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Optimal Infrastructure Investments under a Two-tier Government Structure in the Global Economy

Weizhao Sun
University of Colorado Boulder

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Department of Economics

University of Colorado Boulder
Boulder, Colorado 80309

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Weizhao Sun[1]

Abstract

This paper develops a spatial equilibrium model to study endogenous infrastructure under a two-tier government structure where a benevolent national government, followed by self-interested provincial governments, optimally solves the planners' problems by allocating highways and tunnels to maximize aggregated welfare within their jurisdictions. I estimate the trade-cost mitigating effect of highways and tunnels by introducing two novel instrumental variables and incorporating bilateral elevation. The model is calibrated to 309 prefectures across 23 Chinese provinces. Results show that, compared to complete centralization, a two-tier approach promotes equality, lowering the Gini and Theil's index by 0.4 to 0.8 percent at the expense of lowering average real wage by 0.4 percent. In contrast, complete decentralization leads to a 2.36 percent decrease in average real wages and an 8 percent increase in inequality.

Keywords: spatial equilibrium; endogenous infrastructure; two-tier government; bilateral elevation; tunnel

JEL Classification: R13, R42, R53, H54, F12

[1] 256 UCB, Boulder, CO 80309, Weizhao.Sun@colorado.edu.

1 Introduction

Highway infrastructure is typically the result of collaborative planning between central and local governments. In the United States, the Federal Highway Administration coordinates the planning and funding of the Interstate Highway System, while state transportation departments manage state highways. A similar division of responsibilities exists in Germany, where the federal government oversees the Autobahn network, and state governments manage the Landesstraßen (state roads). In China, the central government plans the national expressways, while provincial governments are responsible for provincial expressways. This two-tier government structure, common across various countries, plays a crucial yet understudied role in shaping infrastructure development, especially in the context of trade models. Highways and tunnels are two crucial types of infrastructure. Although the economic benefits of highways, particularly in reducing trade costs, have been extensively studied, tunnels remain relatively underexplored by the literature despite their critical importance. Tunnels are essential for overcoming geographic obstacles and ensuring year-round connectivity but are more costly to build.

This paper examines how the interplay of centralization and decentralization influences the provision of highways and tunnels and the consequent effects on welfare and equality. I develop a quantitative spatial model where a benevolent national government, followed by self-interested provincial governments, optimally invests in highways and tunnels to maximize aggregated welfare within their jurisdictions. The model assumes that governments recognize that investments in highways and tunnels on a particular road have differentiated impacts in reducing trade costs and promoting regional and international trade. However, the model also assumes that provincial governments focus only on their jurisdictions, disregarding the spillover benefits and costs their investments impose on other provinces. This paper finds that central and provincial planning leads to divergent infrastructure outcomes despite assuming identical welfare-maximizing objectives and complete information. A collaborative effort between national and provincial governments in infrastructure planning preserves much of the efficiency gains from centralized planning while allowing provincial governments to address local needs and mitigate inequality.

The spatial model features a set of locations connected by the transport network and mobile workers with heterogeneous preferences across locations. Locations are heterogeneous in productivity, residential land, elevation level, and geographic position. In each location, monopolistically competing firms produce an endogenous measure of differentiated varieties in the spirit of Krugman (1980). These goods are traded between locations, including the rest of the world, with transport costs influenced by distance and bilateral elevation. The latter is an asymmetric measure that reflects trucks' costs when going uphills and downhills from origins to destinations, following Sun (2024). Locations can engage in international trade through ports. Building on the family of quantitative spatial models, this study is particularly aligned with Redding (2016) and Santamaria (2020), extending the framework by allowing for optimal investment decisions by both the leading national and the following provincial governments in a leader-follower manner, subject to endogenously determined budgets. I propose a solution to the planner's problem involving two tiers of government. The solution algorithm includes that, initially, the national government determines the total budget under a scenario with no infrastructure investment and allocates funds to provincial governments according to an exogenous plan. Subsequently, the national government optimally invests in highways and tunnels across all locations, subject to spatial equilibrium conditions. Provincial governments then solve their respective optimization problems, aiming to improve upon the preexisting national investments within their jurisdictions. Ultimately, locations receive investments from both national and provincial governments. The results indicate that a location is more likely to receive greater investment from its provincial government when it is relatively more central to the provincial trade network than to the national network. For instance, consider Boulder, Colorado. As the home of the University of Colorado, Boulder plays a significant role in the state's economy and has a substantial population. However, it is less critical within the broader U.S. transportation network. Thus, the model predicts that Boulder would attract more infrastructure investment from the state of Colorado than from the federal government.

To quantify the implications of the two-tier government structure, the model is calibrated to 309 prefectures across 23 provinces in China, using data primarily from 2019. An additional region representing the rest of the world is included, and 25 of China's largest coastal ports serve as gates for international trade. China provides an interesting case study for the two-tier government structure. China's expressway system, comprising National and Provincial Expressways, has undergone a significant transformation. Between 2015 and 2017, the approval power for various transportation projects, including local highways, was delegated to provincial governments. Overall China's infrastructure is governed by a complex system where national and provincial governments share authority over highway construction projects.

The impact of highways and tunnels in reducing internal trade costs in China is estimated using gravity equations, with the use of two novel shift-share instrumental variables (IVs). The first IV, for highways, is derived from historical courier routes and post stations from the Ming dynasty, arguing that the share of historical post stations predicts a region' s contemporary importance and centrality. The second IV, for tunnels, leverages the lithological distribution in China, exploiting the fact that some rock types are easier to drill through and using the relative abundance of these types of rock to construct the IV for tunnels. Cost-mitigating effects of highways and tunnels are found. The results indicate that highway density reduces the cost associated with distance, while tunnel density decreases the cost of bilateral elevation. A 0.01 unit increase in highway density reduces the cost of distance by 0.01174 percentage points, while a 0.01 unit increase in tunnel density reduces the cost of bilateral elevation by 0.00141 percentage points. To get a sense of how big 0.01 units are in highway density, for example, consider the case of Beijing and Tianjin: in 2019, Beijing had 819 kilometers of highway, and Tianjin had 1,128 kilometers. To increase the average highway density between the two cities by 0.01 units, the total increase in highway length would need to be approximately 275.65 kilometers.

Two counterfactual analyses are conducted. The first counterfactual analysis compares the efficiency and equality outcomes of the two-tier structure with those under complete centralization. The findings suggest that the two-tier structure promotes greater equality, lowering the Gini coefficient by 0.4 percent and Theil's index by 0.8 percent. This improvement stems from the provincial government's tendency to invest in central areas within their jurisdictions but peripheral to the nation—regions that would likely be neglected under centralization. However, this reduction in inequality comes at the expense of efficiency, measured by real wages, as the national government perceives provincial reallocations as misallocations. Consequently, the two-tier system results in a 0.4 percent decrease in the average real wage relative to a fully centralized approach.

The second counterfactual analysis assesses the effects of complete decentralization, revealing that a fully decentralized scenario results in lower aggregate welfare and higher inequality compared to the two-tier structure. The average real wage decreases by 2.36 percent, while the Gini and Theil indices increase by approximately 8 percent, dampening inequality. This outcome arises because provincial governments fail to internalize the spillover effects of their infrastructure investments in other provinces. This leads to underinvestment in critical trade routes connecting the western inland regions to the eastern coast. As a result, western landlocked provinces experience the most significant losses under decentralization, while coastal provinces benefit modestly due to their increased infrastructure investments and sustained access to international trade at relatively low costs.

This paper is related to four strands of literature. First, it is related to the literature on endogenous infrastructure investment. Balboni (2019) examines the dynamic effects of infrastructure investment in coastal Vietnam. Jannin and Sotura (2020) models how endogenous local public goods provided by local governments create spillovers across jurisdictional boundaries. Santamaria (2020) considers how the central government in Germany endogenously chose highway investments before and after the country's division, while Felbermayr and Tarasov (2022) explores how multiple planners non-cooperatively decide on transport infrastructure, explaining the border effect in Europe (also see Meurers and Moenius (2018) and Fajgelbaum and Schaal (2020)). This paper contributes to this strand by introducing a two-tier government structure to the endogenous infrastructure problem.

Second, this paper is related to the large literature on estimating the impact of infrastructure on trade. (See Faber (2014), Donaldson (2018), Asturias et al. (2019), Xu and Nakajima (2017), Jaworski and Kitchens (2019), Banerjee et al. (2020), Baum-Snow et al. (2020), Coşar et al. (2021), Gallen and Winston (2021), Loumeau (2023), Egger et al. (2023).) This paper contributes to this strand by investigating the impact of highways and tunnels on internal trade costs in China and introducing two novel instrumental variables to evaluate the impact of infrastructure. The first IV is based on historical courier routes from the Ming dynasty, and the second leverages the lithological distribution of China.[2]

Third, this paper is connected to the literature on the political economy of transport infrastructure. For instance, Brueckner and Selod (2006) examine how the socially optimal transport system contrasts with the one selected through the voting process, demonstrating that voting equilibria can lead to a transportation system that is slower and less costly than the social optimum. Glaeser and Ponzetto (2018) investigates how voters' perceptions of various transportation project costs can distort the types of projects chosen by politicians. Additionally, Fajgelbaum et al. (2023) analyzes how political preferences influenced the development of California's High-Speed Rail.[3] This paper contributes to this literature by exploring how the interaction between national and provincial governments affects infrastructure investment decisions.

Lastly, this paper is related to the research that utilizes spatial equilibrium models to analyze trade outcomes (see Redding (2016), Redding and Rossi-Hansberg (2017), Davis and Dingel (2019), Fajgelbaum and Schaal (2020), Allen and Arkolakis (2022), and Barwick et al. (2024)). This paper contributes to this literature by incorporating elevation as a location attribute, introducing bilateral elevation as an edge attribute, and allowing it to play a role in trade costs.

The rest of the paper is organized as follows: Section 2 introduces the background of China's highway system. Section 3 shows the stylized facts. Section 4 introduces the spatial equilibrium model, the government structure, and the solution algorithm. Section 5 details the calibration process. Section 6 presents the baseline and counterfactual results. Section 7 concludes.

[2]Also see Limao and Venables (2001), Turner (2006), Möller and Zierer (2018), Duranton and Turner (2012), Duranton and Turner (2011), and Duranton et al. (2014), Banerjee et al. (2020).

[3]Also see Castells and Solé-Ollé (2005) who empirically estimated the main determinants of the allocation of infrastructure investment among Spanish regions.

2 Background

2.1 China's National and Provincial Expressway System

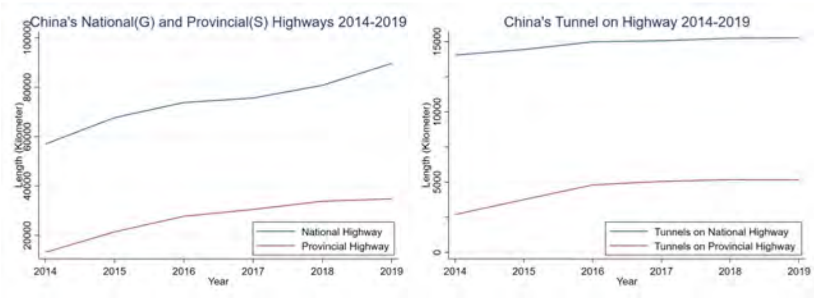
China's expressway network is one of the most extensive and well-developed in the world, comprising two major systems: the National Expressways (starting with "G," short for "Guodao," meaning "National Road" in Chinese) and the Provincial Expressways (starting with "S," short for "Shengdao," meaning provincial road in Chinese).

The National Expressway Network, also known as the National Trunk Highway System (NTHS), was conceived in the early 1990s. The network has been developed in phases. According to Xu and Nakajima (2017), "the first......National Trunk Highway System(NTHS)......was intended to connect transport hubs, main ports, all cities with a population above one million, and most cities with populations above 500,000." NTHS, also known as the "7918 Network," established a clear blueprint and laid the foundation for a coordinated and standardized approach to highway construction nationwide. In the 2000s, more national highways are extended to remote areas.

The Provincial Expressway Network complements the national network by providing links within provinces and to neighboring regions. This network expanded significantly in the early 2000s, focusing on less densely populated and economically underdeveloped areas. Provincial expressways are designed to meet local needs, connecting provincial capitals, major cities, airports, and ports. Although the standards for provincial expressways are generally comparable to national expressways, the total length of provincial highways and tunnels is shorter as of 2019, as shown in Figure (1). This is primarily due to the later commencement of provincial expressway development. When the provincial expressway networks began to expand, a substantial national expressway network was already in place.

National expressways are marked with a red background and white text on their signs. Provincial expressways are marked with a yellow background and black text on their signs. Based on their alignment, expressways are categorized into vertical, horizontal, radial, ring, connecting, and parallel lines, each differentiated by different numerical codes. The numbering of China's National Expressways uses one-digit, two-digit, and four-digit Arabic numerals, distinct from the three-digit numbering of national primary roads. The numbering is composed of a letter identifier and Arabic numerals. Capital radial lines use one-digit numbers, such as G1; vertical and horizontal lines use two-digit numbers, such as G35; city ring lines use two or four-digit numbers, such as G9511; and parallel lines and connecting lines also use four-digit numbers. The naming and numbering principles of the provincial expressways generally align with those of the national. The letter identifier for provincial expressways is "S."

The development of highway infrastructure in China from 1990 to the present follows a staged leader-follower style. In this approach, the national government acts as the leader by first establishing a substantial national expressway network, beginning in the 1990s. By the time provincial expressway networks began to expand significantly in the 2000s and 2010s, this national framework was already well-established. In addition, the national government releases its highway construction plans approximately every 8 to 10 years, outlining objectives for the next decade and beyond. This timing ensures that provincial governments are fully aware of the national government's plan when designing their own highways. For example, the national highway plan published in 2005 set clear goals for 2010 and outlined broader objectives for the 20 years that followed. The 2013 plan laid out the roadmap for highway development from 2013 to 2030. Most recently, the 2022 national highway plan set goals from 2022 to 2035, continuing this strategic planning process.



(a) Highways (b) Tunnels on Highways

Figure 1: China's Highways and Tunnels

Note: These figures show the length of highways and tunnels belonging to National (G) and Provincial (s) Expressway networks from 2014 to 2019.

2.2 Decentralization in Approval Authority of Infrastructure Projects

Since 2015, China has implemented significant reform in the approval processes for infrastructure projects. Three key documents issued by China's National Development and Reform Commission (NDRC) and State Council (SC) played a central role in these changes. The first document, NDRC (2015), significantly delegated approval authority for various transportation projects, including highways, to provincial governments. A subsequent document, SC (2016), further clarified that projects within the national highway network and national roads would be approved by provincial governments, provided that they adhere to the national plan. It also stipulated that local highway projects should be approved at the provincial level, while other road projects should be entrusted to local governments.

Building on these reforms, additional measures were introduced in NDRC (2017) to streamline the approval process further. By 2018, the NDRC had reduced its involvement in transportation project approvals by over 90 percent, retaining authority only for major projects requiring substantial public funds, resources, or complex coordination. Provincial governments were given the responsibility to approve the preliminary stages of highway construction, including the feasibility reports, design, and construction bidding, as outlined in the "Guidelines for Preliminary Work on Expressway Construction Projects" by the Department of Transportation of Zhejiang Province. According to this document, the approval authority for provincial highway projects has been fully delegated to provincial governments. Specifically, it states that projects such as the reconstruction and expansion of the national expressway network, general national and provincial road construction, and similar infrastructure projects have been handed over to provincial governments for approval, with only a few exceptions. This delegation of authority allows provincial governments to plan and approve these highway projects within their jurisdictions.

