flow (Level 1) is nested within two communities (Level 2): origin communities representing home communities and destination communities representing work communities. This model isolates the effects of area-based variables in home communities and work communities, respectively, from the effects of flow-based variables on CAB.

Mathematically, suppose commuting flow h ($h=1 \dots l$) between home community i ($i=1 \dots n$) and work community j ($j=1 \dots m$), then the flow-based level (Level 1) of CCMM is given by:

$$Y_{hij} = \alpha_{ij} + \beta X_{hij} + \varepsilon_{hij} \quad (1)$$

Where

Y_{hij} is the commuting flow h between home community i and work community j .

α_{ij} is the intercept term.

X_{hij} indicates flow-based variables of commuting flow h between home community i and work community j .

β indicates coefficients of flow-based variables.

ε_{hij} is the random error term between commuting flows.

Level 2 of the CCMM is the community-based level. This study controls for the random effects on the constant of the equation α_{ij} across two types of communities, as follows:

$$\alpha_{ij} = \delta + \gamma Z_i + \lambda U_j + \theta_i + \varphi_j \quad (2)$$

Where

δ is the intercept term.

Z_i indicates socioeconomic and land-use variables in home community i.

U_j indicates socioeconomic and land-use variables in work community j.

γ indicates coefficients of socioeconomic and land-use variables in home community i.

λ indicates coefficients of socioeconomic and land-use variables in work community j.

θ_i is the random error term for home community i.

φ_j is the random error term for work community j.

Compared to traditional multilevel methods, the CCMM has several advantages (Claus et al., 2020). First, this model can distinguish the influence of different contexts (e.g., home community and work community) by calculating several random error terms in level 2, such as θ_i and φ_j in this case. The uncertain geographic context problem (UGCOP) posits that land-use contexts in different locations can influence individuals' travel behavior (Kwan, 2012). This theory suggests that commuting flows may vary in their formation and change based on the specific characteristics of the origin and destination communities (Zhang et al., 2024). In addition, the CCMM enables testing for potential moderation effects of specific contexts on intercity rail connectivity variables by introducing interaction variables. Understanding how to optimize land use in different contexts and how to improve intercity rail connectivity in different contexts would greatly benefit CAB. Second, this model can handle spatial heterogeneity and dependency (Ding & Cao, 2019). Third, this model can partially address the issue of multicollinearity due to its multilevel and cross-classified structure (Snijders & Bosker, 2011).

To assess the need for stratification in the model, we calculated the intraclass correlation coefficient (ICC). For ICC calculation, we built a null model with only constants. In equations (1) and (2), error terms ε_{hij} (Level 1), θ_i (Level 2), and φ_j (Level 2) are assumed to follow a truncated normal distribution. The Level 1 variation is estimated as σ_ε^2 and the Level 2 variations of home and work community are estimated as σ_θ^2 and σ_φ^2 , respectively. The ICC in the null model is calculated as follows:

$$ICC = \frac{\sigma_\theta^2}{\sigma_\varepsilon^2 + \sigma_\theta^2 + \sigma_\varphi^2} \text{ or } \frac{\sigma_\varphi^2}{\sigma_\varepsilon^2 + \sigma_\theta^2 + \sigma_\varphi^2} \quad (3)$$

The structure of this model is dependent on the ICC test. For example, if the sum of two ICC values approaches zero, the Level-2 variations between home and work communities are small, and the multilevel model can be collapsed into a regular single-level regression model. If one of two ICC values approaches zero, the multilevel model can be collapsed into a traditional multilevel model. If each of the two ICC values is larger than 10%, a cross-classified multilevel analysis is needed (Snijders & Bosker,

2011). All the CCMM models were estimated by using the xtmixed package in STATA 17.0.

