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Transportation infrastructure and good health in urban China

Tao Bu[1] & Daisheng Tang[2]✉

The process of rapid urbanization has brought forth severe health problems for the urban populations. Examining the health effect from the perspective of transportation systems, rather than solely focusing on the accessibility and utilization of healthcare services, is beneficial in enhancing the well-being of urban populations in China. By incorporating elements such as transportation and health investment, labor productivity, economic growth, and time efficiency into the endogenous growth framework, this article establishes a multiple equilibrium model between transportation infrastructure and laborers' health capital, which explains how transportation infrastructure affects individual health status through income levels, healthcare services, health literacy, and time allocation. Furthermore, using ordinary least-squares regression under the data of China Health and Nutrition Survey and the China City Statistical Yearbook from 2000 to 2015, the empirical study revealed that laborers living in places with limited medical resources and county-level city experienced a greater improvement in their health status when these places got significant road improvement between cities but not within the city. The mechanism is that intercity roads can help foster economic growth and provide more provision of healthcare services, as well as boost individual incomes and health investment. It can also improve health literacy and time allocation efficiency. The net effect of health outcomes from transportation infrastructure depends on all the influencing factors. Therefore, appropriate policy should encourage multi-level medical cooperation across cities and hospitals to facilitate patients to access to optimal healthcare.

[1] Faculty of Education, Beijing Normal University, Beijing, China. [2] School of Economics and Management, Beijing Jiaotong University, Beijing, China.
✉email: daisheng_tang@163.com

Introduction

In the 21st century, urbanization is a major trend, with over 55% of the population living in the cities[1]. The city with the quickest rate of urbanization is mostly in developing nations, especially in China. Since 1978, China has experienced a dramatic rise in urbanization, with the urbanization rate soaring from 17.9% to 65.22% in 2022[2], surpassing the global average of 54.5% (Ouyang et al. 2021). With the urban population increasing rapidly, the investment in medical resources often falls behind, leading to overcrowding and making it more expensive to receive medical services (Dupas, 2011). It needs to be noted that China has enough medical resources to cope with the growing urban population, but most high-quality medical resources are concentrated in large cities, which seriously hinders the use efficiency of medical resources, and it is difficult for residents in small city and/or county to obtain high-quality medical resources.

In China, hospitals are usually classified into primary, secondary, and tertiary hospitals[3], and the tertiary hospitals are usually allocated in large cities. However, approximately half of the new urban populations, who have a rural household registration and have moved from the countryside to live in the city[4], live in county-level city[5], the rapid concentration of population in small cities and the high concentration of high-quality medical resources in large cities increase the concern of health inequality under rapid urbanization. China has the resources to address this issue, while the poor transportation infrastructure impedes the efficient use of healthcare services in most disadvantaged areas (Aggarwal, 2021; Tao et al. 2018; Xiao et al. 2021; Chen et al. 2024). The health problems brought by rapid urbanization need to be paid more attention. What can be done to address the health problems of urban populations at a low cost?

People with serious diseases often bypass primary medical centers and directly go to advanced tertiary hospitals, which are mostly located in large cities (Liu et al. 2019). As such, a reliable transportation infrastructure is essential to guarantee that patients in need of medical attention can reach the right hospital quickly. Studies have demonstrated that inadequate transportation infrastructure can result in inadequate healthcare utilization, such as missed appointments, improper medication utilization, and delayed medical interventions (Syed et al. 2013; Surendran et al. 2024). Moreover, people's medical treatment-seeking behavior is not limited to their living area, and they can seek healthcare in remote cities outside their area of residence (Xiao et al. 2021). Spatial isolation and transport inequity may lead to a spiral of poverty and inadequate use of healthcare services (Zimmer, 2008; Kukla et al. 2017; Haj-Younes et al. 2022) because poor access to infrastructure and public transportation affects the accessibility and utilization of healthcare services (Lyeo et al. 2024). Facing rapid urbanization and unequal distribution of medical resources, it is crucial to investigate whether transportation infrastructure can improve the health status of urban populations, and what type of transportation changes their medical treatment-seeking behavior? Such findings will help China to reach its goal of universal health coverage through the external benefits of transportation infrastructure.

To answer the above questions, this paper first establishes a theoretical framework to analyze the impact of transportation infrastructure on people's health status, which illustrates how transportation infrastructure affects the government's public investment and laborers' decisions on health investment and time allocation, as well as the result of laborers' health outcome through the mechanism of wage, time allocation, health literacy, and public healthcare services. Then, empirical data from the China Health and Nutrition Survey (CHNS)[6] from 2000 to 2015 are used to examine the health effects of transportation infrastructure on urban populations. Considering that health behavior involves local medical treatment and long-distance medical treatment, this study further focuses on the impact of different types of transportation infrastructure on individual health, including intra-city and inter-city transportation. Inter-city transportation means people want to get high-quality healthcare services in a large city through long-distance medical treatment. This study finds that only inter-city transportation has a significant impact on individual health status through the mechanism of providing healthcare services, boosting individual incomes and health investment, and improving health literacy and time allocation efficiency. This study provides the new findings that the impact of transportation infrastructure on individual health status is a result of multidimensional factors, not just of improved access to healthcare services. This provides profound theoretical and empirical evidence that enables us to gain a better understanding of transportation's effect on individual health capital from the novel perspectives of endogenous economic growth, rather than exogenous improvements in access to healthcare and health investment.

This study rigorously examines the optimal allocation of public expenditures between health and transportation, while simultaneously analyzing the efficient distribution of transportation resources across working hours, leisure time, and health investments. To our knowledge, this represents the first comprehensive analysis of the complementary relationship between transportation infrastructure and healthcare services, incorporating the optimization of government spending between these two sectors within a balanced growth of economics. A more theoretically sound approach treats individual health as an endogenous factor enhancing labor productivity, rather than modeling it as an exogenous production input. This specification better reflects how laborers' effectiveness influences subsequent public and private health investments. The incorporation of public healthcare services into household utility functions directly affects welfare outcomes. Consequently, the health-transportation nexus depends on multiple interdependent factors, including production technologies, healthcare service supply parameters, and household preferences across expenditure categories and time allocation, extending beyond mere healthcare utilization patterns.

The primary theoretical contribution lies in developing an endogenous growth framework that explicitly incorporates the dynamic relationship between transportation infrastructure development and labor health outcomes. Under the endogenous growth framework, we established a long-term equilibrium model, which considers government spending on both transportation and health expenditure as well as laborers' time allocation among working, child-rearing, commuting, and leisure, to examine how changes in transportation investment can affect laborers' health level. Our research also contributes to the literature by providing the finding that the effect of transportation infrastructure on individual health is the result of multiple factors in urban China. As such, we integrate the mechanism of providing healthcare services, boosting individual incomes and health investment, and improving health literacy and time allocation efficiency into the theoretical analytical framework, to illustrate how transportation infrastructure affects urban health, which not only considers the utilization of preventative healthcare services but also considers the perspective of government strategy and laborer' health behavior. Finally, our research additionally examined the health treatment-seeking behaviors through different roads of transportation, which revealed that the improvement of roads between cities has led to medical substitution behavior from local primary hospitals to remote tertiary hospitals.

The rest of this article is organized as follows. Section "Literature review" presents the literature review and contribution.

Section "Background" presents the background of China's transportation infrastructure construction plan and the health status of urban population. Section "Theoretical framework" provides a theoretical conception for understanding how transportation infrastructure influences the health status of laborer. Section "Data and identification strategy" outlines the data and identification strategies. Section "Results" summarizes the main findings from the empirical testing. Section "Potential mechanism" examines the mechanism. Lastly, section "Conclusion" summarizes the findings and presents our conclusions.

Literature review

Previous literature was more focused on the relationship between transportation and the economy (Banerjee et al. 2020; Magazzino and Mele, 2021; Jin et al. 2024), as well as the impact of transportation infrastructure on the accessibility of healthcare services (Liu et al. 2021; Bu et al. 2022). Banerjee and Sachdeva (2015) find that the provision of roads in India increases the use of preventive healthcare, Aggarwal (2021) further identifies that road construction led to more institutional antenatal visits and deliveries, which translated into better medical care and vaccination coverage. Under the viewpoint of improving the use of preventive healthcare, Chen et al. (2022) and Bu et al. (2025) further evidenced that transportation infrastructure can improve health and alleviate health inequality. However, these ignore the endogenous relationship between investments in transportation, health, and economic growth, economic level is endogenously associated with transportation investment and health investment, as well as the result of individual healthcare utilization and health status. Our study proposes that optimal investment in transportation should be included in the endogenous growth model, rather than just focusing on the effects of transportation infrastructure on health outcomes because more investment in transportation needs to be offset by other types of investments, which may have a negative impact on economic growth and subsequent investment in health.

This existing literature does not adequately examine the trade-off between health and transportation investment when exploring government spending strategy in an endogenous growth framework. From the perspective of healthcare services, much of the existing literature fails to adequately elucidate how such services influence the macroeconomy by enhancing laborers' health and, consequently, their productivity. Instead, many studies treat healthcare as a consumer good exogenously supplied by the government (Barro, 1990). This approach often adopts a dichotomous view of public expenditure, assuming that health-related spending aimed at improving utility has no impact on production, while productive expenditures (such as transportation infrastructure) do not contribute to service efficiency or productivity gains, as they are tied to exogenous government spending. However, government investments in both healthcare services and transportation infrastructure can enhance economic efficiency and workforce productivity. Thus, it is crucial to examine the relationship between transportation and health within an endogenous growth framework. In order to improve health capital without worsening economic growth, it is more urgent to explore the trade-off of government decisions between transportation and health investment.

From the theoretical correlation between transportation and health, Agénor and Agénor (2014) created an overlapping generations (OLG) model under the endogenous growth framework to examine how infrastructure affects women's decisions about their time allocation between work, child-rearing, self-health, and housework, as well as how these allocations affect their education and health outcomes. It also examined whether the increased infrastructure from the government can shift the economy to a high-growth equilibrium crucially depending on women's time allocation. These provide a useful reference value for us to construct the equilibrium model between China's transportation infrastructure and health, but they still ignore the optimized transportation infrastructure for individual working time and commuting time. The change in working time between work and leisure may produce significant substitution effects. Time efficiency and transport efficiency brought by the improvement of transportation infrastructure will influence the working time of laborers (Redding and Turner, 2015), thus influencing their leisure preferences and health investment. Additionally, the saved time (improved by time efficiency due to the improved transportation infrastructure) can be used for other activities, thus further influencing the health investment strategy (Klimaviciute, 2024). Meanwhile, improved access to a transportation infrastructure increases people's communication with other cities, which facilitates the dissemination of health information and the reallocation of medical resources (Banerjee and Sachdeva, 2015). Our study argues that the optimal investment decision of transportation infrastructure and health capital should be incorporated into the endogenous economic model, rather than directly evaluate the impact of transportation infrastructure on the health of urban populations.