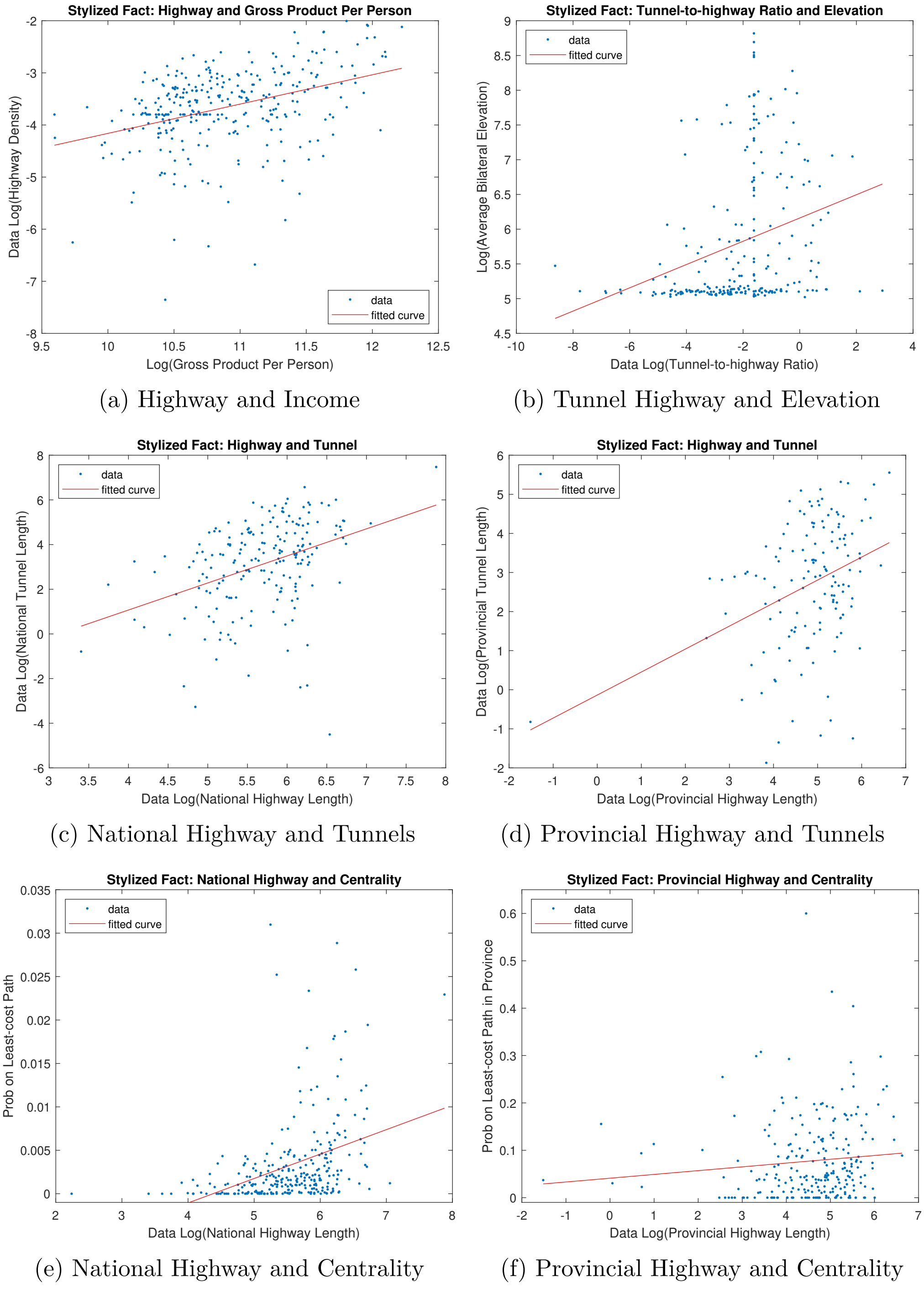
3 Stylized Facts

This section presents five stylized facts illustrated in Figure (2), which not only offer interesting insights but also provide guidance for structuring the model. First, Panel (a) reveals a positive correlation between highway length in each prefecture and local income, measured by gross product per person. This correlation hints at potential two-way causality: on the one hand, infrastructure investments play a crucial role in driving welfare and economic growth; on the other, governments prioritize wealthier regions when allocating infrastructure investments.

Second, prefectures with higher average bilateral elevation to destinations across the country tend to exhibit higher tunnel-to-highway ratios, as depicted in Panel (b). Bilateral elevation, calculated as per equation (21), reflects the average change in elevation trucks must traverse when transporting goods from origin to destination. This observation suggests that tunnels are primarily constructed in regions where elevation significantly increases trade costs, indicating a strategic use of tunnels to mitigate these geographic barriers and reduce transportation costs associated with steep terrains.

Third, Panel (c) reveals a positive correlation between national highways and tunnels, while Panel (d) shows a similar correlation at the provincial level, underscoring the complementary relationship between highways and tunnels across both tiers of government. This suggests that highways and tunnels should be modeled as complementary goods, such that governments aiming to reduce trade costs will naturally invest in both types of infrastructure, especially in regions with substantial bilateral elevation relative to the rest of the country.

The fourth and fifth stylized facts emphasize that governments at both levels tend to prioritize infrastructure planning in regions that are central to their respective jurisdictions. Fourth,



(a) Highway and Income (b) Tunnel Highway and Elevation

(c) National Highway and Tunnels (d) Provincial Highway and Tunnels

(e) National Highway and Centrality (f) Provincial Highway and Centrality

Figure 2: Stylized Facts

Note: These figures demonstrate several stylized facts that provide guidance for model assumptions. Data points are at the prefecture level. Panel (a) shows a positive correlation between highway density and gross product per person, a measure of income. Panel (b) shows a positive correlation between the tunnel-to-highway ratio and the average bilateral elevation to destinations. Panels (c) and (d) show positive correlations between the length of highways and tunnels for national expressways and provincial expressways. Panel (e) shows a positive correlation between national highways and centrality within the nation. Panel (f) shows a positive correlation between provincial highways and centrality within provinces.

Panel (e) indicates that the length of national highways in prefectures is positively correlated with the likelihood of being on the least-cost path, a metric representing the geographic centrality of prefectures within China. These least-cost paths, calculated using Dijkstra's algorithm, minimize transportation costs due to distance and bilateral elevation, as specified in the transportation cost function in Equation (23). The probabilities reflect natural geographic centrality, assuming zero infrastructure investment.

Fifth, Panel (f) demonstrates that the length of provincial highways in prefectures is positively correlated with the likelihood of being on the least-cost path within each province. These probabilities, calculated similarly to those in Panel (e), are constrained to origin and destination pairs within the same province, capturing within-province geographic centrality. The last two facts hint at the model assumption that centrality should be a key determinant of infrastructure investment decisions. More central regions, whether in relation to the country or their respective provinces, are likely to attract greater investment in highways and tunnels because of their strategic importance in reducing trade costs for other regions.

4 Theory

4.1 A Spatial Equilibrium Model

The model follows Redding (2016) and Santamaria (2020). There are $N+1$ regions in the model, N regions within the country, and one additional region representing the rest of the world(ROW). Each location, $i, n \in N+1$, is endowed with exogenous land, H_n, exogenous elevation level, E_n, and exogenous productivity, A_n. There are L workers within the country. Workers are perfectly mobile across locations within the country with no migration costs and immobile across countries.

The assumption of perfectly mobile labor in China is a simplification, especially given that migration costs within China are well-documented and widely recognized by economists. By relying on this assumption, the model likely underestimates the true potential of the two-tier government structure to mitigate inequality. Introducing migration costs would create persistent wage disparities that cannot be easily mitigated by labor movements. As the national government continues to focus its investments on central regions, the resulting wage increases in those areas would be exacerbated, with fewer offsetting labor inflows to dampen the rise. However, under a two-tier system where provincial governments allocate more resources to peripheral areas, the redistribution of infrastructure investments could have a much greater impact on reducing inequality. Therefore, the model likely provides a lower bound for the two-tier government structure's ability to mitigate inequality. However, the author believes that relaxing the assumption of labor mobility would not change the direction of the findings.

In this model, workers either produce goods inelastically in their location of residence or are hired as construction workers for infrastructure. Each worker ω draws $b_n(\omega)$, an idiosyncratic preference parameter for each location, from a Fréchet distribution.

$$G_{b_n}(b) = prob(b_n \leq b) = e^{-B_n b^{-\epsilon}} \tag{1}$$

where ϵ is the shape parameter and B_n is the location parameter. The preference for the worker ω, living in location n, depends on consumption $C_n(\omega)$, housing $H_n(\omega)$, and idiosyncratic preference shock for the location of residence $b_n(\omega)$.

$$U_n(\omega) = b_n(\omega)(\frac{C_n(\omega)}{\alpha})^{\alpha}(\frac{H_n(\omega)}{1-\alpha})^{1-\alpha} \tag{2}$$

where parameter α governs the share of tradable goods. The consumption index in location n, C_n, depends on endogenously-determined quantity M_i of differentiated varieties z.

$$C_n = [\sum_i^N \int_0^{M_i} c_{in}(z)^{\frac{\sigma-1}{\sigma}} dz]^{\frac{\sigma}{\sigma-1}} \tag{3}$$

where $\frac{\sigma-1}{\sigma}$ is the elasticity of substitution between goods. The production follows Krugman (1980) and is characterized by monopolistic competition. Each firm supplies a unique variety. Let $l_n(z)$ be the labor required to produce $q_n(z)$ units of the variety z in location n. $l_n(z)$ is given as:

$$l_n(z) = F + \frac{q_n(z)}{A_n} \tag{4}$$

The profit maximization price for variaty z,$p_n(z)$, at the factories' gate is:

$$p_n(z) = \frac{\sigma}{\sigma-1}\frac{w_n}{A_n} \tag{5}$$

where w_n is the wage in location n, and A_n is the productivity. Consumer price $p_{in}(z)$ of goods produced in i, and consumed in n is given as:

$$p_{in}(z) = p_i(z) * T_{in} = \frac{\sigma}{\sigma-1}\frac{w_i}{A_i}T_{in} \tag{6}$$

$T_{in} \geq 1$ is the iceberg transportation cost for shipping one unit of goods from i to n. Free entry drives profits to zero, which helps determine the optimal quantity, $y_n(z)$, that each firm produces.

$$y_n(z) = (1-\sigma)A_n F \tag{7}$$

where F is the fixed cost of production. In equilibrium, the optimal quantities, $y_n(z)$, will require $l_n(z)$ units of labor.

$$l_n(z) = \sigma F \tag{8}$$

Labor market clearing condition for each location suggests that the number of firms (and varieties), M_n, in each location is determined by local labor supply after infrastructure construction:

$$M_n = \frac{(1-\lambda)L_n}{\sigma F} \tag{9}$$

where λ is the share of construction workers in the labor force. Workers solve the utility maximization problem for optimal consumption, C_n^*, and housing, H_n^*, given budget v_n.

$$C_n^* = \alpha \frac{v_n}{P_n} \tag{10}$$

where P_n is the price index.

$$H_n^* = (1-\alpha)\frac{v_n}{r_n} \tag{11}$$

where r_n is the rent. The indirect utility of worker ω is:

$$U_n^*(\omega) = \frac{b_n(\omega)v_n}{P_n^{\alpha} r_n^{1-\alpha}} \tag{12}$$

The indirect utility is a transformation of $b_n(\omega)$, which has a Fréchet distribution.

$$G_n(U) = Pr(U_n^* \leq u) = e^{-\Phi_n u^{-\epsilon}} \tag{13}$$

where $\Phi_n = \frac{v_n}{P_n^{\alpha} r_n^{1-\alpha}}$. The expectation of the indirect utility, $\bar{U}$, of worker ω in n is the same across all locations and equals that for the nation as a whole.

$$\bar{U} = \Gamma(\frac{\epsilon - 1}{\epsilon})\Big[\sum_{n \in N}(v_n / P_n^{\alpha} r_n^{1-\alpha})^{\epsilon}\Big]^{\frac{1}{\epsilon}} \tag{14}$$

where Γ is the gamma function. This is the objective function of the social planner's problem. Expenditure share is derived from CES expenditure function, equilibrium price p_{in}, and labor market clearing condition:

$$\pi_{in} = \frac{X_{in}}{X_n} = \frac{M_i p_{in}^{1-\sigma}}{\sum_{k\in N} M_k p_{kn}^{1-\sigma}} = \frac{(1-\lambda)L_i}{\sigma F}(\frac{\sigma}{\sigma-1}\frac{w_i}{A_i}T_{in})^{1-\sigma}P_n^{\sigma-1} \tag{15}$$

where $X_{in} = M_i p_{in}^{1-\sigma}$ is the expenditure on goods produced in i and consumed in n. X_n is the total expenditure in location n. The price index is defined as:

$$P_n^{1-\sigma} = \sum_k M_k p_{kn}^{1-\sigma} = \sum_k \frac{(1-\lambda)L_k}{\sigma F}(\frac{\sigma}{\sigma-1}\frac{w_k}{A_k}T_{kn})^{1-\sigma} \tag{16}$$

Similar to Redding (2016), the expenditure on land in each location is redistributed lump-sum to the workers residing there. Therefore, the before-tax income in location n is the following:

$$w_n L_n + (1-\alpha)v_n L_n = \frac{w_n L_n}{\alpha} \tag{17}$$

where $v_n = \frac{w_n}{\alpha}$. The national government imposes a flat tax on households' total income with tax rate $\tau < 1$. So, the aggregate income after-tax in location n is:

$$v_n L_n = (1-\tau)\frac{w_n L_n}{\alpha} \tag{18}$$

and the aggregate tax income is

$$\tau \sum_n \frac{w_n L_n}{\alpha} \tag{19}$$

The probability, $\pi_n(\omega)$, that a worker ω chooses location n is the probability that living in n gives the highest utility:

$$\begin{aligned}\pi_n(\omega) &= Pr(U_n(\omega) \geq max[U_k(\omega), \forall k \neq n.]) \\ &= \frac{(v_n/P_n^{\alpha} r_n^{1-\alpha})^{\epsilon}}{\sum_{k\in N}(v_k/P_k^{\alpha} r_k^{1-\alpha})^{\epsilon}}\end{aligned}$$

Therefore, labor supply in location n is:

$$L_n = \pi_n(\omega) * L = \frac{(v_n/P_n^{\alpha} r_n^{1-\alpha})^{\epsilon}}{\sum_{k\in N}(v_k/P_k^{\alpha} r_k^{1-\alpha})^{\epsilon}} L \tag{20}$$

The geography of the model contains $N+1$ locations and $N+1$ regions. One region contains one location, which is assumed to be the region's center. There are N regions in the nation and one additional region representing the rest of the world. Locations of two adjacent regions are connected by edges(links). Edges serve as roads, and goods can only be transported along edges between two adjacent locations. Figure (3) shows N locations and edges in the sample. The rest of the world is connected to the port regions, allowing the export and import of goods via ports. There are two edge-specific exogenous attributes, distance and effective bilateral elevation (EBE) following Sun (2024), assumed to be costly for goods transportation. Let $dist_{in}$ be the length of edges (distance) between two adjacent locations i, n. Distance is symmetric $dist_{in} = dist_{ni}$. Besides distance, this paper includes elevation as a location endowment and effective bilateral elevation as an edge attribute in order to evaluate the influence of tunnels. As shown in Equation (23), tunnels are assumed to mitigate the trade cost of EBE. EBE from location i to neighboring location n is denoted as $elev_{in}$ and defined as follows:

$$elev_{in} = \frac{|Elev_n - Elev_i| * w_{grade}}{dist_{in}} \tag{21}$$

where $w_{grade} > 0$ is the trucks' fuel-consumption ratio of driving on the road with a specific

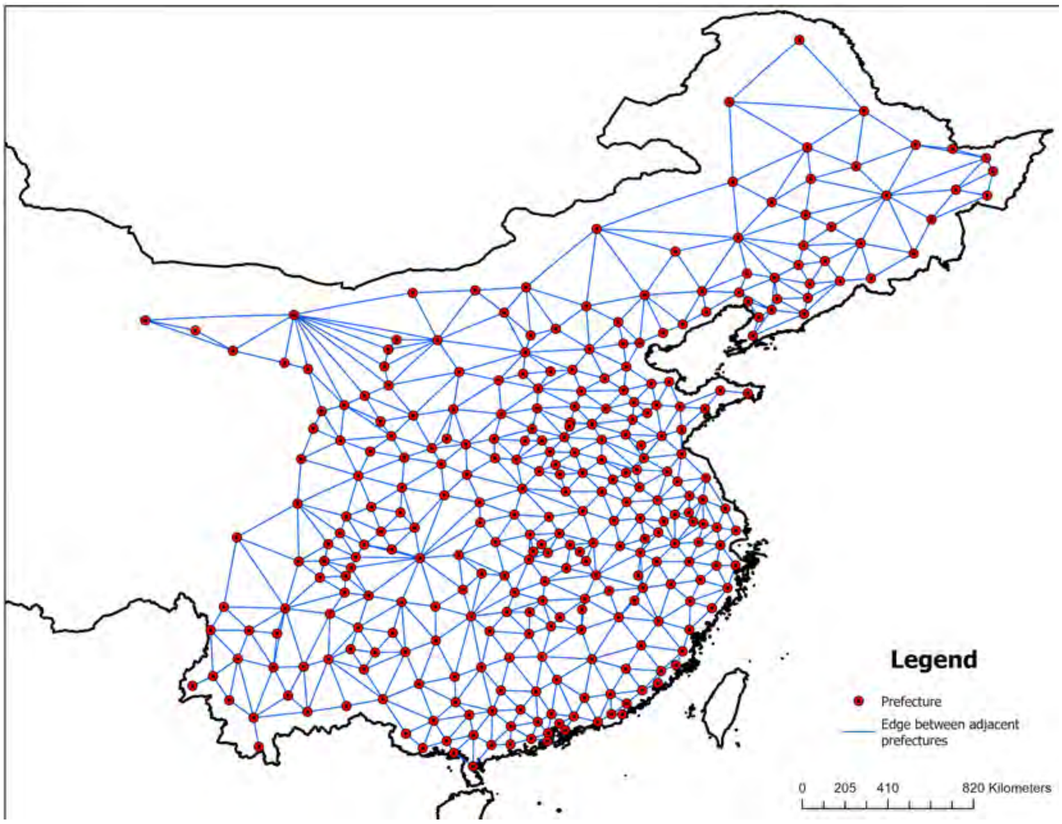


Figure 3: Locations and Edges

Note: This figure illustrates the distribution of locations and edges in the model. The locations are in the center of prefectures in China. Locations of adjacent prefectures are connected by edges.

grade (slope). w_{grade} is greater than one for uphill roads and less than one for downhill roads, indicating that uphills are more costly than downhills. Therefore, EBE is asymmetric, $elev_{in} \neq$

$elev_{ni}$. Specifically, if location i has a higher altitude than location n, traveling from n to i (ascending uphill) results in a larger EBE than the reverse direction, meaning $elev_{in} < elev_{ni}$. The bilateral elevation in this paper is simplified from Sun (2024) in that it only depends on the elevation level at the origin and destination and not on roads, as infrastructure is endogenous in this paper. In addition, note that distance and EBE only along the edge of two adjacent locations are relevant for this paper, as shown by the trade cost functions in Equations (23) and (25).