5 Sensitivity analysis for defining optimal buffer size

We conducted a sensitivity analysis to identify the optimal buffer distance at which intercity rail stations affect CAB. The estimated distance defines the effective service area of each station and provides the basis for determining whether residential and employment communities are connected by HSR, bullet trains, or commuter rail. By using a gradient-boosted decision trees (GBDT) machine learning model, the simulations can calculate the nonlinear relationship between the distance to intercity rail stations and CAB, as well as capture the effective threshold (Zhang et al., 2022). We constructed two GBDT models to separately analyze the contexts of the home and work communities, each controlling for land use and socioeconomic variables. We validated the GBDT regression model parameters using 5-fold cross-validation with the *gbm* R package, employing a learning rate of 0.001, 3,000 trees, and a depth of 6. The R-squared values for the two GBDT models are 0.82 (left) and 0.80 (right), respectively. Figure 2 presents partial dependence plots (PDPs) of the nonlinear relationship between distance to the nearest intercity rail station and CAB. Rug marks are included along the x-axis to indicate the distribution of observed distances. The results show a negative nonlinear relationship, with CAB reaching its lowest level beyond 20 kilometers for both home and work communities, suggesting that the maximum effective influence of an intercity rail station in the PRD is about 20 kilometers.

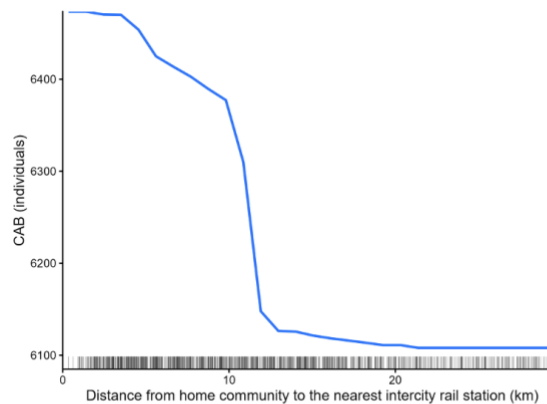


Figure 2a. Distance from home communities to intercity rail stations

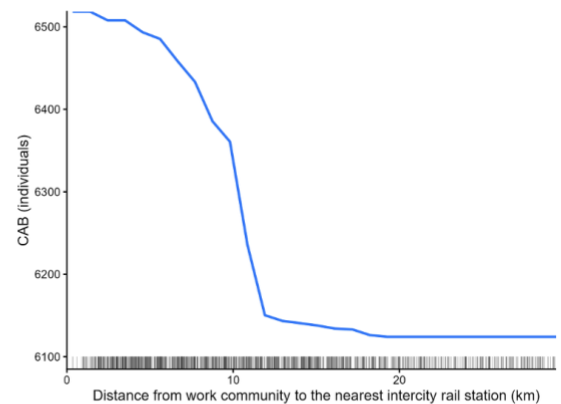


Figure 2b. Distance from work communities to intercity rail stations

Figure 2. Nonlinear associations between CAB and distance to intercity rail station

6 Findings

In this study, we first developed a null model that considered random constants between community variations in home and work communities. According to Equation (3), we calculated the ICC value of two random-effects parameters and ensured that each proportion of variance is not less than 10%. The results show that the Level 1 variation in flow on CAB is 2,040. The Level 2 variations in home and work communities are 319 and 313, respectively. The corresponding ICC in home and work communities accounts for 11.93% and 11.71%, respectively, indicating that the sample data have a significant cross-classified multilevel nature. The estimated Akaike's Information Criteria (AIC) and

Bayesian Information Criteria (BIC) of the null model were 3,389,150, and 3,389,193, respectively. These values serve as a baseline for comparison with the subsequent models that incorporate explanatory variables.

We estimated the final model by introducing all independent variables as the baseline model. The AIC, and BIC change to 3,376,552, and 3,376,851, respectively. Compared to the null model, the baseline model is improved with the sample data. To investigate moderation effects, we extended the baseline model by including two types of interaction terms. Table 2 shows the regression results based on Eq. (1) and (2). Model 1 is the baseline model, while Models 2 and 3 present the estimation results for moderation effects of administrative boundary variables and density variables, respectively.