Grossman's (1972) health demand model suggests that higher wage rates increase the opportunity cost of lost working time, thereby raising the demand for health. The health demand model indicates that the rising cost of healthcare services reduces the utilization of healthcare services by customers, but the model neglects the impact of transportation infrastructure on healthcare accessibility and individual income. Considering the endogenous relationship between transportation infrastructure and health capital, how to incorporate transportation infrastructure and health capital into the analytical framework is particularly important. Within the constraints of time and financial capital in Grossman's health demand model, this study argues that transportation infrastructure improvements reshape laborers' time allocation, thereby influencing individual investment decisions, including income generation, working hours, health investment, child-rearing, education, and leisure. There would be a complex trade-off between government transportation and health investment as well as individual working and leisure time, for the result of health capital. On the one hand, improved transportation infrastructure enhances regional economic growth and individual income (Li et al. 2023), thereby stimulating both public and private health investment. At the same time, the marginal utility of wages endogenously shapes the opportunity cost of time allocation (Becker, 1965), rising wages introduce a trade-off between income and leisure, where increased leisure and working time exert opposing effects on health capital. Consequently, our analytical framework must account for the endogenous concerns between wages, working time, and health investment when transportation infrastructure improves time efficiency.

Regarding the influencing mechanism of health improvement from transportation, previous research has consistently demonstrated that travel time and travel cost constitute significant barriers to formal healthcare utilization (Choi et al. 2019; Aggarwal, 2021). However, transportation infrastructure development contributes to urban health improvements through the accessibility of healthcare services, but also better their health status through other channels (Herberholz and Phuntsho, 2021). First, access to healthcare services is hampered by high travel costs and lengthy travel distances, while an increased supply of healthcare services boosts the use of them (Banerjee et al. 2010; Surendran et al. 2024). Using the ordinary least-squares (OLS) method, Banerjee et al. found that access to transportation

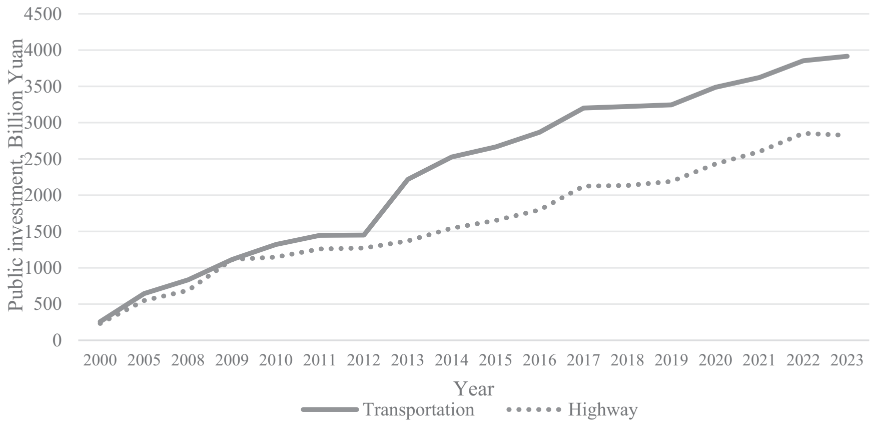

Fig. 1 Transportation infrastructure investment in China.

infrastructure can promote economic growth in China, thus ensuring government financial support for investment in local healthcare services (Li et al. 2023). Second, financial barriers significantly constrain healthcare access for low-income populations (Meredith et al. 2013). Improved transportation infrastructure can mitigate these disparities by reducing both geographical isolation and associated transportation costs, thus increasing household income and subsequent more consumption on health and education (Aggarwal, 2018; Asher and Novosad, 2020; Banerjee et al. 2020). Third, health literacy usually influences the health management strategy, so geographically isolated regions and low-income households often face informational barriers regarding preventive healthcare and the returns on health investments. This challenge is particularly acute in developing countries with limited internet access, where enhanced transportation infrastructure facilitates population mobility and thereby improves the dissemination of health information and government-led health initiatives (Agénor, 2015). Moreover, transportation infrastructure improvements critically influence laborers' time allocation. In areas with underdeveloped infrastructure, individuals typically devote excessive time to commuting or accessing healthcare facilities, leaving limited time for other activities. Efficient transportation systems optimize time use, enabling reallocation toward productive work, child-rearing, or health maintenance. Furthermore, by affecting wage levels and working hours, transportation infrastructure indirectly shapes the trade-offs between leisure, healthcare utilization, and labor productivity (Jara-Diaz, 2020). The concern of health improvement from transportation cannot be viewed through a single perspective of improved accessibility, this study proposes that the net effect of transportation infrastructure on the health of laborers is the comprehensive result of all these factors.

Background

Roads program. The transportation infrastructure is composed of both inter-city at the prefecture level and intra-city at the community level. The intra-city transportation infrastructure mainly connects different communities and suburbs of the city, which usually belong to district units, the inter-city transportation infrastructure mainly connects the prefecture-level city and above, including highways and railways. Considering that the location of medical treatment may be in the local area or outside, this study focuses on two types of transportation, inter-city at prefecture level and intra-city at community level.

China's transportation infrastructure has undergone a remarkable transformation since the economic reforms launched in 1978. Prior to these reforms, the nation's transport networks were severely underdeveloped, characterized by limited connectivity and poor-quality infrastructure. The subsequent decades have witnessed unprecedented investment and modernization across all transportation modes, fundamentally reshaping China's economic geography and mobility. The total mileage of national transportation routes was 1.235 million kilometers, which included 52,000 km of railways and 890,000 km of highway, and the total social investment of fixed assets in the transportation field was only 6.36 billion yuan. However, with the reform and opening up, a new era of economic and social development began in China, and transportation experienced a period of rapid growth. In 1988, the Shanghai–Jiading expressway was opened, marking the first expressway. In 2008, the first high-speed railway (HSR) was constructed, with a speed of 350 km/h, reducing the large travel time spent between cities. Five years later, the construction of the Motuo Highway in Tibet implies China has paved road in every county. In 2019, the Chinese government implemented the strategy of constructing a strong transportation infrastructure, aiming to form a multi-level rapid transportation infrastructure with rail transit and highways.

Up to 2023, China had the highest mileage of highways in the world, amounting to 5.437 million kilometers, with a highway density of 56.03 km 100 square kilometers. The coverage rate of highways for the city with a population of over 200,000 was over 98%. From Fig. 1, it can be seen that China's transportation investment has continued to increase, it is worth noting that the improved transportation infrastructure can help to enhance regional economic level and long-distance medical treatment-seeking behavior, providing evidence to further investigate the effect of improved transportation infrastructure within and between cities on the health of urban populations.

Population health. Over the four decades following China's economic reforms, the nation achieved remarkable gains in population health, with average life expectancy increasing by nearly 10 years, from 68 years in 1978 to 78.6 years in 2023 (shown in Fig. 2). Furthermore, Fig. 2 shows that the maternal mortality ratio plummeted from 1500 per 100,000 live births in 1949 to 15.1 per 100,000 in 2023, while the infant mortality rate dropped from 200‰ to 4.5‰ during the same period. These remarkable improvements have brought China's key health indicators to levels comparable with many developed nations (Qiao et al. 2021).

In terms of medical resources between 1980 and 2023, The density of licensed physicians increased from 1.17 to 3.4 per 1000 population, while registered nurses grew from 0.47 to 4.00 per 1000 population between the reference years. Hospital bed capacity similarly expanded from 2.85 to 7.23 per 1000 population (National Health Commission, 2023)[7]. These

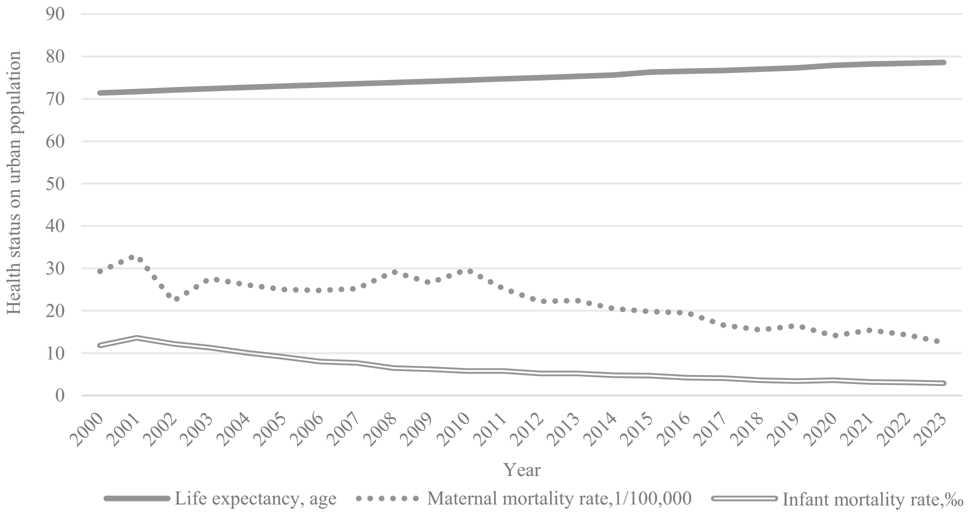

Fig. 2 The health status of urban populations in China.

developments reflect significant improvements in the availability of public medical resources. However, these achievements coincide with emerging public health challenges. According to the China Report on Nutrition and Chronic Diseases in 2019, the prevalence of overweight and obesity among adults (≥18 years) reached 34.3% and 16.4%, respectively. Concerning trends that are also evident among younger populations, 11.1% of adolescents (6–17 years) were overweight and 7.9% obese, while 6.8% and 3.6% of children under 6 years fell into these categories, respectively. Furthermore, the report indicates high prevalence rates of hypertension (27.5%), diabetes (11.9%), and hypercholesterolemia (8.2%) among adults, with all metrics demonstrating an upward trajectory compared to 2015 baseline data (Pan et al. 2021).

The 7th population census in 2020 revealed that China's total population is about 1.41 billion, of which 902 million are urban populations, accounting for 63.89%. However, the urbanization rate of China's registered urban population is 45.4%, meaning there are 376 million rural population who are not living in their household registration areas, in most of these migrants live in county-level cities. Nevertheless, rapid urbanization has resulted in a series of new issues in terms of improving health. The disparity between the inadequate supply of healthcare services and the increasing demand is still evident, and health disparities can be seen in the city, particularly among migrants. According to the China Medical and Health Statistical Yearbook (as indicated in Appendix T1), the occupancy rate of beds in tertiary hospitals was 85.3%, in secondary hospitals was 71.1%, and in primary hospitals was 52.2%, it reveals that patients tend to access to tertiary hospitals. Additionally, the average daily outpatient service treated by doctors was higher in tertiary hospitals, followed by secondary and then primary hospitals. This is largely because individuals tend to seek medical treatment from advanced medical institutions, due to their better facilities and higher quality of doctors (Liu et al. 2018). However, high-quality hospitals are mainly distributed in big cities, data shows that the top 100 hospitals in China are mostly located in provincial capitals[8], which makes it difficult for residents living in county-level city to access timely and appropriate medical treatment for serious diseases (Varkevisser et al. 2012).