The elevation measure used in this paper is related to Nunn and Puga (2012) and Hirte et al. (2020), who create measures to quantify the impact of geographical barriers to trade. Also, see Fajgelbaum and Schaal (2020), who evaluate the impact of mountains in optimal infrastructure networks in a quantitative spatial model.

Endogenously determined infrastructure (highways and tunnels) can be constructed in each region to mitigate the transportation cost from distance and elevation. Let ϕ_n^r and ϕ_n^t denote the length of highways and tunnels built in region n, respectively, measured in kilometers. Also, define highway and tunnel density in each region as $\rho_n^r = \frac{\phi_n^r}{area_n}$ and $\rho_n^t = \frac{\phi_n^t}{area_n}$, where $area_n$ is the area of region n. To build infrastructure, construction workers compensated at the local wage rate are hired by two tiers of government. The construction is funded by an endogenously raised government income based on an exogenous flat-rate income tax. It is assumed that workers can build infrastructure in any region, not restricted to the worker's location of residence. In other words, local infrastructure is not required to be built by local workers.[4] For simplicity, it is further assumed that the same proportion of labor in each region is hired as construction workers.[5] Let $\lambda < 1$ denote the share of construction workers in the labor force. λ will be determined endogenously after the optimal infrastructure. Each kilometer of highways and tunnels require c_n^r and c_n^t units of workers, respectively. Let L_n^{infra} denote the number of construction workers in each region.

$$L_n^{infra} = c_n^r * \phi_n^r + c_n^t * \phi_n^t = \lambda L_n \tag{22}$$

Construction workers are compensated at the local wage rate. The total government expenditure paid to construction workers is $G = \sum_n w_n * L_n^{infra} = \lambda \sum_n w_n * L_n$.

Trade cost is modeled as follows. Define adjacent-location-pair-specific costs as t_{in} for an adjacent

[4] This assumption is trivial for most regions with abundant labor supply. It comes in handy when a region with a small population needs to borrow labor from other areas due to insufficient local labor supply. In this case, labor borrowing takes place implicitly when the model is solved as long as there is enough labor for the country as a whole.

[5] This simplifying assumption assumes that every region has a positive quantity of labor left to produce goods.

location pair, i, n.

$$t_{in} = exp\left[\frac{1}{2} * \frac{(\beta_{dist} + \beta^r_{dist}\rho^r_i) * log(dist_{in})}{1-\sigma} + \frac{1}{2} * \frac{(\beta_{dist} + \beta^r_{dist}\rho^r_n) * log(dist_{in})}{1-\sigma}\right]$$
$$* \, exp\left[\frac{1}{2} * \frac{(\beta_{elev} + \beta^t_{elev}\rho^t_i) * log(elev_{in})}{1-\sigma} + \frac{1}{2} * \frac{(\beta_{elev} + \beta^t_{elev}\rho^t_n) * log(elev_{in})}{1-\sigma}\right] \quad (23)$$

where $\rho^r_i = \frac{\phi^r_i}{area_i}$ and $\rho^t_i = \frac{\phi^t_i}{area_i}$ represent the highway and tunnel density(length per area). β_{dist} and β_{elev} are coefficients that governs the trade costs from distance and EBE, respectively. β^r_{dist} is the coefficient on the interaction term between distance and highways, which shows the trade cost mitigating effect of highways. Similarly, β^t_{elev} is the coefficient on the interaction term between EBE and tunnels which indicates the trade cost mitigating effects of tunnels. Equation (23) will be estimated using IV in Section (5) to evaluate the values of the coefficients. Equation (23) assumes three things: First, distance and bilateral elevation are costly for transportation, so that β_{dist} and β_{elev} are expected to be negative. Secondly, highway density mitigates the cost of distance, and tunnel density mitigates the cost of bilateral elevation so that β^r_{dist} and β^t_{elev} are expected to be positive. Third, the weight, $\frac{1}{2}$, assumes that infrastructure in the origin and destination has equal impacts in reducing trade costs along the connecting edge.

Next, for any two locations k and l that may not be adjacent, the cost of going from k to l is the product of the costs of traversing all edges on the least-cost path. These least-cost paths are determined using Dijkstra's algorithm, which accounts for the level of infrastructure investments. When infrastructure investments change, paths will be endogenously re-routed if the current path no longer represents the least-cost option. Define $\mathcal{I}^{in}_{kl}$ as the indicator function that shows whether the edge from i to n is on the least-cost path from k to l.

$$\mathcal{I}^{in}_{kl} = \begin{cases} 1 & \text{if edge from } i \text{ to } n \text{ is on the least-cost path between } k \text{ and } l \\ 0 & \text{if edge from } i \text{ to } n \text{ is not on the least-cost path between } k \text{ and } l \end{cases} \quad (24)$$

Lastly, the general form of trade costs from any origin k to any destination l is the following:

$$T_{kl} = \prod_{in \in \mathcal{L}} (t_{in} | \mathcal{I}^{in}_{kl} = 1) \quad \forall k, l \in N \quad (25)$$

where $\mathcal{L}$ is the set of all edges.

4.2 General Equilibrium

The following equations solve the spatial general equilibrium. Goods market clears:

$$w_n L_n = \sum_{n \in N} \pi_{in} w_n L_n = \sum_{n \in N} \frac{(1-\lambda)L_i}{\sigma F} (\frac{\sigma}{\sigma - 1} \frac{w_i}{A_i} T_{in})^{1-\sigma} P_n^{\sigma - 1} w_n L_n$$

Trade cost along the least-cost path:

$$\text{argmin} T_{k,l} = \prod_{in \in \mathcal{L}} (t_{in} | \mathcal{I}_{in}^{in} = 1)$$

Labor market clears:

$$L_n = \pi_n(\omega) * L = \frac{(v_n / P_n^{\alpha} r_n^{1-\alpha})^{\epsilon}}{\sum_{k \in N} (v_k / P_k^{\alpha} r_k^{1-\alpha})^{\epsilon}} L$$

where and $\sum_i L_i = L$. Price index:

$$P_n^{1-\sigma} = \sum_k \frac{(1-\lambda)L_k}{\sigma F} (\frac{\sigma}{\sigma - 1} \frac{w_k}{A_k} T_{kn})^{1-\sigma}$$

Rent:

$$r_n = \frac{1-\alpha}{\alpha} \frac{w_n L_n}{H_n}$$

The four equations above solve the: $\{w_n, L_n, P_n, r_n\}$.

4.3 Government Structure

Infrastructure is determined by two tiers of government: the national government and the provincial government. The national government collects tax income and reallocates a portion to the provincial governments. Let Z denote the tax income the national government keeps for itself. Let $p \in \mathcal{P}$ denote the index for provinces. Let Z_p be the tax income allocated to the provincial government, p. While the total budget is endogenously solved, the budget allocation plan is exogenous and will be calibrated to match the observed provincial highway distribution in China in 2019. Keeping the reallocation plan exogenous is crucial in order to study its impact on the counterfactual analyses. Equation (26) shows that the total government income is split between two tiers of government.

$$Z + \sum_p Z_p = \tau \sum_n \frac{w_n L_n}{\alpha} \tag{26}$$

Let $\phi^r_{upper,n}$ be the investment on highways in location n from the national government. Let $\phi^r_{lower,n}$ be the provincial investment on highways in location n. Let $\phi^t_{upper,n}$, and $\phi^t_{lower,n}$ be the investments in tunnels from national and provincial governments, respectively. Let ϕ^r_n and ϕ^t_n be the total investment in highways and tunnels in location n. All investments are measured in kilometers.

$$\phi^r_n = \phi^r_{upper,n} + \phi^r_{lower,n} \tag{27}$$

$$\phi^t_n = \phi^t_{upper,n} + \phi^t_{lower,n} \tag{28}$$

With a budget of Z, the national government solves the following social planner's problem by maximizing the expected utility for the country:

$$\underset{(\phi^r_{upper,n},\phi^t_{upper,n})}{Max} \bar{U} = \Gamma(\frac{\epsilon-1}{\epsilon})\Big[\sum_{n\in N}(v_n/P_n^{\alpha}r_n^{1-\alpha})^{\epsilon}\Big]^{\frac{1}{\epsilon}} \tag{29}$$

subject to the budget constraint in Equation (30) and the construction worker labor supply constraint in Equation (31). In practice, the labor supply constraint is almost always non-binding. This is because the tax rate will be calibrated to be relatively small so that only a small fraction of workers are hired as construction workers. Moreover, the government's problem is implicitly subject to the equilibrium conditions of the spatial equilibrium model.

$$Z \geq \sum_{n\in N} w_n L_n^{infra} \tag{30}$$

$$\frac{\sum_{n\in N} L_n^{infra}}{\sum_{n\in N} L_n} \leq 1 \tag{31}$$

Unlike the national government, which takes care of the nation, provincial governments are self-interested. Provincial governments $p \in \mathcal{P}$ with budget Z_p improves upon the national government's equilibrium outcome by building infrastructures within their province. Without loss of generality, let p also denote the set of locations in the provincial government's jurisdiction. Let $n \in p \in N$ be the locations within province p of the country N. It is assumed that provincial governors maximize the expected utility of people only within their jurisdiction. The planner's problem for provincial governments is given as

$$\underset{(\phi^r_{lower,n},\phi^t_{lower,n})}{Max} \quad \bar{U}_p = \Gamma(\frac{\epsilon-1}{\epsilon})\Big[\sum_{n}^{p}(v_n/P_n^{\alpha}r_n^{1-\alpha})^{\epsilon}\Big]^{\frac{1}{\epsilon}} \tag{32}$$

subject to the budget constraint and the labor supply constraint below.

$$Z_p \geq \sum_{n}^{p} w_n L_n^{infra} \quad \forall p \tag{33}$$

$$\frac{\sum_{n\in p} L_n^{infra}}{\sum_{n\in p} L_n} < 1 \quad \forall p \tag{34}$$

The problem of provincial government p is implicitly subject to the equilibrium conditions for locations within province p.

4.4 Solution Algorithm

Following the steps below, I solve the model for the optimal infrastructure investments of the national and provincial governments while adhering to their leader-follower relationship, as discussed in section 2.

1. Starting with zero investment, the trade cost matrix is updated, and the spatial equilibrium is solved using an iterative procedure. This process yields initial wages. The government tax income is then calculated based on initial wages and then allocated to different governments.
2. The National government starts with zero investments in infrastructure.
3. The trade cost matrix is updated. Spatial equilibrium is solved using an iterative procedure. The expected utility in equilibrium is calculated.
4. An interior-point algorithm is used to take a utility-maximizing step to obtain investment in highways $\phi^r_{upper,n}$, and tunnels $\phi^t_{upper,n}$.
5. Go back to step 3 and repeat until convergence to a local optimum.
6. Optimal investment from the national government $(\phi^{r*}_{upper,n}, \phi^{t*}_{upper,n})$ is found, and the national government's problem is solved.
7. Provincial governments update the trade cost matrix with optimal investment of the national government and continue to improve upon them. Each provincial government solves for the optimal provincial investment, $(\phi^{r*}_{lower,n}, \phi^{t*}_{lower,n})$, following the same procedure in steps 3-5.

4.5 Model Predictions

Let's start by considering the Lagrangian of the national government's problem:

$$
\begin{aligned}
\mathcal{L} =& \Gamma(\frac{\epsilon-1}{\epsilon})\Big[\sum_{n\in N}(v_n/P_n^{\alpha}r_n^{1-\alpha})^{\epsilon}\Big]^{\frac{1}{\epsilon}} \\
& - \sum_{n}^{N}\mu_{n,1}\Big[w_nL_n - \sum_{i\in N}\frac{(1-\lambda)L_i}{\sigma F}(\frac{\sigma}{\sigma-1}\frac{w_i}{A_i}T_{in})^{1-\sigma}P_n^{\sigma-1}w_nL_n\Big] \\
& - \sum_{n}^{N}\mu_{n,2}\Big[\frac{(v_n/P_n^{\alpha}r_n^{1-\alpha})^{\epsilon}}{\sum_{k\in N}(v_k/P_k^{\alpha}r_k^{1-\alpha})^{\epsilon}} - \frac{L_n}{L}\Big] \\
& - \sum_{kl\in\mathcal{L}}\mu_{kl,3}\Big[\prod_{in\in\mathcal{L}}(t_{in}|\mathcal{I}_{kl}^{in}=1) - T_{kl}\Big] \\
& - \mu_4(\sum_{n\in N} w_n(c_n^r\phi_{upper,n}^r + c_n^t\phi_{upper,n}^t) - Z) \\
& - \mu_5(\frac{\sum_{n\in N}L_n^{infra}}{\sum_{n\in N}L_n} - 1)
\end{aligned} \tag{35}
$$

where $\mu_{n,1}$, $\mu_{n,2}$, $\mu_{kl,3}$, μ_4 and μ_5 are the Lagrangian multipliers. In practice, the construction worker supply constraint is not binding, so $\mu_5 = 0$. The first-order condition with respect to $\phi_{upper,n}^r$ implies:

$$
\begin{aligned}
&\frac{\partial\mathcal{L}}{\partial\phi_{upper,m}^r} = 0: \\
&\underbrace{\frac{\partial\bar{U}}{\partial\phi_{upper,m}^r}}_{\text{Direct Effect}} + \underbrace{\sum_n\sum_i\mu_{n,1}\frac{\partial x_{in}}{\partial\phi_{upper,m}^r}}_{\text{Wage Effect}} + \underbrace{\sum_n\sum_i\mu_{n,2}\frac{\partial\frac{L_n}{L}}{\partial\phi_{upper,m}^r}}_{\text{Labor Effect}} + \underbrace{\mu_3\frac{\partial T_{kl}}{\partial\phi_{upper,m}^r}}_{\text{Path Effect}} = \underbrace{\mu_4 w_m c_m^r}_{MC}
\end{aligned} \tag{36}
$$

where $x_{in} = M_i p_{in}^{1-\sigma} = \frac{(1-\lambda)L_n}{\sigma F}(\frac{\sigma}{\sigma-1}\frac{w_i}{A_i}T_{in})^{1-\sigma}$ is the expenditure on goods produced in i and consumed in n. Equation (36) suggests that infrastructure affects local outcomes in four ways. First, through the direct effect, infrastructure lowers edge-specific trade costs, which reduces the consumer prices of goods and increases their utility. Second, there is the wage effect, in which wages are influenced by changes in trade flow. Thirdly, the labor effect influences households' residence choices, leading to labor reallocation. Fourthly, there is the path effect in which new infrastructure may redirect the least-cost paths.