Table 2. Coefficients estimated in the CCMM

Variables	Model 1	Model 2	Model 3
Level-1: Flow-based variables			
HSR	1.91***	105.28***	1.42***
Bullet-train	0.52	261.73***	0.79***
Commuter-rail	0.68**	41.24***	0.85***
Cross-city	-180.04***	-4.87*	-180.04***
Cross-district	-165.23***	-5.18*	-165.23***
Driving time	-1.49***	-3.80***	-1.51***
Level-2: Land-use variables of home community			
Residential density	-1.33	-0.79	-1.60*
Job density	-0.19	-0.06	0.16
Subway accessibility	1.53***	0.71	1.52***
Distance to the nearest city center	8.36***	5.35	8.23***
Level-2: Land-use variables of work community			
Residential density	-1.80**	-1.25*	-1.25
Job density	0.60***	0.74***	0.13
Subway accessibility	0.94*	0.12	0.93*
Distance to the nearest city center	-6.13**	-3.11	-6.34**
Level-2: Socioeconomic attributes of home community			
Housing price	-7.60***	-7.81***	-7.67***
GDP	3.96***	3.47***	3.90***
Gender ratio	0.99	1.09	0.97
Children ratio	2.50	11.45**	2.79
Aging population	-22.00***	-22.55***	-21.45***
Level-2: Socioeconomic attributes of work community			
Housing price	5.74***	5.95***	5.75***
GDP	3.58***	3.10***	3.62***
Gender ratio	1.76	-1.88	1.76
Children ratio	2.05	11.01***	2.03
Aging population	18.26***	18.86***	18.63***
Interaction terms			
HSR×Cross-city		-104.35***	
HSR×Cross-district		-90.18***	
Bullet-train×Cross-city		-261.82***	
Bullet-train×Cross-district		-253.26***	
Commuter-rail×Cross-city		-41.73***	
Commuter-rail×Cross-district		-31.10***	
HSR×Residential density of home community			0.85*
HSR×Job density of home community			-0.42
HSR×Residential density of work community			-0.34
HSR×Job density of work community			0.66**
Bullet-train×Residential density of home community			-0.26
Bullet-train×Job density of home community			-0.02
Bullet-train×Residential density of work community			-0.30
Bullet-train×Job density of work community			0.38
Commuter-rail×Residential density of home community			0.12

Variables	Model 1	Model 2	Model 3
Commuter-rail×Job density of home community			-0.25
Commuter-rail×Residential density of work community			-0.35
Commuter-rail×Job density of work community			0.20
Random effects			
Var ($\varepsilon_{level\ 1}$)	1,963	1,888	1,963
Var ($\theta_{level\ 2}$)	315	314	315
Var ($\varphi_{level\ 2}$)	309	310	309
Goodness-of-fit statistics			
AIC	3,376,552	3,364,031	3,376,720
BIC	3,376,851	3,364,394	3,377,148
No. of observations	323,850		

Note: *significant at the 0.1 level; **significant at the 0.05 level; ***significant at the 0.01 level.

6.1 Comparison of three types of intercity railways and administrative boundaries

Model 1 in Table 2 shows the direct impact between all independent variables and CAB. HSR is positively associated with commuter numbers between communities, with a significant coefficient of 1.91 at the 0.01 level. The coefficient for commuter rail (0.68) is significantly positive at the 0.05 level, while the coefficient for bullet train is insignificant. These findings indicate that HSR and commuter rail have a positive impact on facilitating CAB, consistent with previous research on the intercity railway (Cummings & Mahmassani, 2022; Diao et al., 2017; Wang et al., 2019), while bullet train cannot significantly influence CAB. Because HSR and commuter rail connectivity are measured on the same binary scale, their coefficients are directly comparable. The larger coefficient for HSR connectivity (1.91) than for commuter rail connectivity (0.68) suggests that HSR has a stronger estimated association with CAB. This difference may reflect the distinct roles of the three types of intercity rail within the PRD region. HSR facilities mainly serve major cities, with six of the nine HSR stations in the PRD region located in Guangzhou and Shenzhen, the region's two largest cities. In this case, almost 84.79% of CAB occur in Guangzhou and Shenzhen due to the concentration of residents and jobs. This CAB pattern between major cities aligns with the case study in the Madrid metropolitan area rather than that of Germany (Guirao et al., 2017; Heuermann & Schmieder, 2019). In contrast, commuter rail facilities mainly serve small-sized cities. While small cities offer lower living costs and rent, larger cities provide better amenities and services. One possible explanation is that the potential savings in living costs do not outweigh the reduced services, so most CAB travelers prefer large cities and HSR over small cities and commuter rail in the PRD.