To address healthcare disparities, China has implemented various policies to promote equitable access to medical services. While national health investments have increased substantially, uniformly distributing medical resources across county-level and prefecture-level cities remains impractical due to significant population density variations, such uniform allocation would fail to maximize social welfare. A more effective approach involves prioritizing equal transportation infrastructure development in remote areas with limited medical resources, this strategy not only reduces health disparities but also enhances the utilization efficiency of existing medical facilities in larger cities, which enables patients from remote regions to access advanced medical facilities in urban centers through improved transportation networks.

Theoretical framework

This study establishes an overlapping generations (OLG) model within an endogenous growth framework to analyze how transportation infrastructure influences individuals' time allocation across five key activities commuting, work, health investment, child-rearing, and household work. The model examines how these time allocations subsequently impact both income levels and health outcomes. By incorporating critical factors including public transportation, healthcare expenditures, income dynamics, and health preferences, we establish a long-run equilibrium framework that specifically investigates the relationship between urban transportation improvements and workers' health outcomes. Furthermore, the model enables us to identify the precise mechanisms through which infrastructure investments affect labor welfare by analyzing the interactions among key parameters.

In this model, it is assumed that goods can either be consumed or invested. The government levies a tax on produced goods and utilizes this tax revenue to fund transportation infrastructure and healthcare services. Within the endogenous growth framework, laborers produce and sell a single good, which can be consumed during the production period or saved to generate capital for the subsequent period. The model is involved in a life cycle, including three stages of childhood, adulthood, and retirement, thus forming an OLG model. During childhood, individuals rely on their parents for consumer goods and healthcare services and do not engage in productive activities. In adulthood, individuals supply one unit of labor, with wages being the sole source of income to finance consumption across all stages. Savings are held in the form of private physical capital. Each household has n children, thus incurring costs associated with maintaining their health, including time spent on parental care and medical expenses for healthcare services. The health status of children is influenced by the effective time parents allocate to child-rearing, access to healthcare facilities, and the health status of the parents. Transportation infrastructure impacts the efficiency of time allocation for child-rearing, so the health status of adults is determined by the effective time spent on health investment and their childhood health status. Poor health in childhood significantly deteriorates adult health, reflecting a "state dependence" characteristic (Agénor, 2017).

The economic framework encompasses laborers, firms, and a perpetual government. Firms utilize labor, private capital, and public capital to generate goods, with laborers' health and productivity exerting significant externalities on transportation infrastructure. The government, funded by taxes on adult wages, invests in transportation, public health, and other non-productive services, offering these services at no cost. It operates on a balanced budget, with no borrowing or deficits, and there are no intergenerational transfers or debts, ensuring all markets are clear.

Households. Suppose parents during a given period $t+1$ have n_{t+1} children, and raising a child incurs two primary costs. Firstly, there is the rearing time $\varepsilon^{\mathrm{R}}_{t+1} \in (0,1)$ allocated to each child, which includes activities like breastfeeding and taking children to healthcare facilities for treatments or vaccinations, summing up to a total of $\varepsilon^{\mathrm{R}}_{t+1} n_{t+1}$ units of time spent on childcare. Secondly, there are the costs of goods and services consumed by children, such as food, healthcare, clothing, education, and other necessities. Each parent invests a fraction $\theta \in (0,1)$ of their net income per child. Given that the net income at $t+1$ is y_{t+1}, the total cost of raising n_{t+1} children is the sum of the opportunity cost of time and the expenditures, represented as $(\varepsilon^{\mathrm{R}}_{t+1}+\theta)n_{t+1}y_{t+1}$. This cost structure presents a trade-off between the quantity and quality of children's health, distinct from educational investments (Galor and Weil, 2000).

In addition to raising children and supplying labor to firms, adults devote a fixed unit of time $\varepsilon^{\mathrm{H}}_{t+1}$ to maintaining their health, which includes activities such as medical visits and exercise. The model assumes a perfect annuity market where individuals save a portion of their income to invest in physical capital K^{P}_t, which becomes productive in the subsequent period. Within this annuity market, the rental rate r_{t+2} of private capital determines the effective return r_{t+2} on savings. Children's consumption in their first period of life is incorporated into parental consumption. Thus, the expected lifetime utility of an individual in period $t+1$ can be expressed as

$$U = \ln c^t_{t+1} + \eta_L \ln\left(1-\varepsilon^{\mathrm{H}}_{t+1}-\varepsilon^{w}_{t+1}-n_{t+1}\varepsilon^{\mathrm{R}}_{t+1}\right) + \eta_{\mathrm{N}} \ln h^{\mathrm{C}}_{t+1} n_{t+1} + \frac{\ln c^t_{t+2}}{1+\rho} \tag{1}$$

Where adult consumption in period $t+1$ is denoted by c^t_{t+1}, with $\rho > 0$ representing the discount rate. The utility of adults not only depends on their household size $\mathrm{n}_{\mathrm{t+1}}$ and consumption but also on the health of their children h^{C}_t. Leisure time $1-\varepsilon^{\mathrm{H}}_{t+1}-\varepsilon^{\mathrm{w}}_{t+1}-n_{t+1}\varepsilon^{\mathrm{R}}_{t+1}$ is defined as remaining time after accounting for work time $\varepsilon^{\mathrm{w}}_{t+1}$. The coefficients η_{L} and η_{N} capture adults' relative preferences for leisure and children's health. Although adult health outcomes do not directly benefit the utility, as will be explained later, they do have an indirect impact on household utility through wages. There is no such consumption during childhood because all the resources that children use come from their parents. Thus, the following defines individual budget constraints during the $t+1$ period:

$$c^t_{t+1} + s_{t+1} = (1-\theta n_{t+1})(1-\tau)a_{t+1}\omega_{t+1} \tag{2}$$

$$c^t_{t+2} = (1+r_{t+2})s_{t+1} \tag{3}$$

where s_{t+1} is savings, $\tau \in (0,1)$ is the tax rate, and a_{t+1} is labor productivity. Here, the wage rate ω_{t+1} is determined by the product of hourly wage $\omega^{\mathrm{w}}_{t+1}$ (measuring production efficiency per actual work hour) and hours worked.

These components combine to form the following consolidated budget constraint:

$$c^t_{t+1} + \frac{c^t_{t+2}}{1+r_{t+2}} = (1-\theta n_{t+1})(1-\tau)a_{t+1}\omega_{t+1} \tag{4}$$

Firms. The economy features a continuum of identical firms $i \in (0,1)$ producing non-storable goods for final consumption and investment. Production requireselements of labor, private capital, and public capital encompassing transportation infrastructure. Following Krugman (1991), transportation infrastructure influences production efficiency through iceberg-type costs affecting shipping and competitiveness. Public capital exhibits non-excludability but partial rivalry due to congestion effects, where utilization by one firm reduces availability for others. The congestion externality scales proportionally with aggregate private capital stock.

The production technology follows a Cobb–Douglas specification as follows:

$$Y^i_t = \left(\frac{K^{\mathrm{I}}_t}{\bar{K}^{\mathrm{P}}_t}\right)^{\alpha} (A_t N^i_t)^{\beta} \left(K^{\mathrm{P},i}_t\right)^{1-\beta} \tag{5}$$

The production technology utilizes private capital $K^{\mathrm{P},i}_t$ at firm i, aggregate private capital $\bar{K}^{\mathrm{P}}_t = \int_0^1 K^{\mathrm{P,i}}_t$, public transportation infrastructure K^{I}_t, and labor N^i_t with average productivity A_t,In which $\alpha, \beta \in (0,1)$.This specification generates constant returns to scale in effective labor $A_t N^i_t$ and capital inputs $K^{\mathrm{P},i}_t$.

Inadequate transportation infrastructure diminishes productivity gains due to congestion externalities from excessive private capital utilization. For example, truck proliferation increases traffic delays in a critical concern for resource-constrained economies. Optimal provision requires public capital to grow proportionally with private capital stocks.

Firms operate in perfectly competitive factor markets, maximizing profits π^i_t through optimal combinations of effective labor and private capital, given the K^{I}_t and $\bar{K}^{\mathrm{P}}_t$:

$$\max_{A_t N^i_t, K^{\mathrm{P}}_t, i} \pi^i_t = Y^i_t - r_t K^{\mathrm{P}}_t, i - \omega_t A_t N^i_t \tag{6}$$

where r_t is the rental rate for private capital, so the firm's profit maximization yields:

$$\omega_t = \frac{\beta Y^i_t}{A_t N^i_t}, \quad r_t = \frac{(1-\beta)Y^i_t}{K^{\mathrm{P},i}_t} \tag{7}$$

This indicates that firms utilize marginal products to cover private inputs. Given the homogeneity of firms, symmetric equilibrium implies that $N^i_t = N_t$ and $K^{\mathrm{P},i}_t = K^{\mathrm{P}}_t = \bar{K}^{\mathrm{P}}_t$, the modified Eq. (7) can be got.

$$\omega_t = \frac{\beta Y_t}{A_t N_t}, \quad r_t = \frac{(1-\beta)Y_t}{K^P_t} \tag{8}$$

By normalizing the number of firms to 1, it derives the aggregate output.

$$Y_t = \int_0^1 Y_t^i = \left(\frac{K_t^{\mathrm{I}}}{K_t^{\mathrm{P}}}\right)^{\alpha} \left(\frac{A_t N_t}{K_t^{\mathrm{P}}}\right)^{\beta} K_t^{\mathrm{P}} \tag{9}$$

In a stable state, the public–private capital ratio $\frac{K_t^{\mathrm{I}}}{K_t^{\mathrm{P}}}$ and the effective labor–capital ratio $\frac{A_t N_t}{K_t^{\mathrm{P}}}$ keep constant, establishing a linear relationship between output Y_t and K_t^P. Continuous reinvestment in private capital drives endogenous economic growth.

For simplicity, assuming the private capital stock is represented by $K_{t+1}^{\mathrm{P}} = \mathrm{I}_t$, where I_t denotes private investment.

