Article

Does High-Speed Rail Network Access Enhance Cities’ Innovation Performance?

Qunyang Du, Hangdong Yu, Cheng Yan* and Tianle Yang

School of Economics, Zhejiang University of Technology, Hangzhou 310023, China; dqy@zjut.edu.cn (Q.D.); yuhangdong@163.com (H.Y.); yangtianle@zjut.edu.cn (T.Y.)
* Correspondence: Cheng.Yan.1@cass.city.ac.uk

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Abstract: This study investigates the impacts of access to high-speed railway networks (HSRN) on urban innovative performance using a difference-in-difference method and a unique dataset including patents, nighttime lights, and HSRN at the city-level in China. First, access to HSRN significantly and positively affects the city’s innovative performance. Results remain robust after substituting different innovation indicators and controlling for city-level factors. Second, the impacts vary with the size of cities. Specifically, the benefits of access to HSRN for large and small cities are greater than for medium-sized cities, which shows a quasi-U-shaped relationship. Third, the positive effects of access to HSRN on innovation performance are stronger in knowledge-intensive industries for large cities and where there is high population mobility among cities.

Keywords: high-speed railway network; patent; DMSP/OLS; urban specialisation; population mobility

1. Introduction

The fast development of high-speed rail has played a crucial role in economic growth in China (Figure 1 graphs the high-speed rail network for China at the beginning of 2020). According to China’s Ministry of Transport, by the end of 2019, the operating mileage of China’s railways had reached 139,000 kilometres, of which 35,000 kilometres were high-speed rail, ranking at the top of the world. According to the “Medium- and Long-Term Railway Network Plan,” China plans to increase the construction of railway infrastructure, building 30,000 kilometres of high-speed railways and reaching more than 80% of large cities within the country by the end of 2020. By 2030, the provincial capital cities are to be fully connected by high-speed rail. The rapid construction of the high-speed rail network (HSRN) is profoundly affecting China’s economic development and spatial structure, which has attracted academic attention in this research field. Relevant studies from various perspectives include research on the impacts of the railway network on economic growth [1,2], regional industrial division and specialisation [3,4], urban spatial structure [5], etc. However, it is unclear how HSRN affects urban innovation performance, despite its obvious importance. As a fast and convenient means of transportation, the high-speed railway has a significant impact on population mobility across regions. Decreasing the cost of population mobility across regions may also facilitate knowledge mobility and innovation spillover. Technology spillover is bounded by localisation [6], which means that the effects of spillover are greatly limited by geographical distance. As non-standardised tacit knowledge can only be procured and absorbed by face-to-face communication and contact, HSRN may facilitate population mobility and thus significantly enhance the innovation performance of a city.
Two difficulties exist in relevant empirical studies. First, there is an endogenous issue, namely, access to HSRN for a city may have caused or been caused by the enhancement of innovation performance. On one hand, HSNR may accelerate innovation and enhance the level of innovation performance. On the other hand, a city with high innovation performance might be privileged to obtain HSRN resources. Thus, it is difficult to obtain new and valid empirical new findings using traditional econometric analysis methods. Second, there is an issue with the measures of innovation performance. Due to limitations of data access, current studies on innovation performance are mainly undertaken at the provincial level. In measuring innovation performance, most studies consider the number of patents published by the government. While province-level data and the number of patents as indicators of innovation performance may satisfy the requirements of most studies, there are few city-level studies on how access to HSRN affects innovation performance. Cities are the units connected by high-speed railways, rather than provinces. Studies focused on the provincial level neglect the significant discrepancies among cities. In addition, although the number of patents is widely adopted as the measure of innovation performance, Dang and Motahashi (2015) show that a government policy supporting patent applications in China (from 1998 to 2008) has resulted in a 30% increase in patents issued per year [7], which signifies that this indicator might not be accurate enough to reflect the truth of innovation performance.

We fill research gaps and contribute to current research in the following three areas. First, to solve the endogenous issue, this paper sets an event window from 1999 to 2017, in which high-speed rail construction in China experienced its most rapid development period with the number of high-speed railway lines increasing from 0 to 147. Based on a quasi-natural experiment, the study adopts the

![Figure 1. China's high-speed railway (HSR) lines in 2020.](image-url)
difference-in-difference approach to examine the impacts of access to HSRS on urban innovation performance. Second, to satisfy with the requirement of measuring urban innovation performance, data of prefecture-level invention authorisation, utility models, and appearance design in China from 1999 to 2017 is collected from the “China Patent Publication and Public Notice System” (epub.sipo.gov.cn) of the State Intellectual Property Office. Third, the study measures innovation performance by adopting results in the study of geographic remote sensing [8] and DMSP/OLS global stable luminous data published by the US National Oceanic and Atmospheric Administration (www.ngdc.noaa.gov).

The structure of the paper is as follows. The second section introduces the theory and hypothesis development. The third section introduces the research method. The fourth section reports the results. The fifth section adopts alternative cross-section data to examine the interaction effects and their mechanisms. The last section concludes.