Among the administrative boundary variables, the coefficients for cross-city (-180.04) and cross-district (-165.23) are both negative and statistically significant at the 0.01 level, indicating that both city and district boundaries are negatively associated with CAB. Many existing studies have confirmed the impeding effect of city boundaries on CAB, but few have focused on the impact of district boundaries (Bergantino & Madio, 2019; Heuermann & Schmieder, 2019; Karácsy et al., 2021). In China, Administrative boundaries regulate social security systems and social welfare, such as medical insurance, unemployment insurance, and educational opportunities, provided by the local government. Once commuters choose to live and work in different administrative areas, they may lose corresponding social welfare benefits and conveniences. More importantly, district governments possess substantial decision-making authority over social management and welfare services in China, particularly in areas distant from city centers. In addition, we included driving time from home to work as a control variable, finding a negative correlation with CAB (-1.49, $p < 0.01$). Longer commuting times increase costs, reducing the likelihood of choosing long-distance CAB.

This study further investigates the interaction effects between intercity rail variables and administrative boundary variables on CAB (Model 2 in Table 2). To capture potential moderation effects, we calculated the coefficients of six interaction terms between the three intercity rail connectivity variables and the two administrative boundary variables. For example, the interaction coefficients of HSR with cross-city (-104.35) and cross-district (-90.18) are both significantly negative at the 0.01 level. Similarly, the interaction coefficients of bullet trains with cross-city (-261.82) and cross-district (-253.26) are significantly negative at the 0.01 level. Additionally, the interaction coefficients of commuter rail with cross-city (-41.73) and cross-district (-31.10) are also significantly negative at the 0.01 level. These findings indicate that both city and district boundaries significantly diminish the impact of intercity rail on CAB, irrespective of the city's size, whether large, medium, or small. Therefore, reducing administrative barriers between cities and districts, such as those related to public services and social welfare, may facilitate CAB, especially in regions already connected by intercity rail.

6.2 Comparison of three types of intercity railways varying by home and workplace contexts

This study also controlled for land-use variables and socioeconomic attributes in both home and work communities on CAB (Model 1 in Table 2). Regarding home communities, subway accessibility is significantly associated with CAB with a coefficient of 1.53 at the 0.01 significance level. Residents living near subway stations have enhanced accessibility to other communities, enabling them to more conveniently commute and choose employment in those areas. Distance to the nearest city center is significantly associated with CAB with a coefficient of 8.36 at the 0.01 significance level. Due to the concentration of employment opportunities in city centers, residents living far from the city center are more likely to engage in CAB. The coefficient for housing price (-7.60) is negatively associated with CAB at the 0.01 significance level. There is a balance between housing prices and commuting costs. When commuters face higher housing prices, they tend to prefer shorter commuting distances. The coefficient for GDP (3.96) is positively associated with CAB at the 0.01 significance level. High-GDP areas experience extensive and rapid labor mobility, with high incomes and abundant employment opportunities offering residents a broader range of job choices. The coefficient for the aging population (-22.00) is negatively associated with CAB at the 0.01 significance level. In China, the retirement age is 65. An increasing proportion of the population over 65 will reduce employment demand and CAB.