Populations. Let N_t represent the number of laborers in period t, with $n_t N_t$ being the total number of children born in that period. The number of older individuals surviving to period $t-1$ is equivalent to the number of surviving adults N_{t-1} from period $t-1$[9]. Thus, the total population at the start of period t is the sum of survivors and new births $(1+n_t)N_t + N_{t-1}$. The number of adults $n_{t-1}N_{t-1}$ alive in period t is a function of the children born in period $t-1$.

$$N_t = n_{t-1} N_{t-1} \tag{10}$$

Therefore, total population L_t in period t is

$$L_t = (1+n_t) n_{t-1} N_{t-1} + N_{t-1} \tag{11}$$

Health capital and productivity. Child health status h_t^{C} is influenced by several factors, including the amount of expenditure on goods, parental health status h_t^{A}, the effective time parents allocate to their children, and access to public healthcare services.

$$h_t^{\mathrm{C}} = \theta (h_t^{\mathrm{A}})^{\kappa} (\zeta_t \varepsilon_t^{\mathrm{R}})^{\nu_{\mathrm{C}}} \left(\frac{H_t^{\mathrm{G}}}{K_t^{\mathrm{P}}}\right)^{1-\nu_{\mathrm{C}}}, \tag{12}$$

Here, H_t^{G} represents the effective supply of healthcare services, influenced by congestion, and $\kappa, \nu_{\mathrm{C}} \in (0,1), \zeta_t > 0$ is an efficiency parameter dependent on transportation infrastructure. A linear relationship exists between children's health and the share of income parents spend on them, which helps reduce disease vulnerability. Parental health also affects children's health, potentially due to the physical demands of childcare, especially in areas with poor transportation. Additionally, children's health depends on the efficiency ζ_t of parental time allocation, which is influenced by transportation infrastructure congestion. where H_t^{G} is the effective supply (capital stock) of healthcare services (also affected by the congested effect), and $\kappa, \nu_{\mathrm{C}} \in (0,1), \zeta_t > 0$ is an efficiency parameter that depends on transportation infrastructure. First, there is a linear relationship between children's health and the share of income that parents spend on each child. The benefit of the share of income is that it helps reduce the child's vulnerability to disease (Caulfield et al. 2004). Second, the health of children depends on the health of their parents. As mentioned earlier, this may be related to the physical ability of parents to take care of their children (for instance, a parent may take a long walk to a healthcare facility in an area with poor transportation). Third, children's health depends on the efficiency of the time their parents allocate to them. The efficiency parameter ζ_t is assumed to depend on the degree of congestion that the public capital of the transportation infrastructure has relative to private capital.

$$\zeta_t = \left(\frac{K_t^{\mathrm{I}}}{K_t^{\mathrm{P}}}\right)^{\lambda} \tag{13}$$

where $\lambda \in (0,1)$. Improved transportation infrastructure enhances accessibility to healthcare facilities by reducing travel time, thereby improving health outcomes. Similarly, congestion affects the efficiency of transportation infrastructure use.

Adult health status depends on childhood health and the time allocated to self-care.

$$h_{t+1}^{\mathrm{A}} = h_t^{\mathrm{C}} (\varepsilon_{t+1}^{\mathrm{H}})^{\nu_{\mathrm{A}}} \tag{14}$$

where $\nu_{\mathrm{A}} \in (0,1)$, ζ_t represents the efficiency parameter of transportation infrastructure in improving health investment efficiency, in which transportation improvements reduce the time and cost of seeking medical treatment.

Substituting Eqs. (12) and (13) into Eq. (14) yields adult's health status:

$$h_{t+1}^{\mathrm{A}} = \theta (h_t^{\mathrm{A}})^{\kappa} (\zeta_t \varepsilon_t^{\mathrm{R}})^{\nu_{\mathrm{C}}} (\varepsilon_{t+1}^{\mathrm{H}})^{\nu_{\mathrm{A}}} \left(\frac{K_t^{\mathrm{I}}}{K_t^{\mathrm{P}}}\right)^{\nu} \left(\frac{H_t^{\mathrm{G}}}{K_t^{\mathrm{P}}}\right)^{1-\nu_{\mathrm{C}}} \tag{15}$$

where $\nu = \lambda \nu_{\mathrm{C}}$. Grossman (1972) noted that health can be improved through increased consumption or better time allocation for self-care and healthcare service utilization. Combining these elements, we derive a comprehensive model that links childhood and adult health outcomes, influenced by parental health, income allocation, and transportation infrastructure efficiency.

Here, labor productivity is assumed to be linearly related to health capital[10].

$$a_t = h_t^{\mathrm{A}} \tag{16}$$

Government. The government imposes a constant tax rate τ on adults, investing in transportation G_t^{I}, health G_t^{H} (to produce healthcare services capital), and other non-productive areas G_t^{U}. The government must balance its budget in each period, with no debt issuance.

$$G_t = G_t^{\mathrm{I}} + G_t^{\mathrm{H}} + G_t^{\mathrm{U}} \tag{17}$$

Assuming the government allocates a fixed proportion $\upsilon_h \in (0, 1)$ of its revenue to investment, the following equation can be derived:

$$G_t^{\mathrm{h}} = \upsilon_{\mathrm{h}} N_t \tau \omega_t A_t,\ h = \mathrm{I, H, U} \tag{18}$$

Combining Eqs. (17) and (18) obtain the following result:

$$\sum \upsilon_h = 1 \tag{19}$$

Assuming that public capital is fully depreciated at the end of each period t, the government's investment in transportation during period t becomes the capital stock of transportation infrastructure in period $t+1$, as follows:

$$K_{t+1}^{\mathrm{I}} = G_t^{\mathrm{I}} \tag{20}$$

The effective capital of healthcare services provided by the government, which is a function of both transportation K_t^{I} and health G_t^{H} expenditures, exhibits constant returns to scale. This means that if both transportation expenditure and health expenditure are increased proportionally, the effective capital of healthcare services H_t^{G} will also increase proportionally.

$$H_t^{\mathrm{G}} = (K_t^{\mathrm{I}})^{\mu} (\varphi G_t^{\mathrm{H}})^{1-\mu} \tag{21}$$

Here, $\mu, \varphi \in (0, 1)$. As previously highlighted, the model underscores the crucial role of transportation infrastructure in facilitating access to healthcare services in low-income countries, alongside individual health investments. The coefficient φ quantifies the efficiency of government health spending in generating effective capital for healthcare services. Consequently,

$1-\varphi$ represents the proportion of resources lost due to inefficiencies or waste in management.

Assuming that all depreciation is accounted for in each type of capital, the market clearing condition for the commodity market can be derived by combining Eqs. (17) through (20). This integration ensures that the total production of goods matches the total consumption and investment in the economy.

$$Y_t = C_t + K^{\mathrm{P}}_{t+1} + G^{\mathrm{U}}_t + G^{\mathrm{H}}_t + K^{\mathrm{I}}_{t+1} \tag{22}$$

In the given context, $C_t = N_t\left[c^t_t + \theta n_t(1-\tau)a_t\omega_t\right] + N_{t-1}c^{t-1}_t$ represents the total consumption in period t.

The market clearing condition necessitates that the private capital stock in period $t+1$ must be equivalent to the total savings of adults in period t.

$$K^{\mathrm{P}}_{t+1} = N_t s_t \tag{23}$$

Market equilibrium. In the final equilibrium state, the utility of adults is maximized, resulting in optimal health outcomes $\widetilde{h}^{\mathrm{A}}$. This equilibrium is subject to constraints on consumption, child-rearing time, time allocated to self-health care, and working time.

$$\widetilde{h}^{\mathrm{A}} = \left\{\theta(\widetilde{\varepsilon}^{\mathrm{R}})^{\nu_{\mathrm{C}}}(\widetilde{\varepsilon}^{\mathrm{H}})^{\nu_{\mathrm{A}}}\left(\varphi\upsilon_{\mathrm{H}}\tau\beta\right)^{(1-\nu_{\mathrm{C}})(1-\mu)}J^{\Pi_1}\right\}^{1/1-\Pi_2}\widetilde{x}^{\Pi_3/1-\Pi_2} \tag{24}$$

Assuming J denotes the public–private capital ratio k^{I}_{t+1}, which is defined as $k^I_{t+1} = \frac{K^I_{t+1}}{K^P_{t+1}} = \frac{\upsilon_I\tau}{\sigma\left(1-\theta\widetilde{n}\right)(1-\tau)} \equiv J$. Because of $\theta\widetilde{n} < 1$, the propensity to save, which reflects the fraction of after-tax income allocated to savings after accounting for health expenditures, is represented by $\sigma(1-\theta\widetilde{n})(1-\tau)$. Amid a stable transportation investment equilibrium, the public–private capital ratio stays constant. Here, $x_t = K^{\mathrm{P}}_t/N_t$ denotes the capital–labor ratio, defining $\Pi_1 = \nu + (1-\nu_{\mathrm{C}})\left[\mu + \alpha(1-\mu)\right] > 0$, $\Pi_2 = \kappa + \beta\left(1-\nu_{\mathrm{C}}\right)\left(1-\mu\right) > 0$, $\Pi_3 = -\beta\left(1-\nu_{\mathrm{C}}\right)\left(1-\mu\right) = \kappa - \Pi_2 < 0$.

Based on Eq. (24), this study calculates the first-order derivative of workers' health h^{A} with respect to transportation investment υ_{I} in an equilibrium state.

$$\frac{dh^{\mathrm{A}}}{d\upsilon_{\mathrm{I}}} = \frac{\Pi_1}{1-\Pi_2}\upsilon_{\mathrm{I}}^{-1}h^{\mathrm{A}} \tag{25}$$

To determine the direction of $\frac{\mathrm{d}h^{\mathrm{A}}}{\mathrm{d}\upsilon_{\mathrm{I}}}$, we need to explore the direction of $\frac{\Pi_1}{1-\Pi_2}$, as explained by the definitions of Π_1 and Π_2.

$$\frac{\Pi_1}{1-\Pi_2} = \frac{\nu + (1-\nu_{\mathrm{C}})\left[\mu + \alpha(1-\mu)\right]}{1-\kappa-\beta\left(1-\nu_{\mathrm{C}}\right)\left(1-\mu\right)} \tag{26}$$

This enables us to examine the aforementioned equation in light of the parameters κ and β.

$$\frac{dh^{\mathrm{A}}}{d\upsilon_I}\left\{\begin{array}{l} >0, \mathit{if}\ \kappa+\beta\left(1-\nu_C\right)\left(1-\mu\right)<1 \\ <0, \mathit{if}\ \kappa+\beta\left(1-\nu_C\right)\left(1-\mu\right)>1 \end{array}\right\} \tag{27}$$

When $\kappa + \beta\left(1-\nu_{\mathrm{C}}\right)\left(1-\mu\right) < 1$, the equation $\frac{\Pi_1}{1-\Pi_2} > 0$ holds $\frac{\mathrm{d}h^{\mathrm{A}}}{\mathrm{d}\upsilon_{\mathrm{I}}} > 0$ true, implying κ or β must be sufficiently small to satisfy this condition. On one hand, adult health is predominantly influenced by exogenous factors such as transportation infrastructure. When the intergenerational transfer parameter κ for health is small, the long-term effect of health dependence across generations is minimal. On the other hand, Eq. (5) shows that local public capital, private capital, and laborers' health determine the production function. Therefore, improvements in transportation infrastructure affect local health investments through the production effect, which in turn indirectly impacts adult health as per Eq. (18). If the contribution of laborers' health to output β is small, the transportation infrastructure has a more significant positive effect on output. Moreover, under the stricter assumption that when $\kappa < 0.5$ and $\beta < 0.5$, $\kappa + \beta(1-\nu_{\mathrm{C}})(1-\mu) < 1$ must be true. This means that when the contribution of labor to output or the intergenerational transfer parameter of health is sufficiently small, improvements in transportation infrastructure positively impact the health of laborers.

When $\kappa + \beta\left(1-\nu_{\mathrm{C}}\right)\left(1-\mu\right) > 1$, the equation $\frac{\Pi_1}{1-\Pi_2} < 0$ holds $\frac{\mathrm{d}h^{\mathrm{A}}}{\mathrm{d}\upsilon_{\mathrm{I}}} < 0$ true. The intergenerational transfer efficiency of health κ and/or the provision of healthcare services due to increasing economic efficiency β in the production sector have a more significant impact on health. The net health impact of transportation infrastructure investment becomes negative, as reduced health spending offsets potential benefits in transportation investment ($\mathrm{d}\upsilon_{\mathrm{I}} = -\mathrm{d}\upsilon_{\mathrm{H}}$). More strictly, $\kappa + \beta\left(1-\nu_{\mathrm{C}}\right)\left(1-\mu\right) > 1$ holds true when $\kappa = 1$, meaning that the intergenerational transfer efficiency of health is at its maximum. In this case, the health of parents has a direct linear relationship with child health, so the transportation infrastructure has a negative impact on health.