2. Theory and Hypothesis

Innovation studies emphasise the significance of knowledge spillover for a country in improving its regional innovation performance and economic growth [9–11]. Innovation activities are double featured with characteristics of agglomeration and diffusion. In terms of diffusion, the spillover effects are stronger while there is lower cost, higher frequency, and a wider range of movement of innovation elements. A more convenient means of transportation can improve market intensity and breadth, due to its function in decreasing the cost of cross-region population mobility, especially among those conducting innovation activities. There are three main internal mechanisms explaining the cost reductions. First, a more convenient transportation method may contribute to the improved allocation of innovation resources in different spaces. For instance, people conducting innovation activities are given opportunities to choose to work in cities where they can fully exploit their capabilities and to live in other cities away from where they work [12]. Second, with the increase in the size and frequency of people movement, the spatial diffusion radius and spillover extent of innovation knowledge will also improve. Agrawal et al. (2017) measured the radius of knowledge spillover using the geographical distance between locations of applicators and users of patents in a city in the USA in 1983 [13]. As a result of the study, they found that the geographical distance increased by 2.3% while the freeway stock added 10%. Xu et al. (2018) examined the effects of road density on innovation activities among various cities in China [14]. They found that a 10% increase in a city’s road density led to the accession of 0.71% of the average number of patents granted by enterprises. Third, a more convenient transportation method may also improve the possibilities of cross-region cooperation by people conducting innovation activities. Dong et al. (2018) conducted a natural experiment on China’s high-speed rail construction [15]. They found that both the quantity and quality of academic papers are significantly enhanced where a high-speed rail was embedded. Furthermore, enhancements are more significant in social science papers compared to natural science papers, as a high-speed railway also improves the cooperation matching of academic staff among cities. Thus:

**Hypothesis 1.** A city’s access to a high-speed rail network is positively related to its innovation performance.

However, from the perspective of agglomeration, knowledge spillover is significantly featured with characteristics of geographic localisation [6], which has a ceiling restriction of the geographical radius in terms of spillover effects. This is because the more technologically innovative and intensive the industry is, the greater the demand for geographic agglomeration. This is echoed and supported by facts about the geographic distribution of innovation generation in multiple countries.

Crescenzi et al. (2012) found that innovation activities were significantly featured with geographic agglomeration [16], using the number of patents as an indicator and data from 31 provinces in China, 179 economic statistical areas in the USA, and 24 countries of the EU in 2007. According to the ranking for innovation performance, in Europe, the top 10 countries accounted for 50% of all European patents; the top 50 regions of the US accounted for 50% of American patents; the province of Guangdong
accounted for 50% of Chinese patents, and the top 3 states in India accounted for 50% of Indian patents. Unlike the developed countries in Europe and the United States, the innovation performance of developing countries like China is affected by the fact that their industries and populations are still rapidly agglomerating. The agglomeration effects of innovation activities can still cover the related costs. In this case, introducing more convenient transportation might help promote the geographic agglomeration of innovation activities. Lin (2017) supports this argument [4]. Taking China’s high-speed rail construction from 2003 to 2014 as an object, he empirically analysed the impacts of high-speed rail network construction on the geographic distribution of knowledge-intensive industries in cities along the route. The encryption of the high-speed rail network promoted the agglomeration of knowledge-intensive industries in some central cities. In non-central cities, the direction of effects was the opposite. Taking China’s highway construction as a quasi-natural experiment from 1990 to 2010, Baum-Snow et al. (2018) found that the improvement of the highway network promoted the economic development and population concentration of regional central cities [17]. However, highway network improvements had negative impacts on the economic development of neighbouring central cities, especially those that were inland. With the capacity of high-speed railways increasing by 10%, the population of the neighbouring city decreased by an average of 1.2%. Although the construction of HSRN generally helps to improve the level of innovation at the country level, the impacts can be heterogeneous at the city level, with central and non-central cities affected differently. Thus:

**Hypothesis 2.** Access to high-speed rail networks has different impacts on innovation performance for cities of different sizes. Compared to small cities, high-speed rail networks have more significant impacts on large cities’ innovation performance.

### 3. Methodology

A quasi-natural experiment is employed by taking the construction process of China’s high-speed rail as the research object. We examine the impacts of access to the high-speed rail network on urban innovation performance. Since 2003, China has entered a fast development phase in the construction of a high-speed rail network. A considerable number of cities have become high-speed rail cities, which provides ideal quasi-natural experimental samples for the study.

#### 3.1. Empirical Strategy

Theoretically, changes of innovation performance of a city brought by the access to high-speed rail mainly show up in three ways: the “group effect,” caused by the heterogeneity of cities, the “time effect,” caused by the evolution of time and the external macro-environment, and the “processing effect,” brought on by access to the HSRN. It is inappropriate to separate the “processing effect” from the other two effects by simply comparing innovation performance before and after the implementation of high-speed rail, although this is the major concern for this study. Assuming that there were two same parallel worlds with no interaction between them, there is a city i in both worlds. In the first parallel world, city i opened a high-speed rail at some time, while in the second parallel world city I did not. Under the same conditions, the innovation performance of i in the first parallel world, after opening the high-speed rail, is subtracted from the innovation performance of i in the second parallel world. In this way, the impacts of high-speed rail on the innovation performance of city i, could be more accurately measured as the “processing effect.” However, in reality, we can only observe whether a city has opened high-speed rail and the level of innovation performance of the city at various points in time. The difference-in-difference (DID) method is unique in that it can separate pure policy processing effects from the above information. Our model is as follows:

$$ATE_{DID} = E(inn_{after | D=1}) - E(inn_{before | D=1}) - [E(inn_{after | D=0}) - E(inn_{before | D=0})]$$

(1)
where $ATE_{DID}$ is the average treatment effect, and $D$ is a dummy variable signifying whether cities $i$ and $j$ open high-speed rail (1 means open, that is, the city belongs to the treatment group; 0 means not open, that is, the city belongs to the control group). $inn_{i,D=1}^{before}$ and $inn_{i,D=1}^{after}$ indicate the level of innovation performance before and after the high-speed rail is opened in city $i$ in the treatment group, respectively. $inn_{j,D=0}^{before}$ and $inn_{j,D=0}^{after}$ respectively indicate the level of innovation performance of city $j$ in the control group at the corresponding time. The two items on the right side of the equation mean differences between the treatment group and the control group, which signifies the net impacts of high-speed rail network access on urban innovation performance.