For the purpose of simple intuitions, let's focus on the direct effect and assume that only the edge-specific cost is altered by infrastructure while labor, wage, rent, and paths are unaffected. Let

$U_n = v_n / P_n^{\alpha} r_n^{1-\alpha}$. The marginal utility from investment on highways is:

$$\frac{\partial \bar{U}}{\partial \phi^r_{upper,m}} = \frac{1}{2} C_1 C_2 * \sum_i^N x_{in} * \left[\sum_x^V \mathcal{I}^{xm}_{kl} \frac{\beta^r_{dist} log(dist)_{xm}}{area_m} + \sum_x^V \mathcal{I}^{mx}_{kl} \frac{\beta^r_{dist} log(dist)_{mx}}{area_m} \right] \tag{37}$$

where $C_1 = -\alpha(\bar{U})^{-1} \sum_n U_n^{\epsilon} P_n^{\sigma-1}$ and $C_2 = \frac{1}{1-\sigma}$. $\mathcal{I}^{xm}_{kl} = 1$ if edge xm is on the least-cost path from k to l. $\mathcal{I}^{xm}_{kl}$ can be viewed as a measure of geographic centrality because location m is more likely to be on one of the least-cost paths if the location is central. V is the set of all locations near m. Derivation of the marginal utility can be found in Appendix A.1. Similarly, one can derive the marginal utility with respect to investment in tunnels.

$$\frac{\partial \bar{U}}{\partial \phi^t_{upper,m}} = \frac{1}{2} C_1 C_2 * \sum_i^N x_{in} * \left[\sum_x^V \mathcal{I}^{xm}_{in} \frac{\beta^t_{elev} log(elev_{xm})}{area_m} + \sum_x^V \mathcal{I}^{mx}_{in} \frac{\beta^t_{elev} log(elev_{mx})}{area_m} \right] \tag{38}$$

Equations (37) and (38) show that the marginal return of infrastructure investment in location m is positively affected by three factors. First, greater trade flow, x_{in}, that passes through location m increases the return. Note that trade flows originating from m and terminating at m are two special cases that pass through m. Second, the return correlates positively with nationwide centrality, measured by $\mathcal{I}^{mx}_{kl}$ $\forall x \in V$. Lastly, higher trade costs, $dist_{xm}$ and $elev_{xm}$, also increase the return. Thus, the model predicts that infrastructure investment in m will be higher for three cases: if it is a crucial importer/exporter, if it is central to the country, and if distances or bilateral elevations to other regions are significant.

Next, let's consider the relative marginal utility per dollar between highways and tunnels.

$$\begin{aligned}
&\frac{MU^r_{upper,m}/MC^r}{MU^t_{upper,m}/MC^t} \\
&= \frac{\frac{1}{2} C_1 C_2 * \sum_n x_{in} * \left[\sum_x^V \mathcal{I}^{xm}_{in} \frac{\beta^r_{dist} log(dist)_{xm}}{area_m} + \sum_x^V \mathcal{I}^{mx}_{in} \frac{\beta^r_{dist} log(dist)_{mx}}{area_m} \right]}{\frac{1}{2} C_1 C_2 * \sum_n x_{in} * \left[\sum_x^V \mathcal{I}^{xm}_{in} \frac{\beta^t_{elev} log(elev_{xm})}{area_m} + \sum_x^V \mathcal{I}^{mx}_{in} \frac{\beta^t_{elev} log(elev_{mx})}{area_m} \right]} * \frac{w_n c^t_m}{w_n c^r_m} \\
&= \frac{\sum_x^V \mathcal{I}^{xm}_{in} \beta^r_{dist} log(dist_{xm}) + \sum_x^V \mathcal{I}^{mx}_{in} \beta^r_{dist} log(dist)_{mx}}{\sum_x^V \mathcal{I}^{xm}_{in} \beta^t_{elev} log(elev_{xm}) + \sum_x^V \mathcal{I}^{mx}_{in} \beta^t_{elev} log(elev_{mx})} * \frac{c^t_m}{c^r_m}
\end{aligned} \tag{39}$$

Equation (39) reveals the intuition behind the tunnel-highway ratio. It shows that the return on tunnels is greater relative to highways if bilateral elevation imposes a greater trade cost relative to distance. Consequently, the model predicts that regions with particularly pronounced elevation-related trade costs will exhibit a higher tunnel-to-highway ratio in infrastructure development.

To gain insights into the distinction between national and provincial infrastructure planning, let's solve the marginal utility of highways and tunnels for provincial governments. Unlike the national government, provincial governments optimize solely based on the welfare of locations within their own province.

$$\frac{\partial \bar{U}_p}{\partial \phi^r_{lower,m}} = \frac{1}{2} C_1 C_2 * \sum_n^p x_{in} * \left[\sum_x^{V' \in p} \mathcal{I}^{xm}_{in} \frac{\beta^r_{dist} log(dist)_{xm}}{area_m} + \sum_x^{V' \in p} \mathcal{I}^{mx}_{in} \frac{\beta^r_{dist} log(dist)_{mx}}{area_m} \right] \tag{40}$$

$$\frac{\partial \bar{U}_p}{\partial \phi^t_{lower,m}} = \frac{1}{2} C_1' C_2 * \sum_n^p x_{in} * \left[\sum_x^{V' \in p} \mathcal{I}^{xm}_{in} \frac{\beta^t_{elev} log(elev_{xm})}{area_m} + \sum_x^{V' \in p} \mathcal{I}^{mx}_{in} \frac{\beta^t_{elev} log(elev_{mx})}{area_m} \right] \tag{41}$$

where $C_1' = -\alpha(\bar{U}_p)^{-1} \sum_n^p U_n^\epsilon P_n^{\sigma-1}$, where $\bar{U}_p$ is the expected utility within province p, $\bar{U}_p = \Gamma(\frac{\epsilon-1}{\epsilon}) \left[\sum_n^p (v_n / P_n^\alpha r_n^{1-\alpha})^\epsilon \right]^{\frac{1}{\epsilon}}$. V' is the set of all locations adjacent to x and within province p. A key distinction in the provincial governments' solution arises from the altered centrality measure, $\sum_x^{V' \in p} \mathcal{I}^{mx}_{in}$, where only origins and destinations within the province are taken into account. As a result, provincial infrastructure investments are more strongly tied to a region's centrality within the province rather than the broader national network. This localized centrality drives provincial governments to prioritize investments that enhance intra-provincial connectivity and welfare.

To understand the difference in investment priorities between the two tiers of government, consider the relative marginal returns on provincial versus national highways.

$$\frac{MU^r_{lower,m}}{MU^r_{upper,m}} = \frac{C_1' * \sum_n^p x_{in} * \sum_x^{V' \in p} \mathcal{I}^{xm}_{in} \left[\frac{\beta^r_{dist} log(dist_{xm})}{area_m} \right]}{C_1 * \sum_n^N x_{in} * \sum_x^V \mathcal{I}^{xm}_{in} \left[\frac{\beta^r_{dist} log(dist_{xm})}{area_m} \right]} \tag{42}$$

Equation (42) illustrates that regions that are relatively central within their province but peripheral to the nation, experience a higher marginal return on provincial infrastructure investments. Conversely, regions that hold central importance at the national level but are peripheral within the province exhibit a greater marginal return on national infrastructure investments. Define the provincial-to-national centrality ratio for region m as follows:

$$\mathcal{R}_m = \frac{\sum_x^{V' \in p} \mathcal{I}^{xm}_{kl}}{\sum_x^V \mathcal{I}^{xm}_{in}}; \quad \forall k, l \in p; \quad \forall i, n \in N \tag{43}$$

Equation (42) predicts that the ratio of provincial to national highways in region m is positively correlated with the centrality ratio $\mathcal{R}_m$.

5 Calibration

5.1 Method

The model is calibrated to 309 prefectures in 23 provinces in China using data mainly from 2019. Island provinces and prefectures are dropped because they are not connected to the rest of the country via highways. Furthermore, three western provinces of China, Xinjiang, Tibet, and Qinghai, are dropped due to the irregular sizes of prefectures and missing data problems. Direct-administered municipalities (Beijing City, Tianjin City, Shanghai City, and Chongqing City) are cities with provincial administrative power that do not officially belong to any provinces. In this paper, they are merged into nearby provinces so that the nearby provincial governments will choose the infrastructure for those municipalities. Beijing and Tianjin are merged into Hebei Province. Chongqing is merged into Sichuan Province, and Shanghai is merged into Jiangsu Province. In addition, a region representing the rest of the world is included. Data on China's expressway and tunnel network from 2014 to 2019 comes from OpenStreetMap. Prefecture-level economic variables are available in Prefecture Statistical Yearbooks.

In terms of parameters in the model, some are well-studied by the literature and have been borrowed to this paper. The shape parameter of Fréchet distribution: ϵ is assumed to be 3. The location parameter of Fréchet is assumed to be 1. Trade elasticity is assumed to be 7. Other parameters are specific to this paper. The share of tradable goods in total expenditure, α, takes the value of 0.7. It is calibrated using data from the 2014 World Input-output Table (WIOT) by taking China's final domestic demand for tradable goods and dividing it by China's total final domestic demand. The prefectures' adjacency matrix (AM) of China is computed by supplying the prefecture-polygon shape file into the Near function in ArcGIS. The productivity A_i and housing H_i are solved using wage and labor supply after inverting the model, following Redding and Rossi-Hansberg (2017). China's nominal GDP per capita and total employment in 2019 are used to solve the problem of productivity and housing. Both variables are sourced from China's prefecture yearbooks.

The tax rate determines the government's budget, calculated by dividing China's total investments in toll roads (including highways, tolled primary roads, tolled secondary roads, tunnels, and bridges) up to 2019 by China's nominal GDP in 2019.[6] The resulting calibrated tax rate is approximately 9.6 percent. Of the total tax income, two-thirds is allocated to the national government,

[6] As of 2019, China had invested 8,823 billion CNY in highway construction, 400 billion CNY in tolled primary roads, 42.5 billion CNY in tolled secondary roads, 219 billion CNY in tolled bridges, and 23.6 billion CNY in tolled tunnels. China's nominal GDP in 2019 was 99,086.5 billion CNY. These figures are sourced from the 2019 National Toll Road Statistics Bulletin of China.

reflecting the proportion of national expressways in 2019. The remaining one-third is distributed among 23 provinces, proportional to their share of provincial highways in the total highway network. Each province's allocation is further determined by the proportion of provincial highways within that province relative to the total length of provincial highways nationwide. For simplicity, the labor requirement for infrastructure construction is assumed to be uniform across regions and is calibrated to match real-world investment costs using the following formulas.

$$c^r = \frac{\frac{c^r_{data}}{Y_{data}} * Y_{model}}{w_{model}} \tag{44}$$

$$c^t = \frac{c^t_{data}}{c^r_{data}} * c^r \tag{45}$$

where c^r is the labor cost of highway per kilometer in the model. c^t is the labor cost of the tunnel per kilometer in the model. c^r_{data} is the observed average monetary cost of highways per kilometer, which was 61,778.6 thousand Chinese Yuan(CNY) in 2019. This value is calculated by finding the quotient between the total length of highways in China in 2019 and the cumulative infrastructure investment spending by 2019. Y_{data} is the nominal GDP of China in 2019. Y_{model} and w_{model} are the total value of production and the average nominal wage, respectively, predicted by the model under zero infrastructure investment. c^t_{data} is the observed average monetary cost of tolled tunnels per kilometer, which was 189,072.2 thousand CNY, calculated similarly as c^t_{data}.

Trade costs of distance and elevation. The following regressions are estimated using IVs to recover the trade cost of distance and bilateral elevation in China.

$$\begin{aligned} log(X_{ij}) &= \beta_0 + \beta_{dist} * log(dist_{ij}) + \beta_1 * log(dist_{ij}) * \frac{1}{2}(\frac{hwy_i}{area_i} + \frac{hwy_j}{area_j}) \\ &+ \beta_{elev} * log(elev_{ij}) + \beta_2 * log(elev_{ij}) * \frac{1}{2}(\frac{tnnl_i}{area_i} + \frac{tnnl_j}{area_j}) + \delta_i + \delta_j + \epsilon \end{aligned} \tag{46}$$

where the dependent variable is the logarithm of trade value from the origin prefecture i to the destination prefecture j in 2017. Data comes from China's Multi-region input-output (MRIO) tables (Zheng et al. (2022)). $delta_i$ and $delta_j$ capture the origin and destination fixed effects. ϵ is the error term. hwy_i and $tnnl_i$ are the lengths of highways and tunnels, respectively, in the origin in the unit of 1000 kilometers. $area_i$ is the area of prefecture i in the unit of 10,000 square kilometers. The term $\frac{1}{2}(\frac{hwy_i}{area_i} + \frac{hwy_j}{area_j})$ measures the average highway density between the origin and the destination. This term is interacted with the distance variable, allowing the average highway density to impose a mitigating impact on the trade cost of distance. The mitigation impact is captured by the coefficient, β_1, while β_{dist} governs the trade cost of distance. Similarly, β_{elev} governs the trade cost of bilateral elevation. The term $\frac{1}{2}(\frac{tnnl_i}{area_i} + \frac{tnnl_j}{area_j})$ measures the average tunnel density in origin and destination. It interacts with the elevation variable, allowing tunnels to mitigate the trade cost of elevation. This reduction is captured by the coefficient β_2.

Equation (46) is estimated using IV. Two instrumental variables are introduced in section 5.2 to address the widely recognized endogenous problem of infrastructure. The interaction term between distance and highway density is instrumented by $log(dist_{ij}) * (Z_i^{ming,g} + Z_j^{ming,g})$, in which $Z_i^{ming,g}$ stems from the Historical courier routes and post stations in Chinese Ming dynasty and is designed to instrument for China's highways. Additionally, the interaction term between tunnel density and elevation is instrumented by $log(elev_{ij}) * (Z_i^{lithological} + Z_j^{lithological})$, in which $Z_i^{lithological}$ stems from lithological distributions and aims to instrument for tunnels.

Table 1 shows the IV regression results from estimating Equation (46). The coefficients on distance and bilateral election are both negative and consistent with the trade cost. The coefficients on the interaction terms are positive, indicating that the highways and tunnels reduce trade costs of distance and tunnels. The result shows that effective bilateral elevation is indeed a component of trade cost in China along with distance. A one percent increase in bilateral elevation decreases trade by 0.015 percent. On the other hand, the impact of a one percent increase in the distance is a 1.13 percent decrease in trade. The magnitude of the coefficients is aligned with those in Sun (2024). Results suggest a cost-mitigating effect of highways and tunnels. It is found that highway density mitigates the cost from distance, while tunnel density mitigates the cost of bilateral elevation. A 0.01 unit increase in highway density mitigates the cost of distance by 0.01174 percentage points. Also, a 0.01 unit increase in tunnel density mitigates the cost of bilateral elevation by 0.00141 percentage points. Note that the unit of density is a kilometer per ten square kilometers. To get a sense of how substantial a 0.01 unit increase in density is, let's consider the following example. Beijing had an area of 16409 square kilometers and a total length of highway of 819 km in 2019, while its adjacent and crucial trade partner, Tianjin, had 11881 square kilometers in area and 1128 kilometers in highways. To increase the average highway density between Beijing and Tianjin by 0.01 units, the total increase in highways (split between two cities) would need to be approximately 275.65 kilometers, or about 138 kilometers in each city.

The first stage regression results of Equation (46) are shown in Table (2). Coefficients from the first stage are positive and statistically significant at conventional levels indicating that that the proposed instruments are positively correlated with variables being instrumented. Origin and destination fixed effects are controlled for in the first stage regressions.

Rest of the world. The model includes one region representing the rest of the world, with

VARIABLES	$\ln(X_{ij})$
$\ln(dist_{ij})$	-1.284***
	(0.074)
$\ln(elev_{ij})$	-0.015***
	(0.005)
$\ln(dist_{ij})$ * hwy_{ij}	1.174***
	(0.254)
$\ln(elev_{ij})$ * $tnnl_{ij}$	0.141*
	(0.077)
Observations	73,432
Model	IV
Origin FE	Yes
Destination FE	Yes
Min Eigenvalue	324.2
Durbin P-value	0.001

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 1: Regression results

Note: This table summarizes the result from estimating Equation (46) with IVs, in order to estimate the trade costs from distance and effective bilateral elevation and the cost-mitigating effects of highways and tunnels. Variables $dist_{ij}$ and $elev_{ij}$ are the great circle distance and effective bilateral elevation between prefectures i and j. Variable $hwy_{ij} = \frac{1}{2}(\frac{hwy_i}{area_i} + \frac{hwy_j}{area_j})$ is the average highway density between i and j. $tnnl_{ij} = \frac{1}{2}(\frac{tnnl_i}{area_i} + \frac{tnnl_j}{area_j})$ is the average tunnel density between i and j. Highways and tunnels are measured in kilometers, while the area is measured in ten square kilometers. The dependent variable is the logarithm of trade value from prefecture i to prefecture j in China in 2017. Trade data comes from China's Multi-region input-output tables. Origin and Destination fixed effects are included.