Moreover, the direction of $\frac{\mathrm{d}h^{\mathrm{A}}}{\mathrm{d}\upsilon_{\mathrm{I}}}$ is partly contingent on the efficiency parameters ν_{C} associated with time investment in personal health and those related to the production of effective healthcare services μ through transportation investment. As these efficiency parameters ν_{C} and μ increase, the positive effect of transportation infrastructure on workers' health diminishes. This underscores that the net impact of transportation infrastructure on health cannot be predetermined, it must be assessed under specific conditions. It also highlights the complexity of evaluating the effects of transportation infrastructure on health, as direct policy assessments may overlook the mechanisms and external constraints at play. A thorough analysis within the endogenous growth framework is essential to accurately interpret the interplay between transportation infrastructure and health. Misinterpretation can arise if external constraints are incorrectly assumed or disregarded, but this does not negate the existence or clarity of the impact of transportation infrastructure on health.

Hypothesis 1: If $\frac{\mathrm{d}h^{\mathrm{A}}}{\mathrm{d}\upsilon_{\mathrm{I}}} > 0$, improvements to transportation infrastructure will improve the health outcomes of laborers.improvements to transportation infrastructure will reduce the health outcomes of laborers; If $\frac{\mathrm{d}h^{\mathrm{A}}}{\mathrm{d}\upsilon_{\mathrm{I}}} < 0$, improvements to transportation infrastructure will reduce the health outcomes of laborers.

In this framework, a general equilibrium model is established based on the health level which determines the labor productivity, and the parameter of the mechanism are also mentioned in the equilibrium model. From the macro level, assuming that the government imposes a flat tax on the goods and spends part of it on building transportation infrastructure and providing healthcare services. the most direct effect of transportation infrastructure is to promote local economic development. Further local tax revenue provides a guarantee for government expenditure on healthcare services and transportation infrastructure, and forms a sustainable development route of transportation infrastructure construction, which would further promote economic development. From the micro level, by improving regional accessibility that transportation infrastructure reduces the spatial isolation barrier between urban areas and external markets, it can not only improve the trading efficiency and healthcare accessibility with external markets, promote the increase of individual income, but also promote the information exchange regarding in health knowledge, thus improve health literacy. Finally, based on the increase of income and higher health literacy, health investment and health behaviors for themselves will improve their health status. In addition, the accessibility influenced by transportation infrastructure will also allocate the time of workers in different activities to achieve the Pareto optimization. First of all, the improvement of transportation infrastructure will affect the commuting time of workers, and higher income will affect the reallocation of workers' working time, thus resulting their income level. Secondly, the improvement of transportation infrastructure will optimize the allocation of household productive activities, higher commuting efficiency can improve the time efficiency in the process of buying goods, seeking medical treatment or other activities. Then, transportation infrastructure improves access to healthcare facility, affecting the efficiency of time allocated to care for children's health and their own health, thus influencing the allocation of time to care for their own and their children's health status; Finally, in order to seek the optimal allocation of leisure under various time equilibrium allocation due to transportation infrastructure improvement, higher income may stimulate workers to work harder, or reduce workers' working time to seek more leisure, what is the substitution effect between different times and how to maximize the utility between different activities? In this model, factors such as government transportation infrastructure and health expenditure, time allocation, income and health preference are included in the model, the estimated parameters are used to explore the mechanism of transportation infrastructure's improvement of urban workers' welfare changes, these assumptions will be verified in the empirical section.

The above analysis suggests that the economy may shift toward a high-growth development path through increased government productive spending on health and transportation. This in turn will lead to changes in health investment strategies, time allocation, capital accumulation, and labor productivity. However, not all of these changes are necessarily conducive to better health. Specifically, increasing the share of investment in transportation may lead to more time spent at work but less time caring for oneself and one's children, which could have adverse effects on both health and the corresponding economic growth via the channel of productivity. Moreover, from the perspective of a general equilibrium, a faster rate of private capital aggregation may expand the congestion effect, thereby further mitigating the benefits of a higher stock of public capital.

Hypothesis 2: The significant health improving effect from transportation infrastructure can be attributed to raising economic development to provide more public healthcare services, increasing individual income for better health investments, facilitating knowledge communication between laborers to increase health literacy, and optimizing time management for health benefiting activities.

Data and identification strategy

Data. To investigate the effect of improved transportation infrastructure on the health of urban laborers, this article unites multiple rounds of tracking data from the CHNS and the China City Statistical Yearbook at the prefecture-city level. Both CHNS data and Chinese City Statistics Yearbook have the same administrative code at city level, so we matched the CHNS data with the Chinese City Statistics Yearbook at the city level to control the other factors bias when we analysis the impact of transportation infrastructure on individual health status by regression.

The China Health and Nutrition Survey (CHNS) is an ongoing longitudinal study jointly conducted by the University of North Carolina and the Chinese Center for Disease Control and Prevention. Initiated in 1989, the survey has been conducted approximately every 2–3 years, with 10 completed waves (1989–2018). Using a multistage, random cluster sampling method, the CHNS collects data from approximately 7,200 households (over 30,000 individuals) across 15 provinces and municipalities, representing nearly half of China's population. The sampling strategy employs probability proportional to size techniques, incorporating administrative and socioeconomic stratification across multiple levels (individuals, households, communities, cities, and provinces). The survey comprehensively measures individual health indicators, health behaviors, time allocation patterns, and household/individual economic characteristics, while also providing community-level data on economic conditions and transportation infrastructure distribution.

Notably, the 2018 data collection is excluded from analysis due to incomplete data cleansing processes, and pre-2000 records are omitted as they are considered temporally outdated for current research purposes. Thus, this study uses six rounds of the tracking surveys between 2000 and 2015, we only keep the administrative unit of community because it is located in urban areas, the administrative of villages are deleted because they are located in rural areas. Within the context of endogenous growth theory, we restricted the observations to the laborers aged 15 to 64 years, because the incomes and time allocations of these laborers are more sensitive to road improvement.

Empirical strategy. According to the theoretical Eq. (24), this section estimates the effect of transportation infrastructure on the health of urban laborers, the estimating equation of is given:

$$Y_{prit} = \alpha + \beta * R_{prt} + \eta_1 * Z_{pt} + \eta_2 * Z_{it} + \delta_p + \gamma_t + \varepsilon_{prit} \quad (28)$$

Y_{prit} symbolizes outcome variable for subscript i of individuals in community r of city p over period t, including health outcome, the location of medical treatment and mechanism variable. The health outcome is defined by asking respondent "whether you has been sick during the past four weeks", as a dummy variable. This is a real recorded data, which can better reflect the health status. Additionally, the CHNS questionnaire includes information such as the type and location that patient get medical treatment, as well as the respondents' height, weight, and self-rated health. These variables related to health status are used as robustness tests for health indicators, and to analyze the medical treatment seeking behavior.

R_{prt} is an indicator variable indicating whether community r or city p has attained road improvement within the t period, mainly comprising whether the community have been covered by bus station and road density. The bus station is got by asking the community leader if the community is covered by bus station and the road density is got by the Statistical yearbook. Road density mainly uses the total mileage at prefecture-level city divided by the land area of the prefecture-level city (km/100 km^2).

Z_{pt} represents lots control variables at the prefecture-level because health status is usually influenced by economic levels and the number of beds per thousand persons. To eliminate potential endogeneity concerns between GDP and residents' health, the distance from local city to the nearest coastal city was used as a proxy for local economic development and technological differences instead of using GDP directly (Banerjee et al. 2020). Z_{it} are individual and households-level control factors, which mainly takes into account the health status of individuals from gender, education, insurance, age, logarithm of household income, whether the household has flush toilet.

This study directly uses the original data provided from CHNS by the software of Stata 16, and the measurement unit of the used variables are explained in Table 1. Some samples were deleted because they refused or could not remember the answer to a question during the data survey, leading to the missing values in

Table 1 Descriptive statistics.

Variable	Obs.	Mean	Std. dev.	Min	Max
Have been sick	11,069	0.143	0.351	0	1
Bus station	11,069	0.718	0.450	0	1
Highway density (kilometers per square kilometers)	11,069	0.010	0.006	0.001	0.020
Kapital/person	11,069	8.080	5.237	1.260	24.59
Household registration	11,069	0.708	0.455	0	1
Age	11,069	43.65	13.31	16	65
Education	11,069	2.630	1.481	0	6
Gender	11,069	0.522	0.500	0	1
Insurance	11,069	0.695	0.460	0	1
Ln per household income (yuan)	11,069	9.254	1.127	0.882	11.53
Flush toilet	11,069	0.812	0.390	0	1
Distance to port city (km)	11,069	109.6	58.49	0	210.2
Doctor in city (Doctor per thousand persons)	11,069	4.270	1.895	1.609	8.545

this sample. Therefore, this study directly deletes the sample and obtains 11,069 valid samples after limiting the age and household registration information, who live in urban areas no matter what the status of household registration. Considering the lag effect on health, this study employ one-phase lag of health. We systematically trimmed all variables by 0.5% and we also treated household and individual income logarithmically to facilitate the analysis in this study, and other control variables were quantified by binary dummy variables.

Table 1 presents the statistical results of the control variables. The urban sample distribution indicates that the health of the laborers surveyed during the period is poor. The mean value of the indicator variable of sick is 0.143. Given that the conditions for bus station and highway density, 71.8% of the community have been covered by bus station, and the highway density between cities is 0.010 km per square kilometers. The descriptive statistical results of the key variables and other control variables illustrate the rationality and diversity of the sample selection of the respondents.

γ_t reflects year fixed effect and δ_p reflects city fixed effect. Considering the diversity of core explanatory variables and mechanism variables, OLS is employed in order to maintain the unity of identification methods for different types of variables, the estimated parameter obtained from OLS has clear economic implications and can be directly used to explain the relationship between transportation infrastructure and individual health. This study adopted a robust standard error clustering at the community level. In this context, β reflects the average treatment effect of transportation infrastructure improvement on laborers' health improving effect. If $\beta > 0$, the multiple mechanisms caused by the improvement of transportation infrastructure will have a net effect on promoting the health of laborers.

Due to the vast disparities in income, social exclusion, and benefited policies between urban and rural registered populations, no matter where they live in China, urban registered populations typically get more job opportunity and higher incomes, and benefited policies[11]. These imply that urban registered populations can benefit from transportation infrastructure more if they take long-distance medical treatment in other city. Therefore, we further investigate the difference of health effects from improved transportation infrastructure on these two subgroups, because the differences of social welfare suffered by these two subgroups affect their health seeking behaviors, these heterogeneity analysis help identify which groups are benefited by transportation infrastructure.