However, different from the normal DID method, this study features inconsistent timing of policy implementation. The time at which high-speed rail is opened in each city varies, which means there is no specific unified policy implementation time point. Thus, the DID method is further refined for this study. The study follows Beck et al. (2010) as a seminal work [18]. By expanding the general DID model, a multi-period DID model is established as follows:

$$inn_{it} = \alpha + \beta D_{it} \cdot Year_t + \delta X_{it} + A_t + B_i + \epsilon_{it}$$ (2)

where $inn_{it}$ is the innovation performance of city $i$ in year $t$. $A_t$ is a dummy variable of the year to control the overall impacts and trends that may affect the level of urban innovation performance, such as business cycle, national innovation policy, etc. $B_i$ is a city dummy variable to control the invariable characteristics of the city that may affect its innovation performance level. $X_{it}$ is the characteristic control variable of each city and $\epsilon_{it}$ is the error term. The dummy variable of $D_{it} \cdot Year_t$ is the key variable for observation in the analysis. If city $i$ opens high-speed rail in year $t$, $D_{it}$ is equal to 1 in year $t$ and subsequent years and the previous year is equal to 0. $\beta$ indicates the impact of opening high-speed rail on the city’s innovation performance level. If $\beta$ is positive, it means that access to the HSRN helps improve the level of urban innovation; otherwise, it means that the HSRN harms the level of urban innovation performance.

3.2. Data and Measures

**Innovative indicators and data sources.** Measures of innovation performance have always been a difficulty in empirical studies on innovation, and they are even harder to measure for cities at the prefecture-level. Public data on patents is currently available at the province level, which is insufficient for the study. To access prefecture-level data on innovation, software called Python is used. We obtain three types of patents—invention authorisation (in_invnt), utility model (in_utl), and appearance design—from the years 1999 to 2017 at the prefecture-level and above from the Chinese patent announcement system (In_md), which signifies the innovation performance for these cities. (According to Chinese Patent Law, invention authorisation refers to new technical schemes for new product, new method or technology improvement. Utility model refers to a new technical solution for product shape or structure. Appearance design refers to product new appearance or pattern.) Due to the consideration of unreasonable components that may exist in the patent data, this study also refers to DMSP/OLS global luminous data (in_lt) as an alternative measure of urban innovation performance in the field of remote sensing. You et al. (2014) found that, based on US data, urban night light intensity was positively related to innovation performance with a coefficient at 0.76 [8], which means that use of this index could complement the measuring of urban innovation performance.

**Data and sources of high-speed rail.** Defined by the “Regulations for Railway Safety Management” of China, high-speed railways refer to railways with operating speeds faster than 200 km/h. Information about the time of the opening of high-speed railway lines in various cities is collected via China Railway Yearbook, the China Railway Corporation website, and the China Wikipedia on high-speed railways. Data on railway stations and operating speeds by the city are obtained from websites including 12306.com and Ctrip.com.
Data and sources of city characteristics. Data on city characteristics include total population \((pop)\), built-up area \((area)\), regional GDP \((gdp)\), general fiscal expenditure \((fsx)\), number of college students \((hmcp)\), and total foreign direct investment \((fdi)\), drawn from the “China City Statistical Yearbook”, the “China Regional Economic Statistical Yearbook,” and the “Statistical Bulletin of National Economic and Social Development.” A small amount of missing data was filled in by linear interpolation using the provincial price index from the “China Statistical Yearbook.” The GDP of the corresponding cities was deflated. The absolute value variable was logarithmised. In order to control the geographic location characteristics of each city, we collected data on geographic distance \((dst)\) of the three regional innovation centres (Beijing, Shanghai, and Shenzhen) using software called ArcGIS. After excluding samples from cities such as Lhasa with significant data missing, 263 cities in China were finally selected as research samples. The descriptive statistics of the main variables are shown in Table 1.

Table 1. Descriptive Statistics of Main Variables.

| Variable       | Treatment Group | Control Group | Overall Sample |
|----------------|-----------------|---------------|----------------|
| Obs            | Mean            | St. Dev.      | Obs            | Mean            | St. Dev.      | Obs            | Mean            | St. Dev.      |
| \(Ln(pop)\)    | 685             | 5.30          | 1.87           | 3378           | 2.47          | 1.72           | 4063           | 2.95          | 2.04           |
| \(Ln(area)\)   | 685             | 7.14          | 1.52           | 3750           | 4.38          | 1.67           | 4435           | 4.80          | 1.93           |
| \(Ln(fsx)\)    | 685             | 6.11          | 1.81           | 3595           | 3.59          | 1.88           | 4280           | 3.99          | 2.08           |
| \(Ln(fdi)\)    | 392             | 11.68         | 0.67           | 3613           | 10.93         | 0.81           | 4005           | 11.01         | 0.83           |
| \(Ln(fdx)\)    | 686             | 7.30          | 1.01           | 3692           | 7.40          | 0.94           | 4378           | 7.36          | 0.95           |
| \(Ln(gdp)\)    | 687             | 10.87         | 0.52           | 3232           | 10.02         | 0.76           | 3919           | 10.17         | 0.79           |
| \(Ln(hmcp)\)   | 682             | 4.92          | 1.11           | 3526           | 3.87          | 1.10           | 4208           | 4.04          | 1.17           |
| \(Ln(pop_d)\)  | 690             | 7.23          | 0.72           | 3474           | 7.08          | 1.16           | 4164           | 7.12          | 1.11           |
| \(Ln(fsx_sc)\) | 695             | 10.65         | 1.38           | 3258           | 8.42          | 1.94           | 3953           | 8.81          | 2.04           |
| \(Ln(area)\)   | 685             | 3.66          | 0.64           | 3712           | 3.54          | 0.21           | 4402           | 3.56          | 0.21           |
| \(Ln(fd)\)     | 678             | 10.91         | 1.52           | 3524           | 8.85          | 1.88           | 4202           | 9.19          | 1.98           |
| \(Ln(pop)\)    | 690             | 7.49          | 0.99           | 3713           | 7.32          | 0.93           | 4403           | 7.35          | 0.94           |
| \(Ln(pop_d)\)  | 684             | 7.42          | 0.86           | 3700           | 7.23          | 0.95           | 4384           | 7.26          | 0.94           |
| \(area\)       | 682             | 196.01        | 203.27         | 3703           | 83.20         | 116.18         | 4385           | 100.75        | 139.60         |