As for work communities, most land use and sociodemographic variables are significant. Residential density in work communities is negatively associated with CAB, with a coefficient of -1.80 at the 0.05 significance level. Meanwhile, the coefficient for job density in work communities is positive at the 0.01 significance level, with a value of 0.60. This is reasonable because residents of the work communities will occupy job opportunities, thereby reducing commuters from other communities. Conversely, job opportunities in the work communities will attract commuters from other communities. These findings are consistent with prior studies by Mitra and Saphores (2019) and Lee et al. (2011), which highlighted that residential density inhibits and employment density promotes CAB in areas concentrated with employment. Subway accessibility in work communities has a significantly positive impact on CAB (0.94, $p < 0.1$). This finding suggests that work communities near subway stations can attract commuters from other communities due to reduced commuting costs and time. Distance to the nearest city center from work communities is significantly associated with CAB with a coefficient of -6.13 at the 0.05 significance level. Employment opportunities located far from the city center typically attract local residents due to limited salary and housing costs. The

coefficient for housing price in work communities (5.74) is positively associated with CAB at the 0.01 significance level. High housing prices in work communities may compel commuters to seek housing in more distant locations to reduce the cost of purchasing or renting. The coefficient for GDP in work communities (3.58) is positively associated with CAB at the 0.01 significance level. This is reasonable because high-GDP areas can offer higher salaries and attract commuters from surrounding regions. Meanwhile, high-GDP areas typically possess advanced transportation infrastructure, which reduces the costs associated with CAB. The coefficient for aging population in work communities (18.26) is positively associated with CAB at the 0.01 significance level. A high percentage of the aging residents in work communities reduces the local labor supply, thereby attracting commuters from other communities.

Model 3 in Table 2 further investigates the interaction effects between four density variables and three intercity rail variables. For example, the interaction coefficient for HSR with residential density in home communities (0.85) is significantly positive at the 0.1 level, and the interaction coefficient for HSR with job density in work communities (0.66) is significantly positive at the 0.05 level. These findings suggest that HSR connectivity amplifies the impacts of residential density in home communities and job density in work communities on CAB. HSR improves regional accessibility, reduces commuting costs, and extends the acceptable distance between home and work, thereby encouraging individuals to live and work in different communities within major cities. As a result, the number of commuters between communities is likely to increase further, particularly in communities with high residential and job density, following HSR connectivity. In contrast, we also found that the moderating effects of bullet-train and commuter-rail on density variables are not significant. One possible explanation is that bullet trains and commuter rail primarily serve small and medium-sized cities, where the proportion of CAB is relatively low. Even though these intercity rail systems reduce commuting costs and time, they lack sufficient employment and housing opportunities to support CAB. This also reflects that regional integration efforts are primarily concentrated between major cities in the PRD region.

7 Conclusion and discussion

Using a 2018 mobile phone signaling dataset for the PRD region of China, we developed a CCMM to compare the impacts of HSR, bullet trains, and commuter rail on CAB and investigate the moderation effects of administrative boundaries and land-use contexts. The findings emphasize the significance of establishing intercity rail systems to promote CAB and underscore the need to integrate rail transport planning, governance strategies, and land-use planning. First, HSR and commuter rail show positive associations with CAB, whereas bullet trains do not. These differences reflect more than variation in speed or train type. They also capture distinct patterns of regional linkage. In the PRD, HSR mainly links large cities, while commuter rail more often links large cities with smaller surrounding cities. Our results suggest that both forms of connection play important roles in supporting cross-boundary commuting. This finding also aligns with Heuermann and Schmieder (2019), who show that HSR can facilitate commuting between large and smaller cities in Germany. More broadly, these results may inform planning in other highly integrated megaregions. In such settings, intercity rail may strengthen regional labor mobility most effectively when it links both major cities and major cities with smaller surrounding cities.

Notably, the differences in service frequency represent a limitation in interpreting the effects of the three rail systems. In 2018, HSR operated approximately 70-82 train pairs per day, compared with 18-45 pairs for commuter rail, representing a substantial service gap. More frequent services may reduce waiting time and provide greater scheduling

flexibility, thereby contributing to the stronger association between HSR connectivity and CAB. Because OD-level service frequency was not directly incorporated into the model, this explanation should be interpreted as a possible mechanism rather than a confirmed causal relationship.