An important challenge of identification strategies for road improvement is the decision of investment in transportation. High costs and potential huge benefits of infrastructure investment mean that transportation investment is typically influenced by local government preferences and economic development potential. This introduces bias of transportation investment into the random distribution of transportation distribution (Lehne et al. 2018). Generally, more politically influential or economically developed urban areas are better able to lobby the government for road investment. Further, these more developed areas usually have more capital stock and investment for healthcare and education, which creates endogenous concerns between R_{prt} and ε_{prit}. In addition, highly productive city may be more inclined to improve their local transportation infrastructure, which can lead higher productivity to be associated with higher income and health investment. To alleviate this concern of non-random road distribution, we adopted the identification strategy of instrumental variable (IV) estimation to deal with the possible endogeneity problems.

When it considers the intra-city transportation, road construction in community-level is usually based on a predetermined priority rule of population size, meaning that with an increase in population size, the probability of road investment increases too (Aggarwal, 2021), this fulfills the exogenous assumption of IV identification strategy. When it considers the inter-city transportation, many highways and railways have been built based on the historical trajectory of railway in1961 in China, which implies that current railway lines are usually built on top of existing historical railway line. These IV identification strategy based on population size and the historical trajectory of railway in 1961 can not influence government and individual health decisions through channels other than current transportation infrastructure. Therefore, using population size as the IV estimation of intra-city transportation and using historical trajectory of railways in 1961 as the IV estimation of inter-city transportation is feasible to hand the endogenous concerns.

An IV estimation strategy needs to meet the following conditions to solve the above concerns.

$$R_{prt} = \alpha' + \beta' * P_{prit} + \eta'_1 * Z_{pt} + \eta'_2 * Z_{it} + \delta'_p + \gamma'_t + \varepsilon'_{prit} \quad (29)$$

where R_{prt} is the population size of the local community (or whether the city had a railway station in 1961). Because ε_{prit} may correlate with R_{prt} in Eq. (28), incorporating Eq. (29) into the estimation resolves such endogenous concerns, so R_{prt} does not correlate with the unobservable term of ε'_{prit}. This meets the arguments for the conditional exogeneity of the instruments.

Results

Health effects from intra-city transportation infrastructure. The results in Column (1) of Table 2 demonstrate that there is not significant difference in the probability of having illness among laborers in the past 4 weeks after the community was covered by bus stations. This article also includes fixed effects of provinces, communities and households, respectively, yet the results in columns (2)–(4) of Table 2 remain insignificant. Considering that the respondents living in urban area may not be urban household registered status, this would cause interference to our estimation of the health effect. In China, rural household registered population working in urban areas that does not have equal access to healthcare services in the inflow place, and migrant population may suffer from certain social exclusion in

Table 2 The impact of community road on laborers' health status.

	Have you been sick in the last 4 weeks					
	(1)	(2)	(3)	(4)	Rural (5)	Urban (6)
Bus station	0.018	0.012	0.021	0.017	0.035	0.015
	(0.012)	(0.013)	(0.019)	(0.019)	(0.032)	(0.013)
Control variables	√	√	√	√	√	√
Year FE	√	√	√	√	√	√
City FE	√				√	√
Province FE		√				
Community FE			√			
Household FE				√		
Obs.	7636	7636	7636	7503	2625	5011
Adjusted R^2	0.050	0.046	0.062	0.276	0.061	0.050

Standard errors are shown in the parentheses and clustered at the community level. All OLS regressions incorporate control variables at the individual, household, and city levels. Columns 1, 5 and 6 encompasses year and city fixed effects, column 2 encompasses year and province fixed effects, column 3 encompasses year and community fixed effects, and column 4 encompasses year and household fixed effects.

Table 3 The impact of community road on laborers' other health status.

	BMI	Self-rated health
Bus station	−0.075	0.049
	(0.088)	(0.038)
Obs.	5620	5589
Adjusted R^2	0.690	0.120

Standard errors are shown in the parentheses and clustered at the community level. All regressions incorporate control variables at the individual, household, and city levels, as well as fixed effects for both year and city.

the inflow place, so the health status of urban population may partly affected by their household registration difference (Song and Smith, 2019). Therefore, we divided the urban observations into two groups by urban household registered status and rural household registered status. The results of columns (5) and (6) of Table 2 reveal that the bus station at community level still do not play significant effect on laborers' health status.

Considering that the independent variable of "have been sick" is a binary variable, this study further uses Probit model for the regression. Appendix T2 also shows the same results.

Investigating the selection bias of health indicators, we further examined the BMI index of laborers. The results in column (1) of Table 3 indicated that the BMI index of laborers did not experience a significant shift after their living community were connected to the bus station. Furthermore, we use laborers' own assessment of their health as a more comprehensive health indicator. Self rated health is determined by asking respondents to evaluate how their health compares to their peers, with the levels marked as 1–5, from very poor to very good. Column (2) in Table 3 reveals that the self-rated health of laborers has not got significant improvement after their living community were connected to the bus station. These results revealed that the road in intra-city have not significant impact on laborers' health status.

The effectiveness of improving community roads on the health of laborers may be limited due to the non-random distribution of road construction. To address this issue, population size is used as an IV estimation, as the probability of regional infrastructure investment typically tend to large population size (Asher and Novosad, 2020). This lack of correlation between population size and laborers' health allows for a more accurate estimation regarding the impact of transportation on health.

Table 4 Impact of community road improvement on individual health by IV estimate.

	Have you been sick in the last four weeks
Bus station	0.187
	(0.322)
First stage	
Community population	0.024**
	(0.009)
F-statistic	57.98
	(0.000)
KP test statistic	57.97
	(0.000)
Obs.	7440
Adjusted R^2	−0.003

Standard errors are shown in the parentheses and clustered at the community level. All regressions incorporate control variables at the individual, household, and city levels, as well as fixed effects for both year and city.
**$p < 0.05$.

Table 4 presents the IV estimation and test criteria for Eq. (29). The Hausman test indicates a significant discrepancy between the OLS and IV estimates. Moreover, the *F*-test statistical value surpasses the standard of 10, and the KP statistical test reveals that the estimates from the population size are not influenced by the weak IV estimation. Nonetheless, Table 4 indicates that the results of IV estimation are still insignificant, implying that the enhancement of intra-city transportation infrastructure does not have significant effect on the health status of laborers.

Despite the multi-dimensional robust test and IV estimation, the impact of community transportation infrastructure on laborers' health has yet to be observed. This could be due to the fact that even in the absence of public transportation, populations living in the city can access to healthcare facilities by walking, and healthcare facilities in the same city are usually not far from them. Statistics from Appendix T3 indicate that the average distance from residents to the nearest primary hospital is ~1 km, and to the nearest tertiary hospital is around 3.742 km, making patients available to access to healthcare facilities without transportation.

Table 5 The impact of intercity road on laborers' health status.

	Have you been sick in the last four weeks					
	(1)	(2)	(3)	(4)	(5) Rural	(6) Urban
Highway density	−0.008 **	−0.007 **	−0.009 ***	−0.009 **	−0.009	−0.007*
	(0.003)	(0.003)	(0.003)	(0.004)	(0.006)	(0.004)
Control variables	√	√	√	√	√	√
Year FE	√	√	√	√	√	√
City FE	√					√
Province FE		√				
Community FE			√			
Household FE				√	√	√
Obs	9816	9816	9816	9543	3036	6780
Adjusted R^2	0.048	0.045	0.067	0.294	0.058	0.049

Standard errors are shown in the parentheses and clustered at the community level. All OLS regressions incorporate control variables at the individual, household, and city levels. Columns 1, 5, and 6 encompasses year and city fixed effects, column 2 encompasses year and province fixed effects, column 3 encompasses year and community fixed effects, and column 4 encompasses year and household fixed effects.
$^*p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.

However, populations living in county-level city still need healthcare services from more advanced medical facilities located in larger city. Statistics in Appendix T3 show that the maximum distance for residents from origins to the nearest tertiary hospital is 100 kilometers, which implies that they heavily rely on the transportation infrastructure between cities to get medical treatment. Therefore, this article further analyze the health effects of laborers in light of the improved transportation infrastructure between cities.

Health effects from inter-city transportation infrastructure. The improvement of transportation infrastructure within the city does not have a significant impact on the health of laborers, which may be the fact that they are more rely on the economic growth, healthcare services and knowledge communication benefits brought by the enhancement of transportation infrastructure between cities. Therefore, we further investigate the effect of improving transportation infrastructure between cities on the health of laborers. Column (1) of Table 5 reveals that an increase in highway density between cities reduces the probability of laborers having illness in the past four weeks. This suggests that one unit (kilometers per square kilometers) increase in highway density between cities decrease the rate of been been sick in the last four weeks by 0.008, which is similar to the study of Bu et al. (2022) that the estimated coefficient of high speed rail can increase individual health status. We further use province and community fixed effects, the estimated results in columns (2) and (3) of Table 5 were still negative. Not only regional differences affect the effect of transportation on laborers' health, but also micro level health investment decision-making factors, such as family health preferences, may bias our estimation results. For instance, families with a higher preference for health tend to place more attention on health investments, leading to better health outcomes. Therefore, we adopted both time and household fixed effects to better control the confounding factors, and the results in columns (4) of Table 5 was consistent with our expectations. Additionally, we divided the urban sample into two groups based on household registered status. The results of columns (5) and (6) in Table 5 indicate that the improvement in road density between cities only has significant effect on the health of laborers with urban registered populations. It is possible that the rural registered populations living in urban area do not get the equal access to healthcare services due to the discrimination of household registration, and their lower income and health awareness also make them less likely to prioritize health. With the improvement of the transportation infrastructure, the urban registered populations can access higher quality tertiary hospitals for getting medical treatment, which encourages us to explore the long-distance medical treatment seeking behavior in the section "Long-distance medical treatment seeking behavior".

Table 6 The impact of intercity road on individual other health status.

	BMI	Self-rated health
Highway density	−0.170*	0.229**
	(0.099)	(0.105)
Obs.	6686	3459
Adjusted R^2	0.688	0.136

Standard errors are shown in the parentheses and clustered at the community level. All regressions incorporate control variables at the individual, household, and city levels, as well as fixed effects for both year and city.
$^*p < 0.1$; $^{**}p < 0.05$.

Considering that the independent variable of "have been sick" is a binary variable, this study further uses Probit model for the regression. Appendix T4 also shows the same results.

Additionally, the results in Table 6 (column 1) demonstrate that the rise in road density between cities can significantly reduce the BMI index of laborers, thus indicating that the enhancement of intercity transportation infrastructure is beneficial to the health of laborers. Additionally, self-rated health status can not only reflect the comprehensive health status, but also forecast the probability of incidence and mortality, we further use self-rated health as the robust proxy variable. The data in column (2) of Table 6 demonstrate same results that the highway density between cities increases the self-rated health of laborers by 0.229, which is similar to Chen's et al. (2021) findings that HSR improves the health of local residents with a coefficient of 0.298. By verifying the multidimensional health outcomes through the improvement of intercity transportation infrastructure, it is evident that the improvement of intercity transportation infrastructure can significantly improve the health level of laborers.