4. Results and Discussion

4.1. The Timing of Access to HSRN and Initial Stage of Urban Innovation Performance

As mentioned above, to study the impacts of access to HSRN on urban innovation performance at the initial stage, the most critical assumption is that the difference in access timing is unrelated to the difference in innovation performance among cities. If the time of policy implementation is exclusive, researchers usually use the time propensity score matching method (PSM). However, PSM is applicable for policy analysis at a single time point, whilst the multiple times of policy implementation in this study make this method inappropriate. As a suboptimal scheme, most current studies have dealt with this situation by using the year in which the most cities opened HSRNs as the exclusive time point, and then applying the DID method to analyse these data (However, this kind of method is likely to lead to a significant reduction in the number of samples. Moreover, it is not scientific enough to adopt “subjective neglect” for the samples of treatment groups that increase in the implementation time of other policies. In this regard, we choose to adopt the method of Beck et al. (2010) [18], namely, a duration model to analyse the relationship between the timing of the city’s access to the HSRN network and its prior (generally the previous year) innovation performance.

Intuitively, large cities such as Beijing, Shanghai, and Tianjin would have accessed HSRN earlier compared than others, while small cities such as Qinhuangdao and Anshan would have accessed HSRN later. However, this is not the case. A city’s initial innovation performance is irrelevant to the timing of its access to HSRN. Furthermore, we examine the relationship between the dependent variable of the number of years between 1999 and access to HSRN, and the independent variable of the
average innovative output of the city before access to HSRN, using a duration model with samples of cities operating HSRN between 1999 and 2017. The results in Table 2 show that the impacts of the initial innovation performance on the time of access to HSRM are rather limited. This result is still robust after adding per capita GDP, the proportion of the tertiary industry, foreign investment, human capital, and other urban characteristic variables. This is inconsistent with current findings of studies in HSRN literature, which mainly suggest that due to construction costs, future benefits, and the lobbying capacity of large cities, large cities are more inclined to access high-speed rail [5]. This assumption is not supported by the results of the empirical analysis in the study. In terms of the irrelevance of the relationship between access timing and initial innovation performance, HSRN is essentially a liner construction project, which is unlikely to be built in several geographically unconnected cities or to operate separately. The innovation performance of the cities the line connects is heterogeneous, which leads to insignificant differences between sample and control groups in the DID analysis. Therefore, a multi-period DID method defined by Equation (2) is appropriate to analyse the impacts of accessing HSRN on the level of urban innovation performance.

Table 2. Timing of HSRN Access and Innovation: The Duration Model.

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Ln(in_invt) | −0.05 | −0.04 | −0.03 | 0.01 | −0.01 | −0.01 | 0.01 | 0.01 | 0.01 |
| Ln(in_utl) | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| Ln(in_md) | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| βn_p | 1.80 *** (0.07) | 1.97 *** (0.07) | 1.71 *** (0.08) | 1.80 *** (0.08) | 1.94 *** (0.09) | 1.71 *** (0.07) | 1.79 *** (0.08) | 1.93 *** (0.09) |
| Controls | - | √ | √ | - | √ | √ | - | √ | √ |
| Province or region controls | - | - | √ | - | - | √ | - | √ | √ |
| obs | 180 | 180 | 180 | 180 | 180 | 180 | 180 | 180 | 180 |

Note: Robust standard errors are in parentheses, *** is a 1% significance level.

4.2. HSRN Access and Number of Urban Patents

Compared with the previous three equations, though the coefficient of HSRN Access has decreased, it is still significant, and it is still statistically the largest in the regression equation with the invention authorisation as the dependent variable (0.150), followed by utility model (0.031) and design (0.011). To further control the influence of other cities’ characteristic factors on the regression results, we added the built-up area variable (area) that controls the size of the city in Equations (3), (6), and (9). The shortest spatial distance variable (dst) of the three innovation centres in Shanghai and Shenzhen shows that the coefficient of the access variable of the HSRN is still significant and is close to the results of Equations (2), (5), and (8), which are 0.143, 0.012, and 0.010, respectively.

Three different types of patent indicators—invention authorization, utility model, and appearance design—are used to measure urban innovation performance and the impacts of access to HSRN on innovation performance. As shown in Table 3, without including control variables in models (1), (4), and (7), the result signifies that a city’s access to HSRN is significantly positively related to these three innovation measures. There are differences among the impacts of these three indicators, namely, authorisation for the largest impact (0.261), followed by utility models (0.041), and appearance design (0.037). Given that urban innovation performance is affected by its own factors, regression Equations (2), (5), and (8) include variables of the index of the number of college students (hmcp), which controls the level of human capital (hmcp); the public fiscal technology expenditure variable, which controls public innovation expenditure (fsx_sc); the proportion of services (ser), which controls the characteristics of urban industrial structure; the scale of foreign investment (fdi), which controls the openness of cities; and the regional GDP (gdp) and population (pop), which control the size of cities.
we add the variable of built-up area (area). The variable of shortest geographical distance (dst) of the three innovation centres of Beijing, Shanghai, and Shenzhen shows that the coefficient of the access variable of the HSRN is still significant and is close to the results of Equations (2), (5), and (8), which are 0.143, 0.012, and 0.010, respectively. Most of these coefficients show a quasi-U-shaped change trend that decreases at first and increases later. Both groups of coefficients show that for smaller cities (with a total population of less than 3 million and a regional GDP of fewer than 100 billion RMB), access to HSRN has a positive effect on improving its innovation performance. For large-scale cities (with a total population between 3 and 6 million and a regional GDP between 100 and 700 billion RMB), the effect is still positive, although the coefficient is smaller. For large cities (with a total population of more than 6 million and a regional GDP of more than 700 billion RMB), the overall effect of access to HSRN on innovation performance is stronger.