	(1)	(2)
VARIABLES	$ln(dist_{ij}) * (hwy_{ij})$	$ln(elev_{ij}) * (tnnl_{ij})$
$ln(dist_{ij}) * (\text{hwy IV}_{ij})$	0.00027***	
	(0.00000)	
$ln(elev_{ij}) * (\text{tnnl IV}_{ij})$		0.07070***
		(0.00028)
Observations	73,441	73,441
Model	OLS	OLS
Origin FE	Yes	Yes
Destination FE	Yes	Yes

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 2: First Stage Regression Results for Equation (46)

Note: This table summarizes the result from the first stage regression for the IV estimation in Equation (46). Variables $dist_{ij}$ and $elev_{ij}$ are the great circle distance and effective bilateral elevation, respectively, between prefectures i and j. Variable $hwy_{ij} = \frac{1}{2}(\frac{hwy_i}{area_i} + \frac{hwy_j}{area_j})$ is the average highway density between i and j. $tnnl_{ij} = \frac{1}{2}(\frac{tnnl_i}{area_i} + \frac{tnnl_j}{area_j})$ is the average tunnel density between i and j. hwy IV_{ij} is the average of hwy IV_i and hwy IV_j which is used as an instrument for highway density, hwy_{ij}. Similarly, tnnl IV_{ij} is the average of tnnl IV_i and tnnl IV_j. The instrument for highways stems from the Ming Courier routes and post stations. The instrument for tunnels stems from the lithological distribution in China. Origin and Destination fixed effects are included.

economic parameters calibrated to be proportional to China's relative size. For instance, employment in the rest of the world is set as China's total employment multiplied by the ratio of China's population to the global population. The wage level in the rest of the world is calibrated based on China's GDP per capita relative to the world's GDP per capita in 2019. The 25 coastal ports with the highest container throughput in 2019 are selected, and these ports are made adjacent to the rest of the world, allowing international trade. Table (8) in the Appendix lists the selected ports and their container throughput. In 2019, Shanghai ports alone accounted for 26 percent of China's total trade value (exports and imports) (SMOPS (2020)). Consequently, the 25 selected ports handled the vast majority of China's international trade. I make a simplifying assumption that the distance and bilateral elevation from the ports to the rest of the world are assumed to be one. This assumption is made to focus on how governments mitigate internal trade costs rather than international ones. Since goods must still be transported to the ports for export, and internal trade involves significant costs, this simplification does not significantly alter the patterns of internal trade or the distribution of internal infrastructure. Additionally, infrastructure investment in the rest of the world is excluded, and international immigration is not considered in the model.

5.2 Instrumental Variables

This section introduces two shift-share instrumental variables. Section (5.2.1) proposes an instrument for highways in China using the Ming Dynasty's Courier routes and post station. Section (5.2.2) introduces an instrument for tunnels in China using Lithological distributions of unconsolidated sediments.

5.2.1 Ming Courier Routes

The first instrument stems from the Chinese Ming dynasty's historical courier routes and post stations. During the Ming Dynasty (1368–1644), China developed an extensive courier system known as the "Ming Imperial Post" for better communication and administration across the empire. This system featured a network of relay stations, or "post stations," where couriers could change horses and rest, ensuring the efficient transmission of official documents and orders. Major routes connected the capital, Beijing, with key cities in all directions, like Nanjing, Hangzhou, Datong, and Xi' an. Notably, many of the crucial cities in the Ming Dynasty remain critical nowadays. Using this dataset to study China's infrastructure is recommended by previous literature (see Egger et al. (2023).) The data comes from Harvard Dataverse, and this paper utilizes version V6. An illustration of the data is shown in Figure 4. The instrument is introduced as follows. Let $Z_{it}^{ming,g}$

Figure 4: Chinese Ming Dynasty's Courier Routes and Post Stations

This figure shows the Chinese Ming Dynasty's courier routes and post stations. Data comes from Harvard Dataverse. Version V6 is utilized.

be the IV representing the length of highways predicted by post stations on Ming courier routes,

$$Z_{it}^{ming,g} = \frac{\#\text{ of Stations}_i}{\Sigma_i \#\text{ of Stations}_i} * \text{Highway Length}_t^g \tag{47}$$

where i stands for prefecture, t stands for year, and g stands for national highways. $\#$ of Stations$_i$ is the number of post stations in prefecture i. Highway Length$_t^g$ is the length of national highways within the border of prefecture i in year t. $Z_{pt}^{ming,g}$ is used as an instrument for China's highway density at the prefecture level in equation (46). It is highly relevant to China's highways in each prefecture because routes and post-stations in the Ming dynasty predicted each prefecture's economic importance and centrality, which also determines the highway distribution today. The exclusion restriction requires that the historical courier routes in the Ming dynasty affected contemporary trade only through their predictive power on contemporary highway density. The author believes that the exclusion restriction is not likely to fail.

5.2.2 Lithology

The second instrument considers the world lithological distribution. Lithological distribution refers to the spatial arrangement and composition of different rock types on the Earth's surface and subsurface. An area's lithology encompasses the rocks' physical characteristics, including their mineral content, grain size, texture, and structural features. These factors are crucial in understanding the geological history of an area but also have significant implications for various engineering projects,

Abbreviation	Name	Problems
su	Unconsolidated sediments	Few problems found
ss	Siliciclastic sedimentary rocks	Hard
py	Pyroclastics	Hard
sm	Mixed sedimentary rocks	Water-soluble
sc	Carbonate sedimentary rocks	Water-soluble
ev	Evaporites	Water-soluble
va	Acid volcanic rocks	Hard
vi	Intermediate volcanic rocks	Hard
vb	Basic volcanic rocks	Hard
pa	Acid plutonic rocks	Hard
pi	Intermediate plutonic rocks	Hard
pb	Basic plutonic rocks	Hard
mt	Metamorphics	Hard
ig	Ice and Glaciers	Meltable

Table 3: Level-1 Lithology Types and Problems for Tunnels Construction

Note: This table summarizes the level-1 lithology types and their associated challenges for tunnel construction. The rock type names and abbreviations are sourced from Hartmann and Moosdorf (2012), and the general challenges posed by each rock type are based on mechanical engineering literature. It is important to note that while the challenges listed generally apply to subcategories within each rock type, the severity of these challenges can vary across different subcategories.

including tunnel construction. For instance, weak rocks that are prone to failure require more extensive support systems while digging tunnels. Porous rocks may require complex drainage systems and waterproofing measures because porous rocks have minute spaces or holes through which liquid may pass. Hard rocks can cause excessive wear on tunnel-boring machines. Therefore, lithology is highly relevant for tunnel construction. Table (3) summarizes the border type of rocks found on Earth (Hartmann and Moosdorf (2012)) and their problems, in simple terms, for tunnel builders (see literature in mechanical engineering: Zhang (2004), Turner (2006), Kurian (2013), Bandara and Gunaratne (2018)). Figure (5) shows the lithological distribution of China. The data is sourced from Hartmann and Moosdorf (2012) and available on Esri.

Due to their inherent hardness, some rocks in Table (3) are challenging to construct tunnels. Siliciclastic sedimentary rocks, pyroclastics, volcanic rocks (acid, intermediate, and basic), plutonic rocks (acid, intermediate, and basic), and metamorphics are all examples of these hard rocks. Additionally, materials like ice and glaciers are problematic because they are meltable, leading to unstable foundations and water ingress, while water-soluble rocks, such as mixed sedimentary, carbonate sedimentary, and evaporites, present challenges due to their potential to dissolve when exposed to water.

Unconsolidated sediment is a sediment that is loosely arranged or unstratified, or whose particles are not cemented together, found either at the surface or at depth. They are usually young, from the Cenozoic age. Examples of unconsolidated sediments are sands, mud, swamp deposits, dunes, loess, and beach sands. Compared to the 13 other types of rocks, unconsolidated sediments have

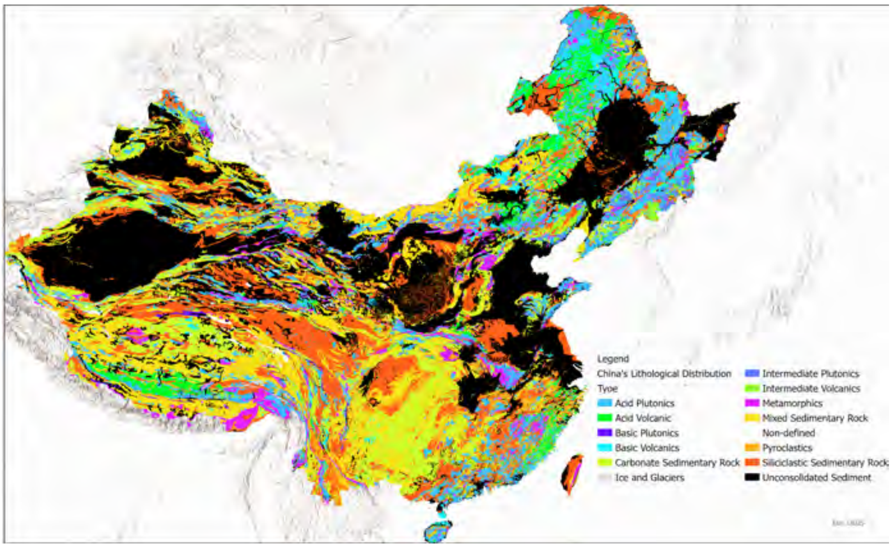


Figure 5: Lithological Distribution of China

Note: This figure depicts the lithological distribution of level-1 lithology types listed in Table (3). The map is sourced from Hartmann and Moosdorf (2012). The unconsolidated sediments are colored in black.

few problems and are the easiest to work on when drilling tunnels.

Unconsolidated sediments in China, depicted in Black in Figure (5), are primarily concentrated in the North China Plain, the Yangtze River Delta, the Tarim Basin in Xinjiang, the Songliao Basin in northeast China and the Loess Plateau in central-north China. These regions have a wide range of climates and precipitation patterns. The North China Plain and the Yangtze River Delta experience a temperate monsoon climate characterized by hot, humid summers and cold, dry winters, with annual precipitation ranging from 600 to 1,500 mm, mostly concentrated in the summer months. In contrast, the Tarim Basin, situated in Xinjiang, has an arid desert climate with very low precipitation, often less than 100 mm per year, making it one of the driest regions in China. The Songliao Basin in the northeast experiences a temperate continental climate, with cold winters, warm summers, and moderate rainfall between 400 and 800 mm annually. The Loess Plateau, known for its semi-arid climate, receives about 400 to 600 mm of rainfall annually. While it's true that unconsolidated sediments are sometimes associated with river valleys and agriculture, this correlation does not universally apply. For example, the Loess Plateau in northern China does not have a rich water network compared to other regions. In addition, while the lower Yangtze River Delta is predominantly composed of unconsolidated sediments, the upper sections of the Yangtze River Basin feature a variety of other geological formations, such as sedimentary rocks and mountainous terrains. In the upper reaches, the Yangtze River flows through regions with significant sedimentary rock formations and rugged highlands, including areas with ancient volcanic rocks and metamorphic terrain. Similarly, the majority of the Pearl River Basin does not predominantly consist of unconsolidated sediments.

Given the relative ease of drilling tunnels in unconsolidated sediment, the abundance of this type of rock will be used to construct the instrumental variable for tunnels. Let $Z_{it}^{Lithology}$ be the shift-share IV representing the length of highway tunnels predicted by the share of the area of unconsolidated sediments(SU). I estimate the following using OLS to predict tunnel shares in 2014 using shares of unconsolidated sediments(SU).

$$\text{Tunnel Share}_{i,2014} = \alpha_0 + \alpha_1 * \frac{\text{Area of SU}_i}{\Sigma_i \text{Area of SU}_i} + \epsilon_i \tag{48}$$

where i stands for prefectures and Tunnel Share$_{i,2014}$ is the share of the length of highway tunnels in prefecture i in 2014 with respect to the total length of highway tunnels in the same year. Next, the lithological instrumental variable for tunnels is calculated below:

$$Z_{it}^{Lithological} = \text{Tunnel}\widehat{\text{ Share}}_{i,2014} * \text{Tunnel Length}_t \tag{49}$$

where Tunnel $\widehat{\text{Share}}_{i,2014}$ is the predicted tunnel share from equation (48) and Tunnel Length$_t$ is the total length of highway tunnels in China in year t. The exclusion restriction for the lithological IV requires that the tunnel shares predicted by the share of unconsolidated sediments affect trade only through their predictive power on the easiness of tunnel constructions. The author believes that the exclusion restriction holds.

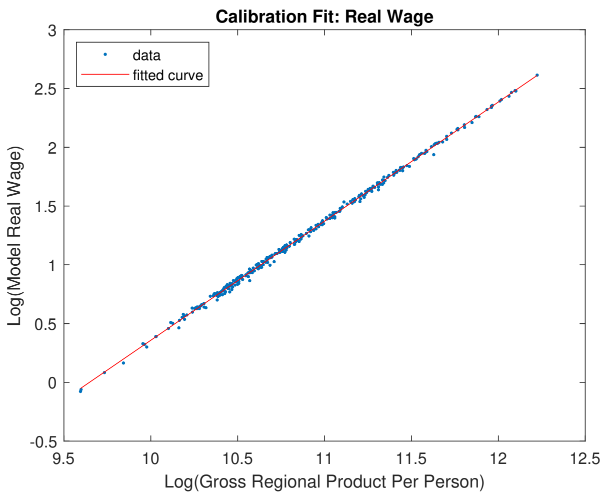
5.3 Calibration Fit

Table (4) shows the mean and standard deviation for highways and tunnels in the data and predicted by the baseline model. As unmatched moments, the means and standard deviation of highways and tunnels predicted by the model do not align perfectly with the data. Note that, the baseline model predicts more highways but fewer tunnels than the data. Also, it predicts a more average distribution (smaller standard deviations). Despite the discrepancy, the model successfully replicates the six stylized facts outlined in section (3), as shown in panels (a)-(f) of Figure (10). These results highlight the model's accuracy in capturing key relationships: the positive correlation between infrastructure and income, the role of elevation in determining tunnel investment, the complementarity between highways and tunnels at national and provincial levels, and the role of centrality within jurisdiction in determining optimal investment. In addition, Figure(6) illustrates an excellent fit between the predicted and actual values for two targeted variables, wage and labor. Figure(7) compares the predicted and actual values for three un-targeted moments: Trade value, length of highway, and tunnel. Positive relations in Figure(7) confirm that the model generates similar values as in the data.

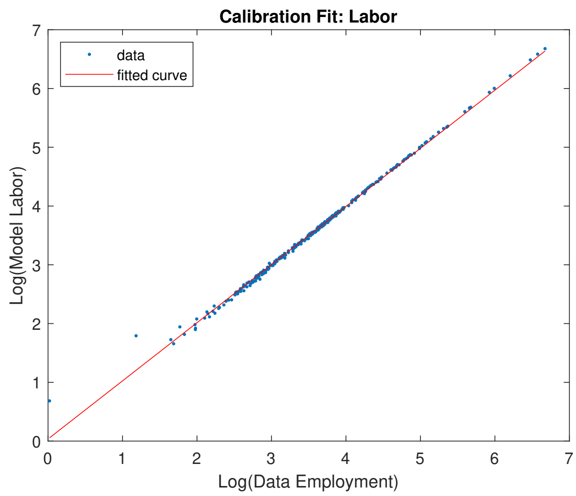
Variables	moment	Data	Baseline Model
Hwy Length	Mean	372.5	358.1
	SD	221.4	350.0
Ntnl Hwy Length	Mean	285.8	267.5
	SD	238.6	325.5
Prvn Hwy Length	Mean	110.9	90.6
	SD	120.5	183.9
Tnnl Length	Mean	73.0	9.4
	SD	149.3	11.4
Ntnl Tnnl Length	Mean	49.1	6.7
	SD	130.2	10.7
Prvn Tnnl Length	Mean	16.6	2.8
	SD	36.9	5.7

Table 4: Calibration Fit: Infrastructure Length in Data and Baseline Result

Note: This table summarizes the mean and standard deviation of the infrastructure length in 2019 and predicted by the baseline model. The unit for length is 1 kilometer. The variables from top to bottom are highway length, national highway length, provincial highway length, tunnel length, national tunnel length, and provincial tunnel length. Only tunnels on highways are included in the sample.