Considering the dependent variable is a dummy variable, we also use the probit model to estimate the result,

To address the endogeneity issues, this article uses whether the city ever has historical railway station in 1961 as an IV estimation for the transportation infrastructure construction. This is because historical railway lines are related to the current transportation infrastructure construction, but unlikely influence current

Table 7 Impact of intercity road improvement on individual health by IV estimate.

	Have you been sick in the last four weeks
Highway density	−0.037***
	(0.012)
First stage	
Railway station in 1961	0.102***
	(0.006)
F-statistic	310.78
	(0.000)
KP test statistic	368.57
	(0.000)
Obs.	9370
Adjusted R^2	0.002

Standard errors are shown in the parentheses and clustered at the community level. All regressions incorporate control variables at the individual, household, and city levels, as well as fixed effects for both year and city.
***$p < 0.01$.

Table 8 Impact of intercity road improvement on individual health by DML.

	Have you been sick in the last four weeks
Highway density	−0.025***
	(0.009)
Obs.	9816
Adjusted R^2	0.035

Standard errors are shown in the parentheses and clustered at the community level. All regressions incorporate control variables at the individual, household, and city levels, as well as fixed effects for both year and city.
***$p < 0.01$.

Table 9 Health effects of transportation infrastructure among different groups.

	Have you been sick in the last four weeks			
	County	Prefecture city	City with low medical resources	City with high medical resources
Highway density	−0.010**	0.006	−0.014*	0.008
	(0.005)	(0.013)	(0.007)	(0.006)
Obs.	4734	5085	5610	4209
Adjusted R^2	0.066	0.045	0.057	0.046

Standard errors are shown in the parentheses and clustered at the community level. All regressions incorporate control variables at the individual, household, and city levels, as well as fixed effects for both year and city.
*$p < 0.1$; **$p < 0.05$.

government and individual health decisions through other channels than transportation infrastructure. In addition, considering that the geographical characteristic variable does not change over time, this study uses the interaction term between historical railway station in 1961 and year as IV, which can get the IV with time-varying characteristics.

Table 7 presents the IV estimation and test criteria for Eq. (29). The Hausman test indicates a significant discrepancy between the OLS and IV estimates. Moreover, the *F*-test statistical value surpasses the standard of 10, and the KP statistical test reveals that the estimates obtained from the historical railway station in 1961 are not influenced by the weak IV estimation. Table 7 reveals that the IV estimation result is negative and statistically significant.

Considering the "dimensional curse" and model setting bias used by traditional OLS methods, this study further adopts a double machine learning (DML) method (Girma and Paton, 2024), which is a statistical method specifically used for causal inference that combines traditional regression analysis and machine learning method to reduce the bias introduced by wrong model setting. The core idea of DML is to decompose the causal inference into two independent predictive steps, using machine learning algorithms to improve the accuracy and robustness of the estimation. First, by predicting the dependent variable (Y_{prit}) using the set of control variables, the prediction residual is obtained, removing the part explained by the control variable. Then, by using the same set of control variables to predict the treatment variable (R_{prt}), its residual is obtained and the influence of the control variable is removed. Finally, the causal effect of the treated variable on the dependent variable is estimated by regression analysis of the two residuals. Table 8 reveals that the DML estimation result is still statistically significant and robust.

Long-distance medical treatment seeking behavior. This study found that the enhancement of intercity transportation infrastructure can improve the health of laborers. However, it is yet unclear how this affects individual medical seeking decisions, and whether the improvement of these networks leads to substitution effects of health care among different level of hospital. Since there is difference in medical resources between prefecture-level city and county-level city, prefecture-level city usually have tertiary hospitals, while county-level city usually only have secondary and primary hospitals, the improvement of the transportation infrastructure may lead to populations transferring from county-level city to large city for better access to healthcare services, thus improving their health outcome. Therefore, we divided these cities into two categories according to their administrative level: county-level city and prefecture-level city. Table 9 reveals that only the health of laborers in county-level city is positively affected by the advancement of the transportation infrastructure. Moreover, we divided the city into two subgroups depending on the quantity of hospitals. The findings indicate that improved transportation infrastructure can lead to better health outcomes for the laborers when the subgroup were distributed by poor medical resources. This supports our hypothesis that the transportation infrastructure has facilitated the long-distance medical treatment from small city to larger city, thus enhancing the health of laborers living in small city via the increasing access to high-quality healthcare services in large city. The agglomeration of medical resources in large cities eliminates the necessity for workers to travel elsewhere for medical treatment.

We have noticed that laborers living in county-level city and city with low medical resource achieve significant health improvement effects, does the improved transportation infrastructure increase the available of getting better healthcare services? Therefore, this article further investigates whether transportation infrastructure affects patients' health strategy of getting medical treatment seeking behavior, by analyzing the different subgroups of locations chosen for getting medical treatment among different urban laborers. The sample is mainly divided into three sub-samples based on the location of patients' medical treatment in their living community, local prefecture-level city, and other prefecture-level cities. The results of Table 10 demonstrate that the enhancement of the intercity transportation infrastructure has a significant impact on getting medical treatment in local cities and other cities, but not in their living community. The findings echo that of Table 2, that is, transportation infrastructure does not have a significant effect on the health of laborers who getting medical treatment in their living community, because getting medical treatment in their living community does not need public transportation, particularly the transportation between cities. This phenomenon is very similar to the ones documented by Aggarwal (2021), who finds that once the transportation infrastructure improves access to medical institutions, individual choices are less constrained, taking them closer to the optimum hospital.

Table 10 Health effect for getting medical treatment among different hospital.

	Have you been sick in the last four weeks		
	Local community	Local city	Other city
Highway density	−0.008	−0.013**	−0.013*
	(0.006)	(0.005)	(0.007)
Obs.	5246	5772	687
Adjusted R^2	0.054	0.056	0.142

Standard errors are shown in the parentheses and clustered at the community level. All regressions incorporate control variables at the individual, household, and city levels, as well as fixed effects for both year and city.
*$p < 0.1$; **$p < 0.05$.

Potential mechanism

Our theoretical framework views the generation of health capital from the improved transportation infrastructure, mainly depending on the endogenous parameter of individual income, health and leisure preferences, time allocation, and government healthcare service supply, rather than exclusively taking transportation as an exogenous factor for affecting laborers' health status. In this framework, ensuring enough financial support, from transportation infrastructure by improved market efficiency, is the essential for the health-related investment by the government and individual. Simultaneously, the elimination of geographical and spatio-temporal obstacles boosts knowledge communication and dissemination between populations. Additionally, the improvement of time efficiency optimizes the time allocation of laborers in terms of leisure, healthcare and work. All the path of mechanism play a comprehensive effect on the health of laborers in the context of improved transportation infrastructure. However, we must notice the substitution effect between governmental transportation and health investment, as well as individual time allocation between leisure and working. By testing these mechanisms separately, we can determine the equilibrium relationship between transportation infrastructure and the health level of urban laborers.

First, the enhancement of the transportation infrastructure decline the spatial isolation and transportation costs (including time cost) between cities, and increases the city's agglomeration of laborers and factors, thus boosting laborers' income due to the market scale effects and efficiency improvement (Combes et al. 2012; Ottaviano, 2012). As mentioned in the model, an increase in income can provide more capital for health investment and enhance the health capital of laborers. The results in column 1 of panel A in Table 11 demonstrate that the improvement of intercity transportation infrastructure increases the income of laborers. This rise in income implies that households are more willing to increase consumption and health investment. Although we do not observe significant increase in health expense for the whole laborers in Column 2 of panel A in Table 11, appendix T6 reveals that urban household registered population significant rise their health expense, these increased health expense would improve their health status, which demonstrate the result of columns (6) in Table 5.

Second, an increase in wages for laborers not only improves their own health investments, but also supports the governmental expenditure in offering more public healthcare services based on the taxes from more wage. Research has shown that lacking healthcare services reduces the motivation of populations to utilize them, (Banerjee et al. 2010). However, there is always a trade-off between public investment in transport, health and other projects, this is because increasing investment in transportation usually need to offset by a decrease in health investment, decreased health investment would cause a decrease in labor productivity and subsequently economic decline. There is a clear trade-off between investing in providing transportation infrastructure and healthcare services. If the contribution of the transportation infrastructure to the economy can be significant enough to counteract the negative effect of a decrease in labor productivity due to the decrease in public health investment, it would promote economic growth. This, in turn, can lead to an increase in health investment, creating a mutually beneficial relationship between transportation and health investment. The net effect depends on the production technology that determines the optimal rate of output growth and the efficiency of the health production function. Consequently, this study further analyze the effect of enhanced transportation infrastructure on regional economic growth and the supply of healthcare services. This article utilizes GDP and the number of beds per thousand people at city level as proxy variables for economic development and public health investment, respectively. The columns 3 and 4 of panel A in Table 11 suggest that transportation infrastructure

Table 11 The mechanical effect of transportation infrastructure on laborers' health status.

Panel A	Income	Insurance expense	GDP	Hospital beds per thousand	Known dietary guidelines
Highway density	202.301*	3.446	25.642***	0.134**	0.091***
	(121.295)	(5.525)	(7.972)	(0.062)	(0.031)
Obs.	7504	6673	2466	2551	9933
Adjusted R^2	0.508	0.216	0.519	0.358	0.215

Panel B	Commute time	Working time	Child-rearing time	Physical activity time
Highway density	−0.311*	3.134*	−0.345	−6.805**
	(0.181)	(1.584)	(0.815)	(3.039)
Obs.	15,856	8448	15,856	15,856
Adjusted R^2	0.214	0.072	0.026	0.115

Standard errors are shown in the parentheses and clustered at the community level. All regressions incorporate control variables at the individual, household, and city levels, as well as fixed effects for both year and city.
*$p < 0.1$; **$p < 0.05$; ***$p < 0.01$.

plays positive effect on regional economic growth, thus supporting the government more revenue to investment public health sector. There is a complementary effect between transportation and health investment, that is, the increase of transportation investment promotes the rapid increase of GDP, which in turn can guarantee the increase of health investment, thus achieving the best equilibrium of transportation and health investment under the optimal output growth rate.

Third, the improvement of transportation infrastructure not only enhances the trade efficiency, but also facilitates communication and dissemination of health information and knowledge. Populations living in low-income countries usually face poor knowledge about preventive healthcare services, investment returns, and the risks and costs associated with diseases. Studies have demonstrated that knowledge about health prevention can influence individual decisions regarding health investments (Meredith et al. 2013; Dowdy and Pai, 2012). transportation infrastructure can not only facilitate better healthcare services, but also raise health literacy through population mobility (Aggarwal, 2021), thus benefiting for health investments and using preventive healthcare services. To gain further insight, this article examines the influence of transportation infrastructure on individual health literacy. We asked whether individuals were aware of the components of dietary regulation. Column (5) of panel A in Table 11 show that the improvement of transportation infrastructure is positive associated with that whether they know dietary guidelines, which, in turn, leads to laborers making healthier behaviors.