Compared with the previous three equations, although the coefficient of HSRN access decreases, it is still significant as the largest coefficient in the regression equation with invention authorisation on the dependent variable (0.150), followed by utility model (0.031), and appearance design (0.011). To further control the influences of other cities’ characteristic factors on the dependent variable, we add the variable of built-up area (area) to control the size of the city in Equations (3), (6), and (9). The variable of shortest geographical distance (dst) of the three innovation centres of Beijing, Shanghai, and Shenzhen shows that the coefficient of the access variable of the HSRN is still significant and is close to the results of Equations (2), (5), and (8), which are 0.143, 0.012, and 0.010, respectively.

To further distinguish the impact of HSRN access on cities of different sizes, we divide the cities into three sub-samples according to the total population (3 million and 6 million people) and regional GDP (100 billion or 700 billion RMB) in the year 2016. Taking the logarithm of the number of authorised inventions as the independent variable, under the control of distance, year, and regional fixed effects, the test is performed according to Equation (3). The results listed in Table 4 show that in the division of population, among these three subgroups, the coefficients of the variable of HSRN access variables are 0.266, 0.103, and 0.382, respectively. In division by regional GDP, the coefficients of HSRN access variables are 0.329, 0.062, and 0.303, respectively. Most of these effects are insignificant at the 10% level. Both groups of coefficients show a quasi-U-shaped change trend that decreases at first and increases later. Both grouping criteria show that for smaller cities (with a total population of less than 3 million and a regional GDP of fewer than 100 billion RMB), access to HSRN has a positive effect on improving its innovation performance. For large-scale cities (with a total population between 3 and 6 million and a regional GDP between 100 and 700 billion RMB), the effect is still positive, although the coefficient is smaller. For large cities (with a total population of more than 6 million and a regional GDP of more than 700 billion RMB), the overall effect of access to HSRN on innovation performance is stronger.

### Table 3. HSRN Access and Patent: Panel Data Estimation at City-level.

|       | Ln (Invention Authorization) | Ln (Utility Model) | Ln (Design) |
|-------|-----------------------------|--------------------|-------------|
|       | (1)                         | (2)                | (3)         | (4)        | (5)        | (6)        | (7)        | (8)        | (9)        |
| HSRN Access | 0.261 *** (0.067)            | 0.150 ** (0.063)   | 0.143 ** (0.063) | 0.041 ** (0.063) | 0.013 ** (0.059) | 0.012 * (0.060) | 0.037 ** (0.088) | 0.011 * (0.083) | 0.010 * (0.086) |
| Ln(hmcp) | 0.007                       | 0.002              | 0.029        | 0.022       | 0.058 *    | 0.074 **   |
| Ln(fsx_sc) | 0.222 *** (0.038)          | 0.196 *** (0.038)  | 0.227 *** (0.038) | 0.205 *** (0.038) | 0.245 *** (0.038) | 0.228 *** (0.038) | 0.028 * (0.016) | 0.014 (0.016) | 0.062 (0.016) |
| Ln(gdp)  | -0.028                       | 0.005              | 0.006        | -0.031 *    | -0.034 *   |
| Ln(ser)  | 0.578 ** (0.238)            | 0.558 ** (0.238)   | 0.405 ** (0.238) | 0.384 ** (0.238) | 0.125 ** (0.238) | 0.116 * (0.238) | 0.089 ** (0.234) | 0.014 (0.234) | 0.062 (0.234) |
| Ln(fdi)  | 0.039                       | 0.035              | 0.006        | 0.003       | 0.005      | 0.022     |
| Ln(pop)  | 0.045 (0.050)               | 0.036 (0.050)      | 0.036 (0.050) | 0.036 (0.050) | 0.39 (0.050) | 0.403 (0.050) | 0.40 (0.050) | 0.403 (0.050) | 0.402 (0.050) |
| Ln(area) | 5.081 *** (0.061)           | 1.160 * (1.019)    | 0.894 ** (1.110) | 6.826 *** (0.058) | 3.083 *** (0.095) | 1.512 * (0.936) | 5.939 *** (0.077) | 2.944 *** (0.119) | 2.085 *** (0.127) |
| R²      | 0.334                       | 0.473              | 0.6573       | 0.333       | 0.523      | 0.6701    | 0.248       | 0.445       | 0.5135      |
| obs     | 4063                        | 3404               | 3313         | 4435        | 3596       | 3495      | 4280        | 3505        | 3414        |
| Distance fixed effect | √                      | √                  | √            | √           | √          | √         |
| Time fixed effect  | √                        | √                  | √            | √           | √          | √         |
| Region fixed effect | √                        | √                  | √            | √           | √          | √         |

Note: Robust standard errors are in parentheses, * p < 0.1, ** p < 0.05, *** p < 0.01.
Table 4. HSRN Access and Patents with Variance in City Scale.