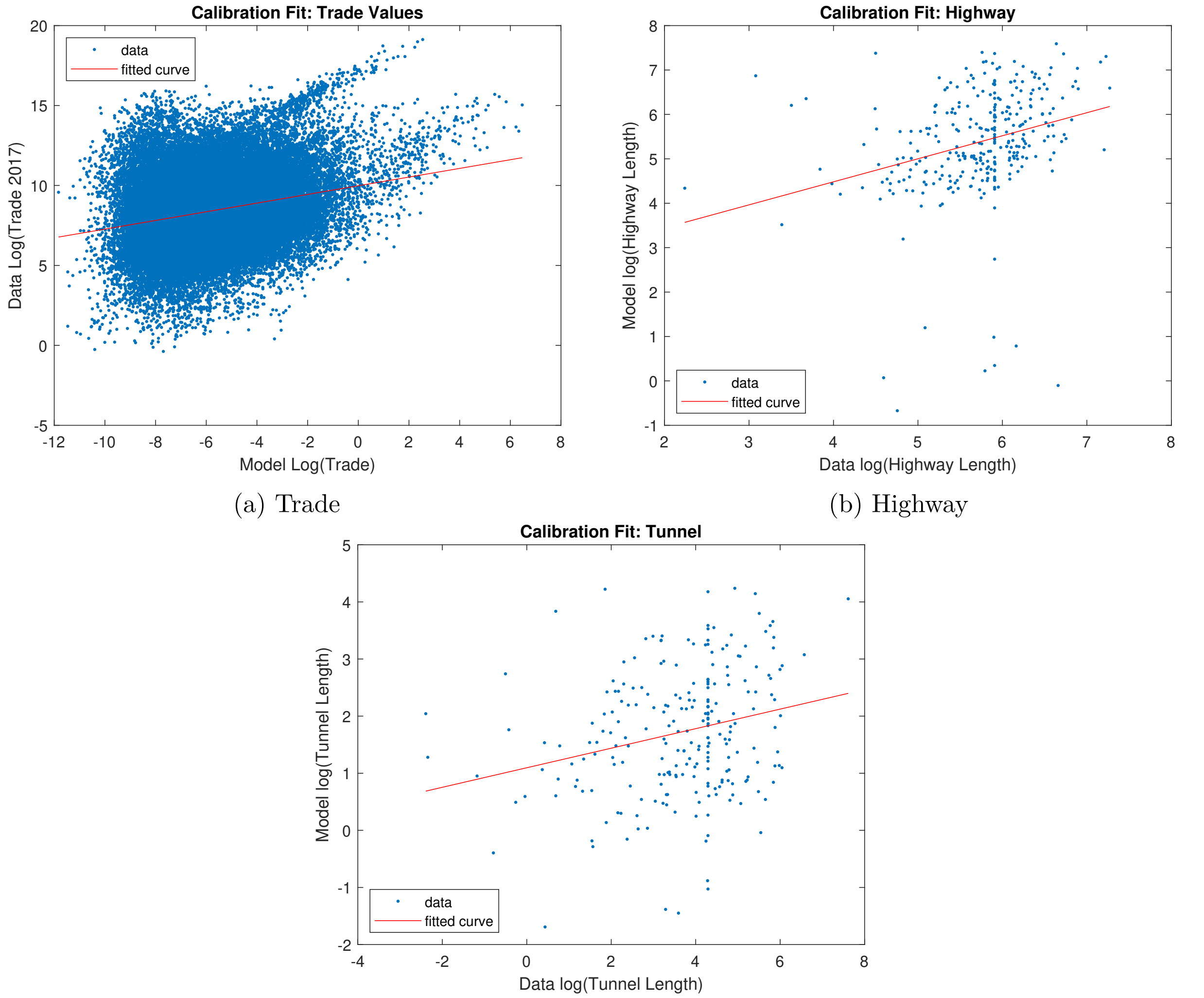
(a) Real Wage



(b) Labor

Figure 6: Calibration Fit: Targeted Moments

Note: These figures show the calibration fit for the targeted moments. It can be seen in Panel (a) that the model predicted real wage aligns with the gross regional product per person in the data. In Panel (b), the model predicted labor is in line with the number of employed people in the data. Data points are at prefecture level. Data on income and employment are sourced from prefecture yearbooks, 2019.



(a) Trade (b) Highway

(c) Tunnel

Figure 7: Calibration Fit: Un-targeted Moments

Note: These figures show the calibration fit for the untargeted moments. Specifically, the trade value (a), the length of highway (b), and the length of tunnel (c) are in line with the corresponding values in the data. Data on trade value comes from China's city (prefecture) level multi-regional input-output table, sourced from Zheng et al. (2022). Data on highways and tunnels are sourced from Open Street Maps.

6 Baseline Results and Counterfactual Analysis

6.1 Baseline Results

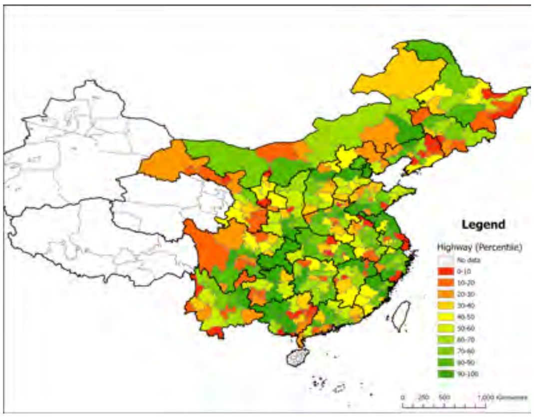
In the baseline setup, both national and provincial governments jointly determine infrastructure investments. Figure (8) presents the resulting baseline infrastructure distributions. The total highway network, depicted in panel (a), is predominantly shaped by the centrally-planned national highways shown in panel (c). This highlights how centralized governments prioritize infrastructure investment in more central regions, allocating fewer resources to peripheral areas. Panel (b) illustrates the baseline model' s predicted distribution of tunnels. The patterns observed for tunnels in panels (b), (d), and (e) closely mirror those of highways, underscoring the complementary relationship between highways and tunnels discussed in section (4). In essence, regions with more highways also tend to have more tunnels. The infrastructure distribution based on the data is presented in Figure (15) in the Appendix. The optimal lengths of highways and tunnels by provinces in the baseline scenario are detailed in Tables (11), (12), and (13), also found in the Appendix. These tables comprehensively compare the infrastructure allocation across provinces in the baseline model, distinguishing between national and provincial highways and tunnels.

6.2 Counterfactual Analyses

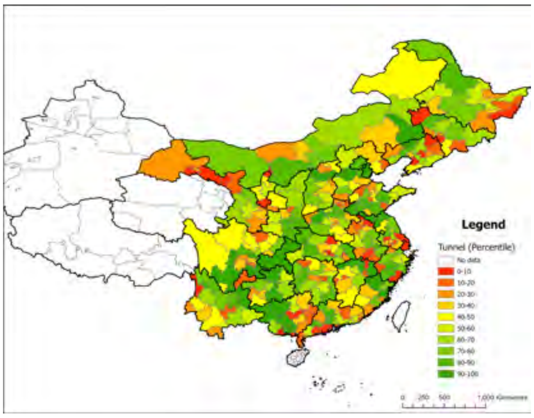
Two counterfactual scenarios are examined. First, I analyze the impact of complete centralization, where the national government exclusively determines optimal infrastructure investments. In this scenario, provincial governments are prohibited from investing, and their budgets are reallocated to the national government. Second, I explore the effects of a fully decentralized structure, in which each provincial government independently optimizes infrastructure investments within its jurisdiction, and the national government does not intervene. In this decentralized case, each province receives a share of the total budget proportional to its actual share of provincial highways in 2019. In both scenarios, other parameters, such as the tax rate, are fixed.

The results for the first counterfactual, under full centralization, are aggregated at the provincial level and presented in columns (1)-(4) of Table (5). Under this scenario, average real wages increase across all provinces, indicating that full centralization is more efficient in enhancing national welfare. This is corroborated by a positive EV margin of 0.40 percent in Table (6), implying that consumers in the baseline scenario would need to be compensated by 0.4 percent of their real wage to be indifferent between the baseline and fully centralized scenarios. The welfare gains are driven by the national government's ability to account for the spillover effects of infrastructure. However, alongside the rise in overall welfare, inequality also increases. Both the Gini and Theil indices, reported in Table (7), show an uptick compared to the baseline, suggesting that the two-tier government structure in the baseline is more effective at reducing inequality than full centralization.

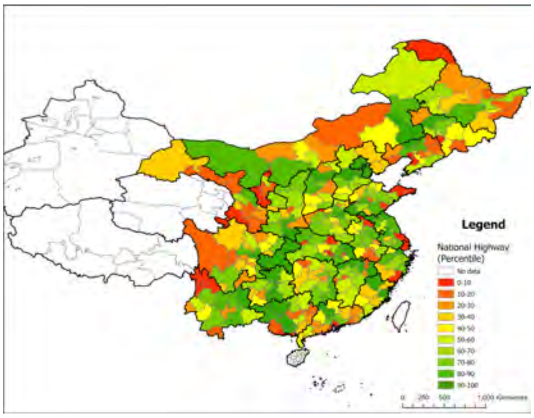
The two-tier government structure mitigates inequality through the following mechanism: while the national government prioritizes infrastructure investments in regions that are central to the entire country, provincial governments tend to focus on regions that are central to their own provinces. Large metropolitan areas, such as Los Angeles in the USA or Hangzhou in China, are simultaneously central to both the country and their respective state or province. However, there are regions that, while central to their state or province, are peripheral to the country. Examples include Des Moines, the capital and largest city of Iowa, and Lanzhou, the capital of Gansu Province in China. The model predicts that it is optimal for the government of Iowa and Gansu province to invest heavily



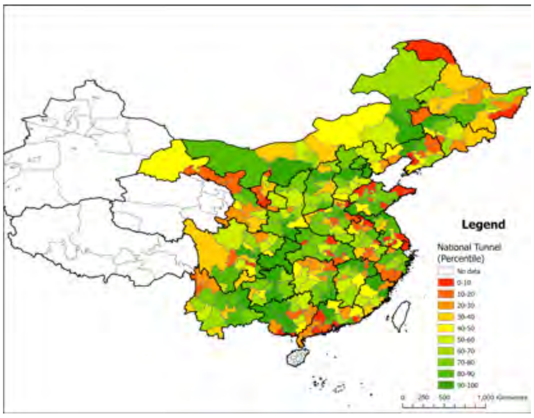
(a) Total Highway



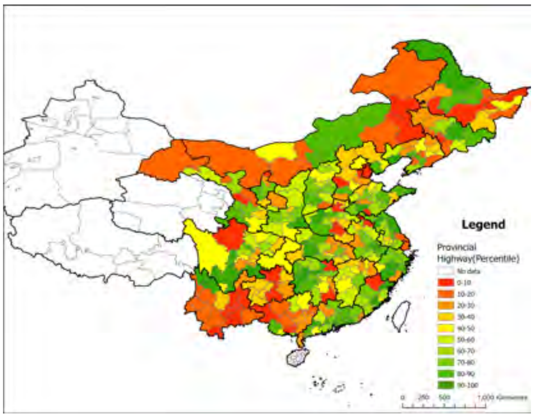
(b) Total Tunnel



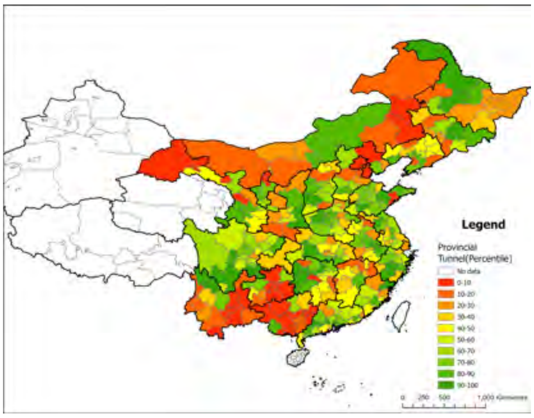
(c) National Highway



(d) National Tunnel



(e) Provincial Highway



(f) Provincial Tunnel

Figure 8: Baseline Results

Note: This figure displays the distribution of highways and tunnels in predicted by the baseline model, broken down by total, national, and provincial investments. Panel (a) shows the distribution of the total highway. Panel (b) illustrates the total tunnels. Panel (c) focuses on the highways constructed by the national government. Panel (d) depicts tunnels constructed by the national government. Panel (e) represents the highways developed by provincial governments. Panel (f) shows tunnels constructed by provincial governments.

in their state/province capital. This additional provincial investment boosts local wages, helping to reduce regional inequality. However, from the perspective of a centralized planner who focused on maximizing national utility, such investments would be seen as a misallocation of resources. Therefore, under a fully centralized system, these areas would receive less investment as they are less crucial to national connectivity. The metric $\mathcal{R}_m$ was introduced in Section (4) to represent the province-to-country relative centrality ratio for prefecture m. This measure can be calculated using the probability of being on the least-cost paths as follows:

$$\mathcal{R}_m \equiv \frac{\frac{\sum_{k,l \in p} \mathcal{I}_{kl}^m}{p^2}}{\frac{\sum_{i,n \in N} \mathcal{I}_{in}^m}{N^2}} \quad , m \in p \tag{50}$$

where m, k and l are locations in province p. i and n are location in the country N. Let p also denote the total number of locations in province p. $\mathcal{I}_{kl}^m = 1$ if location m is on the least-cost path between k and l, and 0 otherwise. p^2 and N^2 calculates the total number of paths in province p and country N. The numerator in Equation (50) represents the probability of a prefecture being on the least-cost path between locations within its province, while the denominator captures the probability of being on the least-cost path between locations across the entire country. Panels (a) and (b) of Figure (10) illustrate that prefectures receiving greater investment under fully centralized planning are those with lower $\mathcal{R}$ values, meaning they are relatively more central on a national scale rather than just within their province. This highlights the national government's tendency to prioritize regions that enhance country-wide connectivity over those that are central only within provincial boundaries.

Figure (11) in the Appendix displays the counterfactual outcomes at the prefecture level. While most regions experience gains under centralization, a few prefectures, highlighted in red in Panel (a) of Figure (11), suffer losses. The primary mechanism behind these losses is detailed in Panel (d) of Figure (12), which demonstrates that the losing regions generally have a low probability of being on the least-cost path. Consequently, these regions receive minimal infrastructure investments from the national government under centralized planning, which leads to a decrease in real wages. Panels (b) and (c) of Figure (12) demonstrate a positive correlation between change in infrastructure and change in the real wage. These regional disparities further explain the pattern of labor migration. Panel (a) of Figure (12) shows that labor tends to reallocate to the regions with positive changes in real wages.