A notable finding is the insignificance of the relationship between bullet trains and CAB. Medium-sized cities often face challenges in attracting cross-city commuting flows due to their disadvantages in living costs and public services. While bullet trains enhance connectivity between large and medium-sized cities, these cities struggle to offer the housing, education, and healthcare options that draw commuters. Additionally, they typically lack the high-paying jobs and economic opportunities found in larger cities, meaning that even with improved transportation, commuting demand remains limited. Furthermore, in the PRD region, medium-sized cities are often situated around larger urban centers, and their commuting patterns are influenced by more than just bullet trains. Other transportation modes, such as highways and intercity rail, play a significant role in connecting these cities. These alternatives often provide equally or more cost-effective options for short-distance commuting, diminishing the relative impact of bullet trains on commuting flows in medium-sized cities.

Second, city and district boundaries have a significant negative impact on CAB, also weakening the positive effect of intercity rail on CAB. This informs planners of nuanced guidance for regional integration strategies, particularly in integrating rail transport planning and governance strategies. For example, future regional strategies should focus on addressing the differences between cities and districts, such as educational opportunities, healthcare access, and housing purchase restrictions, to weaken the boundary effects. Moreover, regional integration policies should prioritize cities and districts already connected by intercity rail to generate greater synergies in promoting labor mobility.

Third, this study is among the first to identify the interaction effects between density and intercity rail on CAB. We found that residential density in work communities negatively impacts CAB, while job density has a positive effect. Additionally, HSR connectivity amplifies the density effect on CAB. The results suggest that densification strategies, whether in residential or employment centers, will enhance labor mobility in large cities, especially where HSR provides convenient and fast commuting options. These findings demonstrate the importance of integrating land-use policy to better guide rail transport planning.

These findings also provide three policy implications for the PRD. First, regional transport planning should prioritize HSR connections between major cities and commuter rail connections between major cities and smaller surrounding cities to support their respective CAB patterns. Second, cities and districts connected by intercity rail should coordinate public services, particularly medical insurance, education access, and social security, to reduce institutional barriers to CAB. Third, within the effective service areas of HSR stations, planners should integrate residential and employment densification strategies with HSR development to strengthen regional jobs-housing connections.

There are several notable limitations to this research. First, like most land use-travel studies, this study used cross-sectional data and demonstrated evidence of association. To establish a causal relationship between intercity rail systems and CAB, future studies should use longitudinal data. Second, this study did not control for the influence of fares and services, which are important factors in explaining CAB in addition to the physical characteristics of intercity rail systems. Therefore, future studies should focus on the influence of related policies on improving CAB, as well as their synergistic effects with land use and transportation policies. Third, this study used an aggregate dataset to test the potential influence of flow-based variables and did not account for individual attributes

such as age, income, education, and household size. To analyze the relationship between intercity rail systems and CAB at the individual level, future research should employ suitable advanced statistical models to handle the cross-classified multilevel structure. Fourth, this study used data from 2018. Given the rapid expansion of intercity rail systems in the PRD in recent years, current network structures and commuting patterns may differ from those reflected in our analysis. Future research should use more recent data to test whether these relationships remain stable as the intercity rail system matures. Fifth, this study derived CAB, population density, and job density from the same mobile phone signaling dataset. Although these variables reflect different levels of analysis, we cannot fully rule out the possibility of same-source endogeneity. Future research should address this issue by incorporating independent data sources to validate the robustness of these relationships. Finally, to better understand the relationship between intercity rail systems and CAB in different megaregions and country contexts, future research should conduct similar studies in other megaregions around the world. This is particularly important because the relationship between HSR, bullet trains, and commuter rail, as well as their moderation effects, may vary across different contexts.

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Author contribution

The authors confirm their contribution to the paper as follows: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis: D. Lu; Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition, Conceptualization: W. Zhang; Writing – review & editing, Conceptualization: M.-P. Kwan.

Data availability

The data supporting the findings of this study are not publicly available due to third-party restrictions.

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