|                  | Population Subgroups (Unit: Ten Thousand People) | GDP Subgroups (Unit: 100 Million RMB) |
|------------------|--------------------------------------------------|---------------------------------------|
|                  | (1) <300                                          | (2) 300–600                           | (3) >600                     | (4) <1000                 | (5) 1000–7000             | (6) >7000                  |
| HSRN Access      | 0.266 *                                          | 0.103 *                               | 0.382 *                      | 0.329 **                  | 0.062 *                   | 0.303 *                   |
|                  | (0.142)                                          | (0.100)                               | (0.215)                      | (0.184)                   | (0.078)                   | (0.201)                   |
| Ln(hmcp)         | 0.045 −0.042                                     | −0.092                                | 0.052 −0.038                 | −0.187*                   | (0.080)                   |                          |
|                  | (0.060)                                          | (0.040)                               | (0.083)                      | (0.076)                   | (0.032)                   |                          |
| Ln(fsx_sc)       | 0.189 ***                                        | 0.188 ***                             | 0.153                        | 0.172 **                  | 0.194 ***                 | 0.162 **                  |
|                  | (0.070)                                          | (0.059)                               | (0.197)                      | (0.088)                   | (0.047)                   | (0.055)                   |
| Ln(ser)          | 0.043 0.817 **                                   | −1.067                                | −0.629 0.694 **              | 0.827                     |                          |                          |
|                  | (0.350)                                          | (0.378)                               | (0.844)                      | (0.480)                   | (0.302)                   | (0.731)                   |
| Ln(fdi)          | −0.056 *                                         | −0.030 −0.015                        | −0.021 −0.065 **             | −0.384 **                 |                          |                          |
|                  | (0.041)                                          | (0.033)                               | (0.085)                      | (0.040)                   | (0.032)                   | (0.104)                   |
| Ln(area)         | 0.645 ***                                        | 0.316 **                              | 1.704 **                     | 0.209 0.414 ***           | −0.116                    |                          |
|                  | (0.217)                                          | (0.142)                               | (0.459)                      | (0.216)                   | (0.119)                   | (0.259)                   |
| constant         | −0.198 −0.739 −0.367                             | 3.633 ** −0.448                       | 10.257 S *                   |                          |                          |                          |
|                  | (1.823)                                          | (1.482)                               | (4.294)                      | (1.959)                   | (1.264)                   | (4.384)                   |
| R²               | 0.769 0.827 0.873                                | 0.768 0.831                           | 0.976                        |                          |                          |                          |
| Obs              | 1021 1438 878                                    | 807 2202                              | 328                          |                          |                          |                          |

Note: Robust standard errors are in parentheses, * p < 0.1, ** p < 0.05, *** p < 0.01.

Fiscal technology expenditure (fsx_sc), the proportion of service industry (ser), the scale of foreign direct investment (fdi), and the size of urban built-up areas (area) have a significant impact on urban innovation performance. Among them, the influences of fiscal technology expenditure variable are the most prominent. In the regression Equations (3), (6), and (9), they are 0.196, 0.205, and 0.228, respectively, with an average value of 0.210, both significant at the 1% level. The sub-sample regression in Table 4 is still robust. This also confirms that public financial input plays an important role in promoting the growth of innovation performance, especially related to the number of patents. However, the coefficient of the human capital variable (hmcp) measured by the number of university students per 10,000 people is not significant, which may be related to the difference in degrees of university graduates conversing into human capital.

4.3. Robustness Test

Drawing on results in the study of geographic remote sensing [8], DMSP / OLS global luminous data was adopted as a substitute for measuring the level of urban innovation performance in the robustness analysis. According to the results at city-level analysis, the Pearson correlation coefficients are 0.3707, 0.503, 0.3745 respectively, all of which are significant at 1%. Due to the uniqueness of DMSP/OLS global luminous data, and factors such as sensor ageing, atmospheric absorption and scattering, and solar altitude angle, which make the data not directly applicable to economic and social analysis, the original data was dealt with using the invariant area method. The total DN of the luminous data of each prefecture-level city was calculated using the grid statistics module of ArcGIS software to substitute the variable of urban innovation performance. The results listed in Table 5 show that in all sample tests, the coefficient of HSNR access is 0.295 with its significance level at 1%, indicating a significant positive effect on overall urban innovation performance. This result is robust after urban characteristics such as human capital, fiscal technology expenditure, and industrial structure are controlled. In addition, the results of sub-sample regression using total population (POP) and gross domestic product (GDP) as grouping indicators show that the coefficient of HSRN access still presents a quasi-U-shaped change trend that decreases first and increases later. However, compared with the results in Table 4, in the robustness test, the value of coefficients of HSRN access in the two groups is closer. This result remains consistent when the grouping standards are substituted (such as
when the total population grouping standard is changed from 4 million to 7 million and the regional GDP grouping standard is changed from 200 billion to 800 billion RMB).

### Table 5. HSRN Access and Nighttime Light DN Value: Overall and Sub-results.

| Overall Population Subgroups (Unit: 10,000 People) | GDP Subgroups (Unit: 100 Million RMB) |
|---------------------------------------------------|----------------------------------------|
| | | | 1 | 2 | 3 | 4 | 5 | 6 |
| HSRN Access | | | 0.295 *** | 0.356 *** | 0.247 ** | 0.189 *** | −0.045 ** | 0.318 ** |
| (0.011) | (0.020) | (0.017) | (0.025) | (0.036) | (0.014) | (0.016) |
| Ln(hmcp) | | | 0.006 * | 0.012 | 0.005 | 0.023 | 0.016 | 0.002 | 0.001 |
| (0.003) | (0.008) | (0.006) | (0.012) | (0.014) | (0.005) | (0.009) |
| Ln(fes_sc) | | | 0.034 *** | 0.036 *** | 0.033 *** | 0.003 ** | 0.032 ** | 0.038 *** | 0.044 ** |
| (0.006) | (0.010) | (0.008) | (0.027) | (0.013) | (0.008) | (0.017) |
| Ln(sen) | | | −0.098 ** | 0.005 | −0.180 *** | 0.132 | 0.024 | −0.106 ** | −0.156 * |
| (0.041) | (0.071) | (0.053) | (0.117) | (0.117) | (0.049) | (0.106) |
| Ln(fdii) | | | 0.012 *** | 0.012 ** | 0.001 | 0.031 ** | 0.016 * | 0.008 * | 0.074 *** |
| (0.005) | (0.007) | (0.007) | (0.009) | (0.009) | (0.006) | (0.022) |
| Ln(area) | | | 0.071 *** | 0.186 *** | 0.028 * | −0.219 ** | 0.126 ** | 0.065 ** | 0.083 |
| (0.024) | (0.057) | (0.022) | (0.079) | (0.021) | (0.033) | (0.075) |
| constant | | | 10.913 *** | 9.734 *** | 11.491 *** | 12.300 *** | 9.689 *** | 11.000 *** | 11.214 *** |
| (0.228) | (0.599) | (0.204) | (0.272) | (0.570) | (0.309) | (0.945) |
| $R^2$ | | | 0.825 | 0.822 | 0.835 | 0.932 | 0.812 | 0.835 | 0.928 |
| Obs | | | 3337 | 1021 | 1438 | 878 | 807 | 2202 | 328 |