The results from the second counterfactual analysis involving complete decentralization are aggregated at the provincial level and are shown in columns (5)-(8) of Table (5). In this scenario, overall welfare declines compared to the baseline, reflected by an EV margin of -2.36 percent. This implies that consumers in the baseline scenario would need to forfeit 2.36 percent of their real wage

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Provinces	W	L	HWY	TNNL	W	L	HWY	TNNL
Hebei	0.78	0.25	-10.62	3.28	1.01	4.92	-38.42	-38.92
Shanxi	0.36	-0.30	-16.54	-12.90	-2.22	1.32	-23.34	-12.99
Inner Mongolia	0.31	-0.37	-22.76	-22.84	-3.89	-0.74	-65.82	-66.98
Liaoning	0.76	0.14	-23.15	-10.75	0.61	4.16	-60.05	-68.19
Jilin	0.51	-0.05	-19.56	-13.27	-10.16	-7.18	-32.19	-37.29
Heilongjiang	0.38	-0.45	-46.29	-39.79	-11.51	-9.12	-13.27	-10.98
Jiangsu	0.74	0.20	-28.25	-20.82	-0.51	3.27	-76.97	-75.31
Zhejiang	0.66	0.05	-38.66	-39.94	0.67	4.63	-34.63	-28.48
Anhui	0.03	-0.42	-30.03	-36.26	-1.54	1.78	-39.19	-48.45
Fujian	0.67	0.08	-25.69	-6.88	1.24	5.21	-39.17	-55.75
Jiangxi	0.86	0.31	0.41	3.07	-3.84	-0.29	-31.99	-32.03
Shandong	0.64	0.09	-31.93	-28.99	-1.43	1.55	-49.18	-53.19
Henan	0.33	-0.15	-23.68	-34.68	-6.12	-2.88	-13.46	-5.33
Hubei	0.63	0.10	-35.30	-40.41	-6.56	-3.57	-36.33	-23.98
Hunan	0.39	-0.38	-39.35	-34.42	-4.86	-1.67	-20.55	-22.19
Guangdong	0.80	0.17	-49.37	-46.13	1.32	5.16	-47.07	-46.92
Guangxi	0.70	0.16	-5.36	-0.51	-0.70	2.97	-63.99	-77.29
Sichuan	0.39	-0.28	-38.11	-35.79	-8.43	-5.67	-15.48	-23.64
Guizhou	0.76	0.25	-6.25	0.90	-7.88	-4.89	-50.06	-51.44
Yunnan	0.65	0.12	-14.81	-16.58	-16.84	-15.88	-84.22	-88.32
Shaanxi	0.36	-0.33	-24.04	-26.79	-9.12	-6.75	-79.81	-80.51
Gansu	0.22	-0.75	-23.37	-20.62	-21.04	-17.99	-80.30	-87.12
Ningxia	0.40	-0.41	-36.02	-18.44	-4.78	-2.02	1.75	-6.35

Table 5: Counterfactual Results at Province Level

Note: This table shows the counterfactual results at the province level from counterfactual analysis one (columns 2-5), in which only the national government makes decisions, and counterfactual analysis two (columns 6-9), in which only provincial governments make decisions. The variables shown in the table are the average percentage change in real wage (W) weighted by population, the percentage change in labor (L), the percentage change in highway length(HWY), and the percentage change in tunnel length(TNNL).

Metric	**Counterfactual 1**	**Counterfactual 2**
EV Margins	0.40 %	-2.36 %

Table 6: EV Margins for Counterfactual Analyses

Note: EV margins, outlined in Equation (61), represent the average percentage change in real wage that must be compensated (if positive) or charged (if negative) in the baseline scenarios for consumers to be indifferent between the respective counterfactual scenario and the baseline scenario. Counterfactual analysis one raises real wages for most regions compared to the baseline scenario (with a few losers); thus, consumers must be compensated with a positive income in the baseline scenario to be indifferent between the counterfactual one and the baseline. Counterfactual analysis two generally yields lower real wages for most regions than the baseline scenario, corresponding with a negative EV margin.

to be indifferent between the baseline and the fully decentralized scenario. Additionally, both the Gini and Theil indices increase, signaling a rise in inequality under decentralization. Figure (13) in the Appendix visualizes the counterfactual outcomes at the prefecture level, revealing heterogeneous impacts. Coastal provinces such as Hebei, Liaoning, Zhejiang, Fujian, and Guangdong experience gains in average real wages, while other provinces suffer wage declines, highlighting the uneven distribution of benefits under a decentralized structure. In general, western inland provinces experienced more pronounced declines in real wages, while eastern coastal provinces saw fewer decreases or even gains. The mechanisms driving these provincial-level outcomes are threefold.

Metric	**Baseline**	**Counterfactual 1**	**Counterfactual 2**
Gini Index	0.2987	0.2998	0.3103
Theil Index	0.1449	0.1461	0.1572

Table 7: Gini and Theil Index under Baseline and Counterfactual Scenarios

Note: This table shows the Gini and Theil indices for the baseline scenario, counterfactual one (national government decisions), and counterfactual two (provincial governments' decisions). The baseline scenario yields the lowest Gini and Theil indices.

First, access to global markets via coastal ports plays a crucial role. In the baseline scenario, the national government ensures sufficient infrastructure along the least-cost paths connecting the eastern coast to the western inland, enabling the inland regions to trade with the rest of the world at relatively low costs. Under decentralization, this national coordination is lost, leading to underinvestment in infrastructure along key national trade routes. As a result, western inland provinces face a more substantial increase in trade costs, limiting their ability to engage in international trade and causing a considerable decline in real wages.

Second, under decentralization, provincial governments neglect the spillover effects of infrastructure, as their investments are focused solely on regions within their own borders. They prioritize areas that are central to the province rather than those benefiting neighboring regions. As shown in Panel (d) of Figure (14), the change in real wages at the prefecture level is positively correlated with a region's centrality within its province. Consequently, as demonstrated in Panels (a), (b) and (c), regions experiencing a decline in infrastructure investment also saw decreases in real wages, further fueling migration away from those areas. To explain the distribution of gains and losses, Panels (c) and (d) of Figure (50) highlight a positive relationship between provincial infrastructure investments and province-to-country relative centrality. This indicates that regions more central to a province but less central to the country receive disproportionate investment under this counterfactual. The failure of provincial governments to internalize the spillover effects of their infrastructure decisions exacerbates these imbalances, leading to a significant national welfare decline under decentralization, as reflected by the negative EV margin.

Third, national governments tend to underinvest in geographic peripheries, particularly non-port prefectures along the coast, such as those in Guangdong, Fujian, Zhejiang, Hebei, and Liaoning. Decentralization reallocates more of the budget to these provinces, allowing for greater infrastructure investment in non-port coastal regions. This explains why these provinces experience mild gains in real wages under decentralization.

7 Conclusion

This paper develops a quantitative spatial equilibrium model to analyze the provision of infrastructure under a two-tier government structure, where a benevolent national government and self-interested provincial governments invest in highways and tunnels to maximize welfare within their respective jurisdictions. The study examines how the interplay between centralization and decentralization shapes infrastructure investment decisions and their effects on welfare and equality. The findings suggest that collaborative planning between national and provincial governments preserves much of the efficiency gains from centralized planning while also enabling provincial governments to address local needs and reduce inequality. Despite having complete information and identical welfare-maximizing objectives, national and provincial governments often pursue divergent infrastructure strategies: the national government prioritizes investments that enhance country-wide connectivity, while provincial governments focus on improving intra-provincial infrastructure and local welfare.

This paper opens up several exciting paths for future research on public policy using spatial models. Firstly, it can be interesting to allow differentiated objective functions to address varying objectives for specific local governments. Secondly, assuming that governments have incomplete information on location and edge attributes may lead to very different efficiency and equality predictions. Thirdly, allowing more interactions (competitions or collaborations) between national and provincial governments and between different provincial governments can be interesting.

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A Theory

A.1 FOC and Marginal Utility for Planner's Problems

The national government's problem is as follows:

$$\underset{(\phi^r_{upper,n},\phi^t_{upper,n})}{Max} \bar{U} = \Gamma(\frac{\epsilon-1}{\epsilon})\left[\sum_{n\in N}(v_n/P_n^{\alpha}r_n^{1-\alpha})^{\epsilon}\right]^{\frac{1}{\epsilon}}$$

subject to (a) budget constraint

$$Z \geq \sum_{n\in N} w_n L_n^{infra}$$

(b) construction worker supply constraint

$$\frac{\sum_{n\in N} L_n^{infra}}{\sum_{n\in N} L_n} \leq 1$$

(c) goods market clears:

$$w_n L_n = \sum_{n\in N}\pi_{in} w_n L_n = \sum_{n\in N}\frac{(1-\lambda)L_i}{\sigma F}(\frac{\sigma}{\sigma-1}\frac{w_i}{A_i}T_{in})^{1-\sigma}P_n^{\sigma-1}\, w_n L_n$$

(d) trade cost along the least-cost paths:

$$\text{argmin} T_{kl} = \prod_{in\in\mathcal{L}}(t_{in}|\mathcal{I}_{kl}^{in}=1) \quad \forall k,l \in N$$

(e)labor market clears:

$$L_n = \pi_n(\omega) * L = \frac{(v_n/P_n^{\alpha}r_n^{1-\alpha})^{\epsilon}}{\sum_{k\in N}(v_k/P_k^{\alpha}r_k^{1-\alpha})^{\epsilon}}L \tag{51}$$

where the price index is given by:

$$P_n^{1-\sigma} = \sum_k \frac{(1-\lambda)L_k}{\sigma F}(\frac{\sigma}{\sigma-1}\frac{w_k}{A_k}T_{kn})^{1-\sigma}$$

the rent is given by:

$$r_n = \frac{1-\alpha}{\alpha}\frac{w_n L_n}{H_n}$$

and $\sum_i L_i = L$

The Lagrangian of the national government's problem is as follows:

$$
\begin{aligned}
\mathcal{L} =&\Gamma(\frac{\epsilon-1}{\epsilon})\Big[\sum_{n\in N}(v_n/P_n^{\alpha}r_n^{1-\alpha})^{\epsilon}\Big]^{\frac{1}{\epsilon}} \\
&-\sum_{n}^{N}\mu_{n,1}\Big[w_nL_n-\sum_{i\in N}\frac{(1-\lambda)L_i}{\sigma F}(\frac{\sigma}{\sigma-1}\frac{w_i}{A_i}T_{in})^{1-\sigma}P_n^{\sigma-1}w_nL_n\Big] \\
&-\sum_{n}^{N}\mu_{n,2}\Big[\frac{(v_n/P_n^{\alpha}r_n^{1-\alpha})^{\epsilon}}{\sum_{k\in N}(v_k/P_k^{\alpha}r_k^{1-\alpha})^{\epsilon}}-\frac{L_n}{L}\Big] \\
&-\sum_{kl\in\mathcal{L}}\mu_{kl,3}\Big[\prod_{in\in\mathcal{L}}(t_{in}|\mathcal{I}_{kl}^{in}=1)-T_{kl}\Big] \\
&-\mu_4(\sum_{n\in N}w_n(c_n^r\phi^r_{upper,n}+c_n^t\phi^t_{upper,n})-Z) \\
&-\mu_5(\frac{\sum_{n\in N}L_n^{infra}}{\sum_{n\in N}L_n}-1)
\end{aligned}
\tag{52}
$$

where $\mu_{n,1}$, $\mu_{n,2}$, $\mu_{kl,3}$, μ_4 and μ_5 are the Lagrangian multipliers. In practice, the construction worker supply constraint is not binding, so that $\mu_5=0$. The first-order condition with respect to $\phi^r_{upper,n}$ implies:

$$
\begin{aligned}
&\frac{\partial\mathcal{L}}{\partial\phi^r_{upper,m}}=0: \\
&\underbrace{\frac{\partial\bar{U}}{\partial\phi^r_{upper,m}}}_{\text{Direct Effect}}+\underbrace{\sum_n\sum_i\mu_{n,1}\frac{\partial x_{in}}{\partial\phi^r_{upper,m}}}_{\text{Wage Effect}}+\underbrace{\sum_n\sum_i\mu_{n,2}\frac{\partial\frac{L_n}{L}}{\partial\phi^r_{upper,m}}}_{\text{Labor Effect}}+\underbrace{\mu_3\frac{\partial T_{kl}}{\partial\phi^r_{upper,m}}}_{\text{Path Effect}}=\underbrace{\mu_4w_mc_m^r}_{MC}
\end{aligned}
\tag{53}
$$

where $x_{in}=M_ip_{in}^{1-\sigma}=\frac{(1-\lambda)L_n}{\sigma F}(\frac{\sigma}{\sigma-1}\frac{w_i}{A_i}T_{in})^{1-\sigma}$ is the expenditure on goods produced in i and consumed in n.

For simpler intuitions, let's focus on the direct effect in Equation (36). Let $U_n=v_n/P_n^{\alpha}r_n^{1-\alpha}$.

The marginal utility from investment on highways is:

$$
\begin{aligned}
\frac{\partial \bar{U}}{\partial \phi^r_{upper,m}} &= \frac{1}{\epsilon}(\bar{U})^{-1}\frac{\partial \sum_n^N U_n^\epsilon}{\partial \phi^r_{upper,m}} \\
&= \frac{1}{\epsilon}(\bar{U})^{-1}\epsilon \sum_n^N U_n^{\epsilon-1}\frac{\partial U_n}{\partial \phi^r_{upper,m}} \\
&= (\bar{U})^{-1}\sum_n^N U_n^{\epsilon-1}\frac{v_n}{r_n^{1-\alpha}}\frac{\partial P_n^{-\alpha}}{\partial \phi^r_{upper,m}} \\
&= -\alpha(\bar{U})^{-1}\sum_n^N U_n^{\epsilon}\frac{1}{P_n}\frac{\partial P_n}{\partial \phi^r_{upper,m}} \\
&= \underbrace{-\alpha(\bar{U})^{-1}\sum_n^N U_n^{\epsilon}P_n^{\sigma-1}}_{\equiv C_1}\sum_i^N M_n p_{in}^{(1-\sigma)}T_{in}^{-1}\frac{\partial T_{in}}{\partial \phi^r_{upper,m}} \\
&= C_1 * \sum_i^N x_{in}T_{in}^{-1}T_{in}\Big[\sum_x^V \mathcal{I}_{in}^{xm,mx}\cdot\frac{1}{t_{xm,mx}}\cdot\frac{\partial t_{xm,mx}}{\partial \phi^r_{upper,m}}\Big] \\
&= \frac{1}{2}C_1 * \sum_i^N x_{in} * \Big[\sum_x^V \mathcal{I}_{kl}^{xm}\underbrace{\frac{1}{1-\sigma}}_{C_2}[\frac{\beta^r_{dist}log(dist)_{xm}}{area_m}] + \sum_x^V \mathcal{I}_{kl}^{mx}\underbrace{\frac{1}{1-\sigma}}_{C_2}[\frac{\beta^r_{dist}log(dist)_{mx}}{area_m}]\Big] \\
&= \frac{1}{2}C_1C_2 * \sum_i^N x_{in} * \Big[\sum_x^V \mathcal{I}_{kl}^{xm}\frac{\beta^r_{dist}log(dist)_{xm}}{area_m} + \sum_x^V \mathcal{I}_{kl}^{mx}\frac{\beta^r_{dist}log(dist)_{mx}}{area_m}\Big] \qquad (54)
\end{aligned}
$$

where $x_{in} = M_n p_{in}^{(1-\sigma)} = \frac{(1-\lambda)L_n}{\sigma F} * (\frac{\sigma}{\sigma-1}\frac{w_i}{A_i}T_{in})^{(1-\sigma)}$. $\mathcal{I}_{in}^{xm,mx} = 1$ if edge xm or mx is on the least cost-path from k to l. V is the set of all locations near m. Similarly, one can derive the marginal utility with respect to investment in tunnels, where, generally speaking, $elev_{xm} \neq elev_{mx}$.

$$
\frac{\partial \bar{U}}{\partial \phi^r_{upper,m}} = \frac{1}{2}C_1C_2 * \sum_i^N x_{in} * \Big[\sum_x^V \mathcal{I}_{in}^{xm}\frac{\beta^t_{elev}log(elev_{xm})}{area_m} + \sum_x^V \mathcal{I}_{in}^{mx}\frac{\beta^t_{elev}log(elev_{mx})}{area_m}\Big] \qquad (55)
$$

Let's consider the relative marginal utility per dollar between highways and tunnels in region m.

$$
\begin{aligned}
&\frac{MU^r_{upper,m}/MC^r_m}{MU^t_{upper,m}/MC^t_m} \\
&= \frac{\frac{1}{2}C_1C_2 * \sum_n x_{in} * \Big[\sum_x^V \mathcal{I}_{in}^{xm}\frac{\beta^r_{dist}log(dist)_{xm}}{area_m} + \sum_x^V \mathcal{I}_{in}^{mx}\frac{\beta^r_{dist}log(dist)_{mx}}{area_m}\Big]}{\frac{1}{2}C_1C_2 * \sum_n x_{in} * \Big[\sum_x^V \mathcal{I}_{in}^{xm}\frac{\beta^t_{elev}log(elev_{xm})}{area_m} + \sum_x^V \mathcal{I}_{in}^{mx}\frac{\beta^t_{elev}log(elev_{mx})}{area_m}\Big]} * \frac{w_m c^t_m}{w_m c^r_m} \\
&= \frac{\sum_x^V \mathcal{I}_{in}^{xm}\beta^r_{dist}log(dist_{xm}) + \sum_x^V \mathcal{I}_{in}^{mx}\beta^r_{dist}log(dist)_{mx}}{\sum_x^V \mathcal{I}_{in}^{xm}\beta^t_{elev}log(elev_{xm}) + \sum_x^V \mathcal{I}_{in}^{mx}\beta^t_{elev}log(elev_{mx})} * \frac{c^t_m}{c^r_m} \qquad (56)
\end{aligned}
$$

Similarly, one can solve the marginal utility of highways and tunnels for provincial governments' problems. The difference is that provincial governors only consider the welfare of residents within their governed province p. Let $C_1^{'} = -\alpha(\bar{U}_p)^{-1}\sum_{n\in p} U_n^{\epsilon} P_n^{\sigma-1}$, where $\bar{U}_p$ is the expected utility within province p, $\bar{U}_p = \Gamma(\frac{\epsilon-1}{\epsilon})\Big[\sum_{n\in p}(v_n/P_n^{\alpha} r_n^{1-\alpha})^{\epsilon}\Big]^{\frac{1}{\epsilon}}$.

$$\frac{\partial \bar{U}_p}{\partial \phi^r_{lower,m}} = \frac{1}{2} C_1 C_2 * \sum_i^p x_{in} * \Bigg[\sum_x^{V'\in p} \mathcal{I}_{in}^{xm} \frac{\beta^r_{dist} log(dist)_{xm}}{area_m} + \sum_x^{V'\in p} \mathcal{I}_{in}^{mx} \frac{\beta^r_{dist} log(dist)_{mx}}{area_m}\Bigg] \tag{57}$$

$$\frac{\partial \bar{U}_p}{\partial \phi^t_{lower,m}} = \frac{1}{2} C_1^{'} C_2 * \sum_i^p x_{in} * \Bigg[\sum_x^{V'\in p} \mathcal{I}_{in}^{xm} \frac{\beta^t_{elev} log(elev_{xm})}{area_m} + \sum_x^{V'\in p} \mathcal{I}_{in}^{mx} \frac{\beta^t_{elev} log(elev_{mx})}{area_m}\Bigg] \tag{58}$$

where V' is the set of all locations adjacent to x and within province p.