Finally, transportation infrastructure can decline commuting time and enhance the time efficiency of other activities (Chen et al. 2024), allowing populations to dedicate more time to production, leisure activities, and health investment. However, it should also be noted Becker' time allocation theory, identifying substitution effects between work, health investment, and leisure (Becker, 1965). On the one hand, improved transportation infrastructure has positive economic effect by increasing the wages of laborers, prompting them to work longer hours to earn more money, thus reducing the time they spend on health investment, which has a negative effect on labor productivity and economic growth. On the other hand, the increased income may lead to more time demand for leisure and health investment. To determine the best equilibrium of time allocation between work, health investment, and leisure under the improved transportation infrastructure, this article further investigates how transportation infrastructure impact the time spent on commuting, working, caring for children, and exercising. Column 1 of panel B in Table 11 demonstrate that the enhancement of intercity transportation infrastructure has reduced the commuting time of laborers. Additionally, we have noticed an augmentation in the working time of laborers (column 2 of panel B in Table 11), which could be the cause of the rise in wages for laborers. The alterations to commuting and working time will modify their time allocation between health investment and leisure. However, we did not detect any enhancement in the time that laborers assign to their children under the improved transportation infrastructure, we noted a decrease in the time spent on their physical activities (as seen in columns 3 and 4 of panel B in Table 11). Since there is not definite boundary between leisure and health investment, it is reasonable to assume that leisure includes taking care of their own health. The results in panel B of Table 11 demonstrate a substitution effect between work and leisure, that is, the improvement of transportation infrastructure leads to an increase in income, causing laborers to spend more time on work lower time on investing their health.

The net effect of time allocation on individual health outcome depends on their leisure, income and health preferences, which are reflected by the utility function of Eq. (1). Typically, rural registered populations have lower health literacy and income level than urban household registered population, so it inevitably drives the rural household registered population to pursue more income instead of leisure when the transportation infrastructure is improved, thereby reducing their leisure time and health investment. On the other hand, urban household registered population may be more likely to prioritize leisure and health investment. Therefore, this paper further investigates the effect of time allocation among between rural and urban registered populations living in urban areas. The results in Appendix T5 demonstrate that the transportation infrastructure has significant effect on the time allocation of the rural household registered population. When the commuting time is reduced by the improved transportation infrastructure, they tend to take more time in work, and consequently, less in leisure, which may lead to adverse effect on their health outcome. This is also indirectly support the health improving effect of urban household registered population shown in Table 5.

It needs to be noticed that the improvement of transportation infrastructure has positive effect on the income of both urban and rural registered populations in Appendix T6, while it need to noticed that the intercity transportation infrastructure only increase the health literacy and health expenditure of urban registered populations and only decrease the leisure time of rural registered populations, so the net effect is significant for urban registered populations. It can be explained that rural registered populations have limited health literacy and income, so they are extremely sensitive to health expenditure due to their preference of risk aversion, thus resulting in low willing to increase health investment due to lower expected future earnings. When rural household registered population face the improved transportation infrastructure, they tend to increase working time and decline leisure time, so the net effect of rural registered populations does not get positive significant. Although this paper does not observe any significant change in the time allocation of urban household registered population under the improved transportation infrastructure, it captures significant improvement in their income and health literacy. Combining the increased government's investment in public health, the net health effect of urban registered populations is positive.

It can be seen that the health improvement effect of transportation is the result of all the influencing factors, it is not limited to the result of improved accessibility (Bell and van Dillen, 2018; Chen et al. 2021), Which is similar to Banerjee and Sachdeva's (2015) findings that the increase in healthcare usage comes not only from reduction in travel cost or increase in income but also from the increase in the awareness amongst individual and households, the improvement increase in social interaction within and between villages and in healthcare supply. Furthermore, we analyze the impact of transportation on urban health in the framework of endogenous growth, which consider the effect in a comprehensive analytical framework, because a single factor may also have a negative effect on individual health, and the net effect of health outcomes needs to be evaluated comprehensively, which depends on all the influencing factors.

Conclusions

This paper builds a general equilibrium model within the endogenous growth framework, which considers government transportation and health investment, economic growth, and time efficiency. This study firstly endogenizes labor's investment decision and government's investment decision into the general equilibrium model, which makes up for the problems that Grossman's health demand model neglects the production sector and the endogenous growth theory does not take into account the production of health capital of laborers. We explored the relationship between transportation improvement and the health outcomes of laborers. Finally, this study assesses the effect of both intra-city and inter-city transportation infrastructure on the health of urban laborers in China. The findings indicate that the intra-city road at community level does not show significant improving effect on the health outcome of urban laborers, yet the inter-city road at prefecture-level city shows significant positive impact on urban registered populations. Further analysis show that the inter-city road have significant health promotion effects on people living in county-level city or city with low medical resource distribution. The significant health improving effect from inter-city transportation infrastructure can be attributed to raising economic development to provide more public healthcare services, increasing individual income for better health investments, facilitating knowledge communication between laborers to increase health literacy, and optimizing time management for health benefiting activities. We have observed significant complementary effect between government transportation investment and urban health investment, the enhancement of transportation infrastructure also resulted in an increased supply of public health investment and subsequently healthcare services. There are a significant substitution effect between the working time and leisure time of rural household registered laborers, but no such effect is found in urban household registration laborers. Therefore, due to the income effect and improving health literacy from transportation infrastructure, it mainly improves the health level of urban registered populations. This is the first paper to estimate the multiple influence of road improvement on health outcome, rather than just focusing on the availability of healthcare services or the utilization of preventive healthcare services..

For county-level city with a large area and sparse population, it goes against the conception of rational economic assumptions to get an equal allocation of medical resources between county-level city and prefecture-level city. Enhancing the transportation infrastructure not only creates physical access, allowing patients to reach suitable areas without being hindered by transportation equity, but also increases the income and health literacy for residents, which is immensely beneficial for investing in health and improving health behavior. This study provides evidence to demonstrate that the health issues of urban populations can be addressed by enhancing their links with external economic and medical markets. This study also helps address the issue of inadequate health capital among cities with different administrative level from a wider viewpoint.

When improving Chinese health and health inequality, only improving the quality and distribution of medical resources is not the optimal solution. Excessive public health investment needs to be offset by other types of investment, which may damage economic growth and thus reduce the next phase of health investment. Fully using the positive externalities of transportation infrastructure is an optimal solution to improve the health of urban populations, especially those in small city. Therefore, appropriate policy should encourage multi-level medical cooperation across cities and hospitals to facilitate patients to access to optimal care, thus optimizing the maximizing the efficiency of medical resources. At the same time, through the transportation network, the staff of hospitals should be strengthened to disseminate health policies and health knowledge, thus improving the health literacy of residents, especially for people living in county-level city and areas with limited medical resources. Highly health literacy can guide residents in these areas to make positive health investments and time allocation, thus them engaging in more industrial activities with relatively high returns, and getting rid of the vicious circle of poverty due to illness. It support an ongoing policy debate, that is, whether costly transportation investments in remote areas can be justified by other external effect (Herberholz and Phuntsho, 2021). The cost of these policy applications is small relative to the cost of transportation infrastructure construction, but can bring large social benefits.

There are still some limitation in this study. Beyond the focus on the transportation infrastructure, this study needs to further consider other transportation infrastructure. The health improving effect can also be affected by high-speed railway, car-owners numbers and airplane, which still needs to explore the contribution of different means of transportation. This study did not obtain detailed information on the types of transportation vehicles for patients, so it was not possible to separate the contribution of transportation vehicles to the travel behavior of laborers. Future studies should also consider the impact of high-speed railway, car-owners numbers and airplane on individual health, as well as the competition and cooperation between different modes of transportation.

Data availability

The datasets used and/or analyzed during the current study are available from the corresponding author on request.

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Notes

1 https://www.worldbank.org/en/topic/urbandevelopment.
2 http://www.stats.gov.cn/xxgk/jd/sjjd2020/202301/t20230118_1892285.html.
3 The first-level hospital is a primary healthcare institution located in community health service centers, township health centers, and clinics in the city. It provides comprehensive services such as medical treatment, prevention, rehabilitation, and health care for local residents. On the other hand, The secondary hospital is situated at a county-level city and serves as a technical center for regional medical prevention. It monitors high-risk patients, receives primary referrals, and provides business and technical guidance to primary hospitals. Lastly, tertiary hospitals are located in municipal cities and are medical prevention technology centers with comprehensive medical treatment, teaching, and research capabilities.
4 Subjected to the urban–rural registered population system in China (also named as the hukou system), populations are defined by two different household registration status of rural and urban registered populations. urban populations are these persons who currently live in urban areas, including both rural and urban registered populations. With large rural registered populations moved to the urban area to live in recent decades, the rigid hukou system creates a distinct "floating population" in urban areas, which describes the population who live outside their household registration place for a long time (usually, it is 6 months and above). Rural registered populations living in urban areas usually face institutional discrimination, social stigma and marginalization, because the targeted populations of local policies are only the registered population living in the area, and the urban registered population usually enjoys higher social welfare than the rural registered population (Song and Smith, 2019).
5 According to the 7th National Population Census of China in 2020, the total number of people who left rural areas was 286 million, with 272 million of them moving into urban areas. Of these, 82 million went to the county they belong to, 100 million of who migrated to the province they belong to, and 82 million of who traveled to other provinces. Additionally, part of these populations who moved to other provinces also relocated to local county-level city.
6 https://www.cpc.unc.edu/projects/china.
7 https://www.nhc.gov.cn/guihuaxxs/c100133/202408/0c53d04ede9e4079afff912d71b5131c.shtml
8 https://new.qq.com/omn/20211124/20211124A02X7300.html.
9 To simplify the analysis, the mortality of child to adult and adult to old on the overall population are ignored.
10 This paper focuses on the impact of health, so it simplifies the impact of heterogeneous education on productivity, we only discusses the direct effect of health on productivity.
11 In China, urban registered population and rural registered population always face different medical insurance systems, and individuals with different household registration status can not arbitrarily change their faced medical insurance system

between each other. Urban registered population must purchase Basic Medical Insurance (BMI), while rural registered populations must purchase the new Rural Cooperative Medical Insurance (NRCMI). NRCMI offers high reimbursement rates and low minimum payment lines for medical treatment at township health centers, while their reimbursement rates is lower than that of the BMI if rural registered populations get medical treatment in tertiary hospital. In contrast, the minimum payment line of BMI is higher than that of the NRCMI, yet BMI offers a higher reimbursement rate and a wider range of reimbursable category of drugs than that of the NRCMI when urban registered populations get medical treatment in tertiary hospital. Therefore, when rural registered populations living in urban areas need to go to tertiary hospitals for serious illnesses, they will face price discrimination in healthcare services due to differences in the type of medical insurance.

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Author contributions

All authors contributed to this work. Daisheng Tang and Tao Bu worked on the study design and method. Tao Bu was responsible for manuscript design, data analysis and paper writing, while Daisheng Tang supervised analysis again. All authors critically reviewed and approved the final manuscript.

Competing interests

The authors declare no competing interests.

Ethical approval

Ethical approval was not required as the study did not involve human participants.

Informed consent

Informed consent was signed by participants.

Additional information

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Correspondence and requests for materials should be addressed to Daisheng Tang.

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