Note: Robust standard errors are in parentheses, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

### 5. Analysis of Interaction Effects

#### 5.1. Interaction Effects between HSRN Access and Urban Specialisation

First, accessing HSRN strengthens the effects of urban specialisation at the level of urban innovation performance. To test this mechanism, cross-sectional data was further collected. We consider the difference between the number of high-speed railway stations (stat) and the proportion of the urban population employed in the information technology industry (infem) between 2003 and 2007. We subtract this value from the 2003 value to reflect the incremental change of the indicator. The number of urban high-speed rail stations signifies the strength of the city’s access to the national HSRN, while the proportion of the urban population employed in the information technology industry signifies the degree of specialisation of the urban knowledge-intensive industry.

Taking the difference between the number of invention patents as the main explanatory variable, and the difference between the level of human capital and fiscal technology expenditure as control variables describing urban characteristics, and the interaction term of these explanatory variables, we established a model to test the interaction effects. To differentiate from the original model, we add “′” for variables of difference. The regression model is as follows:

$$ innovation'_i = \alpha + \beta_1stat'_i + \beta_2infem'_i + \beta_3stat'_i \cdot infem'_i + \delta X'_i + \epsilon_i $$  \hspace{1cm} (3)

Table 6 shows that the coefficient of the interaction term (stat′-infem) in the group of the full sample is 0.163, significant at the 5% level. This suggests that the establishment of high-speed rail stations and the increasing number of facilities increases the proportion of people employed in the information technology industry in these cities. This result verifies the mechanism, as the establishment of high-speed rail stations promotes urban innovation by strengthening the specialisation of the city’s information technology industry. In the sub-sample group, the coefficients of interaction terms in small cities (total population less than 3 million and regional GDP less than 100 billion RMB) are 1.381 and 1.838 respectively, with the significance level at 5%. However, the coefficients of the variables of infem
are −4.597 and −3.105, respectively, indicating that the establishment and number of high-speed rail stations are generally positively related to the innovation performance of cities, although negatively related to the degree of specialisation of the information technology industry in small cities. In the group of medium-sized cities, the interaction term coefficients are −0.110 and −0.089, respectively, indicating that the establishment of high-speed rail stations and an increase in the number of high-speed rail stations are not related to the improvement of the degree of specialisation of the information technology industry. In the group of large cities, the interaction term coefficients are 0.069 and 0.044, respectively, indicating that the establishment of high-speed rail stations and the increase in number are significantly related to the improvement of the degree of specialisation in the information technology industry and thus enhance their level of innovation.

Table 6. The Interaction Effect of HSRN Station and City Specialisation.

|          | Overall                  | Population Subgroups     | GDP Subgroups               |
|----------|--------------------------|--------------------------|-----------------------------|
|          | (Unit: 10,000 People)    | (Unit: 100 Million RMB)  |                             |
| stat     | 0.032 **                 | 0.375 **                 | 0.039 *                    |
|          | (0.037)                  | (0.159)                  | (0.072)                    |
| infem    | 1.232 ***                | −4.597 ***               | −0.465 **                  |
|          | (0.471)                  | (1.552)                  | (1.080)                    |
| stat-infem| 0.163 **                | 1.381 **                 | −0.110 **                  |
|          | (0.086)                  | (0.697)                  | (0.196)                    |
| Ln(hmcp) | −0.067                   | −0.209                   | 0.010                      |
|          | (0.105)                  | (0.189)                  | (0.203)                    |
| Ln(fx_sc)| 0.248 ***                | 0.411 ***                | 0.433 ***                  |
|          | (0.066)                  | (0.137)                  | (0.137)                    |
| Ln(ser)  | −0.292 *                 | −0.960 **                | 0.372 *                    |
|          | (0.218)                  | (0.452)                  | (0.647)                    |
| Ln(fdi)  | −0.074 **                | 0.056                    | −0.097 *                   |
|          | (0.041)                  | (0.126)                  | (0.068)                    |
| constant | 2.742 ***                | 1.106                    | 2.007 ***                  |
|          | (0.299)                  | (0.748)                  | (0.654)                    |
| R²       | 0.144                    | 0.378                    | 0.218                      | 0.113                      | 0.477 | 0.164 | 0.634 |

Note: Robust standard errors are in parentheses, * p < 0.1, ** p < 0.05, *** p < 0.01.

5.2. Interaction Effects between HSRN Access and Urban Population Mobility

The second mechanism for HSRN access to promote urban innovation is that it facilitates inter-city population mobility. Data on railway passenger traffic in cities from the years 2003 to 2017 were collected from the “China City Statistical Yearbook.” A differential variable was created: the proportion of urban railway passenger traffic to total passenger traffic. We further establish a model to examine the effects of the number of high-speed rail stations, population mobility, and urban innovation performance as follows:

\[
\text{innovation}_i = \alpha + \beta_1 \text{stat}_i + \beta_2 \text{pass}_i + \beta_3 \text{stat}_i \cdot \text{pass}_i + \delta X_i + \varepsilon_i
\]  

(4)

Table 7 shows that in the group with the full sample, the coefficient of the interaction term (stat pass) is 0.101 with a significance level at 10%. This result verifies the mechanism of the establishment and increase of high-speed rail stations, namely, by increasing the proportion of the railway travel population; it improves the innovation performance of the city. In the sub-sample group, the coefficients of the interaction term in small cities are negative, at −0.012 and −0.026, respectively. The coefficient of medium cities is positive, at 0.021 and 0.019, respectively. The coefficient of large cities is positive, at 0.103 and 0.102, respectively. The establishment and increase in the number of high-speed rail
This signifies that access to HSRN has both agglomeration and diffusion effects of urban characteristics. Second, there are configurations in the impacts of access to HRSN on variables of patents, illumination, and high-speed rail for 263 cities within China. Access to HSRN has a significant impact on the overall level of urban innovation performance. Our findings are robust to alternative invention licenses, utility models, designs, and nighttime light data, and adding control variables of urban characteristics. Second, there are configurations in the impacts of access to HRSN on the innovation performance of cities of different sizes. In small and large cities, the positive effects of access to HSRN on innovation performance are stronger compared to the effects of medium-sized cities. There is a quasi-U-shaped relationship among cities that decreases first and increases later. This signifies that access to HSRN has both agglomeration and diffusion effects on the geographical distribution of innovation activities in the country. Compared with diffusion effects, the agglomeration effects are even stronger. Third, access to HSRN facilitates the agglomeration of knowledge-intensive industries such as information technology in large cities. It also speeds up population mobility among cities, and thus generally improves the level of urban innovation performance.

Accordingly, this study carries three policy implications. First, from the perspective of promoting national innovation-driven development, the government needs to further support increasing high-speed rail construction in the future, especially in combination with urban agglomerations and metropolitan areas and nearby regional centres and node cities. The government should speed up the process of HSRN integration, further strengthen the transport effects of the HSRN, and accelerate the optimisation of industrial space layout and population mobility, which enable the optimal allocation of innovation elements geographically. Second, it is necessary to optimise the layout of high-speed rail lines and reasonably arrange high-speed rail lines and shifts, taking into consideration the high cost of living in large cities. It is also important to facilitate the creative population’s capacity to separate their city of occupation and residence across large and hinterland cities. Third, in the process of promoting the aggregation of innovation elements by constructing HSRN, more attention should be given to innovation development in small and medium-sized cities. The cultivation of unique innovation.

6. Conclusions and Policy Implications

This study reveals that HSRN access affects urban innovation performance, using the explanatory variables of patents, illumination, and high-speed rail for 263 cities within China. Access to HSRN has a significant impact on the overall level of urban innovation performance. Our findings are robust to alternative invention licenses, utility models, designs, and nighttime light data, and adding control variables of urban characteristics. Second, there are configurations in the impacts of access to HRSN on the innovation performance of cities of different sizes. In small and large cities, the positive effects of access to HSRN on innovation performance are stronger compared to the effects of medium-sized cities. There is a quasi-U-shaped relationship among cities that decreases first and increases later. This signifies that access to HSRN has both agglomeration and diffusion effects on the geographical distribution of innovation activities in the country. Compared with diffusion effects, the agglomeration effects are even stronger. Third, access to HSRN facilitates the agglomeration of knowledge-intensive industries such as information technology in large cities. It also speeds up population mobility among cities, and thus generally improves the level of urban innovation performance.

Accordingly, this study carries three policy implications. First, from the perspective of promoting national innovation-driven development, the government needs to further support increasing high-speed rail construction in the future, especially in combination with urban agglomerations and metropolitan areas and nearby regional centres and node cities. The government should speed up the process of HSRN integration, further strengthen the transport effects of the HSRN, and accelerate the optimisation of industrial space layout and population mobility, which enable the optimal allocation of innovation elements geographically. Second, it is necessary to optimise the layout of high-speed rail lines and reasonably arrange high-speed rail lines and shifts, taking into consideration the high cost of living in large cities. It is also important to facilitate the creative population’s capacity to separate their city of occupation and residence across large and hinterland cities. Third, in the process of promoting the aggregation of innovation elements by constructing HSRN, more attention should be given to innovation development in small and medium-sized cities. The cultivation of unique innovation.

Table 7. The Interaction Effect of HSRN Station and Population Mobility.

| Overall | Population Subgroups (Unit: 10,000 People) | GDP Subgroups (Unit: 100 Million RMB) |
|---------|------------------------------------------|--------------------------------------|
| ALL     | <300          | 300–600           | >600        | <1000     | 1000–700 | >700      |
| stat    | 0.003 *      | 0.185 *          | −0.039     | −0.023 *  | 0.043 *  | −0.103 *  | −0.0218  |
| pass    | 0.014 *      | −0.021 *         | −0.014     | 0.041 *   | −0.017 * | −0.017 *  | 0.031 *  |
| stat-pass| 0.101 *     | −0.012 *         | 0.021 **   | 0.103 *   | −0.026 * | 0.019 **  | 0.102 *  |
| Ln(hmcp)| −0.074       | −0.108 *         | 0.119      | 0.070     | −0.329  | −0.062    | 0.060    |
| Ln(fix_sc)| 0.230 ***   | 0.155 *          | 0.378 ***  | 0.146 **  | 0.566 ** | 0.325 *** | 0.507 *  |
| Ln(se)  | −0.024       | −0.331           | 0.132 *    | 0.447     | −1.546 **| 0.243 *   | 2.123 *  |
| Ln(di)  | −0.042 *     | 0.066            | −0.032 *   | −0.063 *  | 0.023   | −0.038    | 0.013    |
| Cons.   | 2.890 ***    | 2.428 ***        | 2.060 ***  | 3.139 *** | 1.731   | 2.371 *** | 1.196    |
| R2     | 0.122        | 0.159            | 0.299      | 0.160     | 0.438   | 0.233     | 0.677    |

Note: Robust standard errors are in parentheses, * p < 0.1, ** p < 0.05, *** p < 0.01.
performance in small and medium-sized cities should be strengthened to prevent the phenomenon of the hollowing out of these cities.

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