The relative marginal utility per dollar between provincial and national highways is as follows:

$$\frac{MU^r_{lower,m}/MC^r_n}{MU^r_{upper,m}/MC^r_n} = \frac{C_1^{'} * \sum_i^p x_{in} * \sum_x^{V'\in p} \mathcal{I}_{in}^{xm}\Big[\frac{\beta^r_{dist} log(dist_{xm})}{area_m}\Big]}{C_1 * \sum_i^N x_{in} * \sum_x^V \mathcal{I}_{in}^{xm}\Big[\frac{\beta^r_{dist} log(dist_{xm})}{area_m}\Big]} \tag{59}$$

where the marginal costs cancel out because the construction cost is the same for both tiers of government.

A.2 Equivalence Variation

This paper defines equivalence variation (EV) as the change in real wages in the baseline setting that would achieve the same utility level after a counterfactual change in infrastructure investments.

Consider two equilibrium infrastructure investment outcomes: the baseline outcome $\phi_n = \phi_{upper,n} + \phi_{lower,n}$ and the counterfactual outcome $\phi_n^{'} = \phi_{upper,n}^{'} + \phi_{lower,n}^{'}$. They lead to two different levels of expected utility for the country, $\bar{U}$ and $\bar{U}^{'}$. Define $\frac{\bar{U}}{\bar{U}^{'}} \equiv b$. Using the expected utility in equation (14), one can calculate the wage $\mathfrak{w}_n$ that achieves the counterfactual expected utility under the baseline equilibrium.

$$\begin{aligned}
\bar{U}^{'} = \frac{\bar{U}}{b} &= \Gamma(\frac{\epsilon-1}{\epsilon})\Bigg[\sum_{n\in N}(v_n/P_n^{\alpha} r_n^{1-\alpha})^{\epsilon}\Bigg]^{\frac{1}{\epsilon}} * b^{-1} \\
&= \Gamma(\frac{\epsilon-1}{\epsilon})\Bigg[\sum_{n\in N}(w_n\alpha^{-1}b^{-1})/P_n^{\alpha} r_n^{1-\alpha})^{\epsilon}\Bigg]^{\frac{1}{\epsilon}}
\end{aligned} \tag{60}$$

where $v_n = \frac{w_n}{\alpha}$ is the total landlord income, including labor and rent income. w_n is the nominal wage. Equation (61) shows that the wage that achieves the counterfactual expected utility under the baseline equilibrium is $\mathfrak{w}_n = \frac{w_n}{b}$. In other words, by plugging $\mathfrak{w}_n = \frac{w_n}{b}$ into the expected utility with baseline variable values, one will get $\bar{U}'$. The EV is the difference between the two real wages:

$$EV_n = \frac{\mathfrak{w}_n}{P_n} - \frac{w_n}{P_n} = \frac{w_n}{P_n}(\frac{1-b}{b}) \tag{61}$$

EV_n is a constant markup over the baseline real wage, which does not depend on location n. For convenience, define the EV margin as $(\frac{1-b}{b}) * 100$. The EV margin tells the percentage of real wage that each consumer must be compensated(if the margin is positive) or charged (if the margin is negative) so that they are indifferent between the baseline and the counterfactual scenarios. On the other hand, EV_n tells the amount.

B Tables and Figures

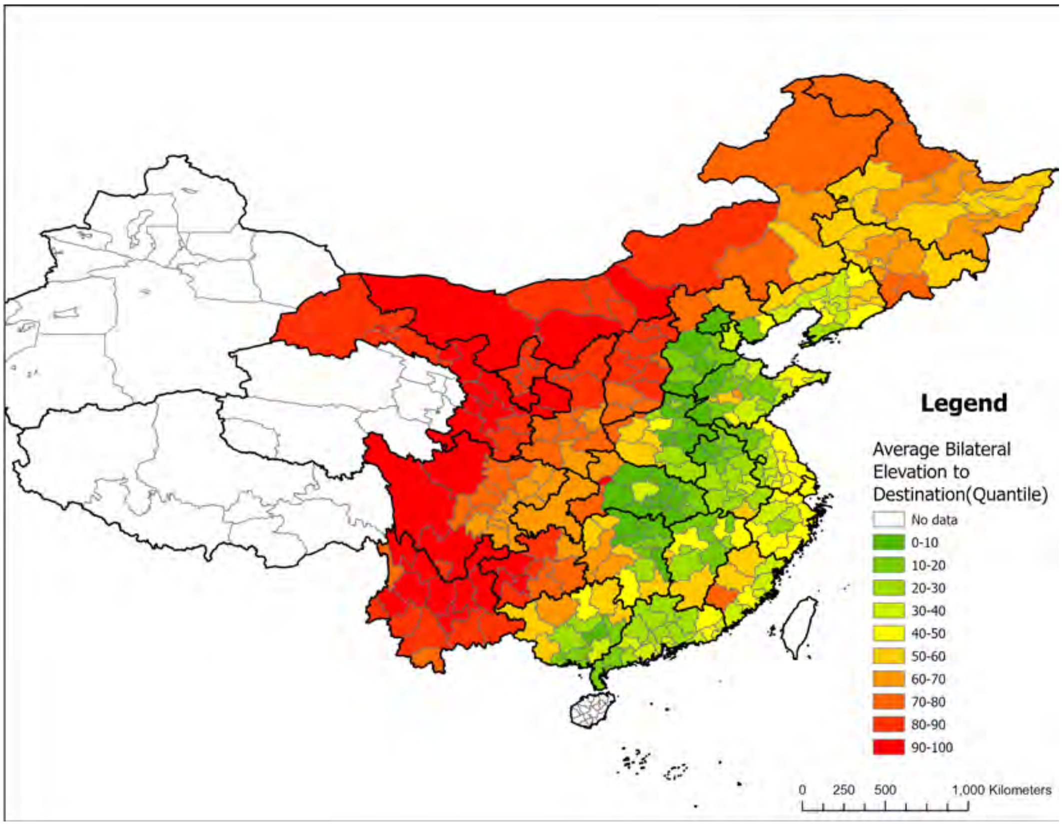


Figure 9: Average Bilateral Elevation

Note: This figure shows each prefecture's average effective bilateral elevation to the rest of the prefectures in the sample. The regions in lower percentiles have relatively flatter routes than the rest of the country. Note that the bilateral elevation in this paper is simplified from Sun (2024).

No.	Port Name	Value(10,000 TEU)
1	Shanghai	4330
2	Ningbo	2753
3	Shenzhen	2577
4	Guangzhou	2283
5	Qingdao	2101
6	Tianjin	1730
7	Xiamen	1112
8	Dalian	876
9	Yingkou	548
10	Lianyungang	478
11	Rizhao	450
12	Beibu Gulf(including Qinzhou, Fangchenggang, Beihai)	382
13	Dongguan	368
14	Fuzhou	354
15	Yantai	310
16	Tangshan	294
17	Quanzhou	258
18	Zhuhai	256
19	Haikou	197
20	Jinzhou	188
21	Jiaxing	187
22	Zhongshan	141
23	Shantou	135
24	Zhanjiang	112
25	Weihai	103

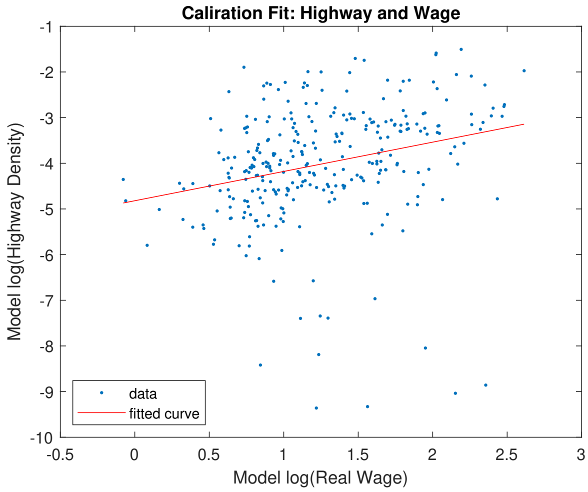
Table 8: Container Throughput of Top 25 Coastal Ports in China, 2019

This table provides the 2019 container throughput (measured in 10,000 TEU, Twenty-foot Equivalent Units) for the top 25 coastal ports in China. Beibu Gulf, represent combined figures for multiple ports (Qinzhou, Fangchenggang, Beihai). Data comes from Ministry of Transport of China.

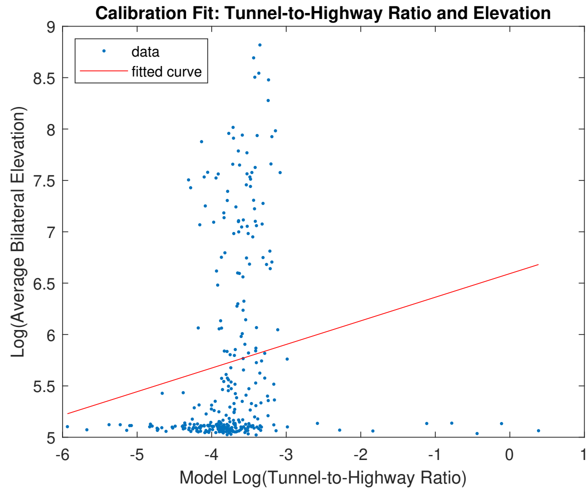
Variables	Moment	Baseline	Counterfactual 1	Counterfactual 2
Hwy Length	Mean	358.11	263.79	198.69
	SD	349.99	317.74	188.28
Ntnl Hwy Length	Mean	267.53	263.79	0.00
	SD	325.50	317.74	0.00
Prvn Hwy Length	Mean	90.58	0.00	198.69
	SD	183.94	0.00	188.28
Tnnl Length	Mean	9.43	7.25	5.01
	SD	11.43	10.66	6.61
Ntnl Tnnl Length	Mean	6.67	7.25	0.00
	SD	10.75	10.66	0.00
Prvn Tnnl Length	Mean	2.75	0.00	5.01
	SD	5.74	0.00	6.61

Table 9: Counterfactual Result Summary

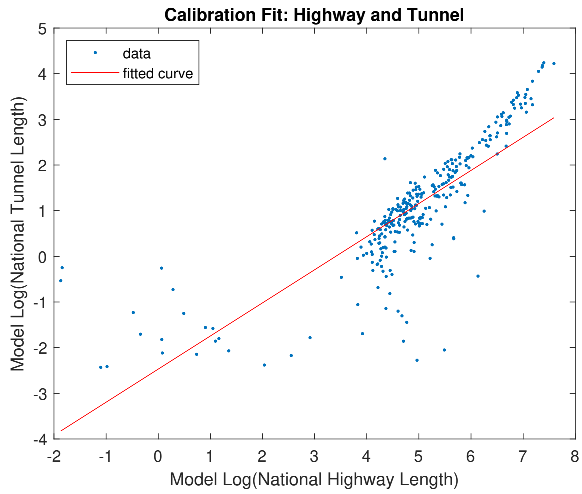
Note: This table summarizes the baseline and counterfactual infrastructure length values. The unit for length is 1 kilometer. The variables from top to bottom are highway length, national highway length, provincial highway length, tunnel length, national tunnel length, and provincial tunnel length.



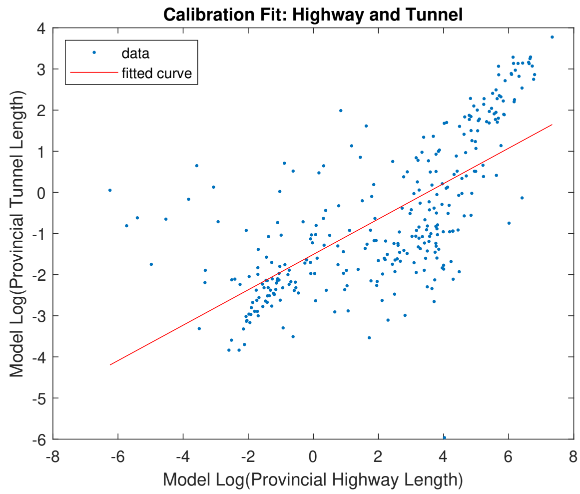
(a) Highway and Income



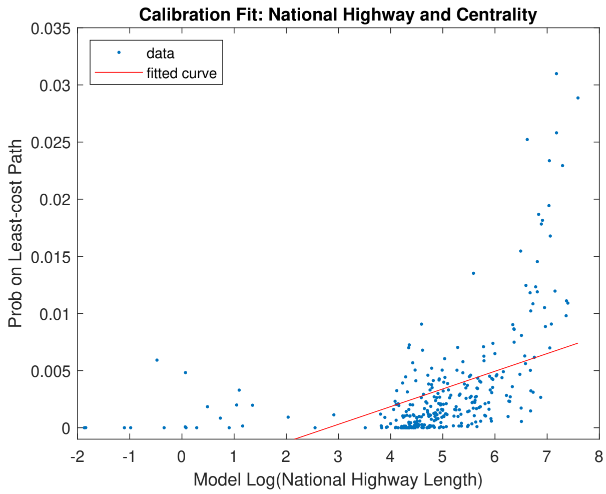
(b) Tunnel Highway and Elevation



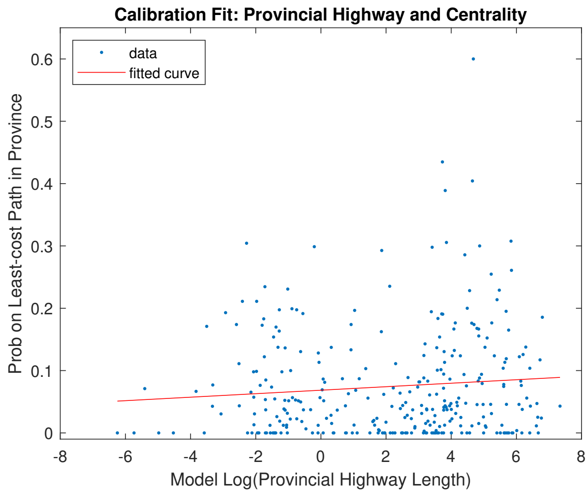
(c) National Highway and Tunnels



(d) Provincial Highway and Tunnels



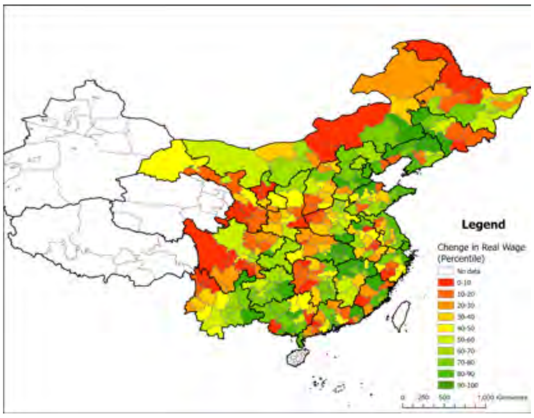
(e) National Highway and Centrality



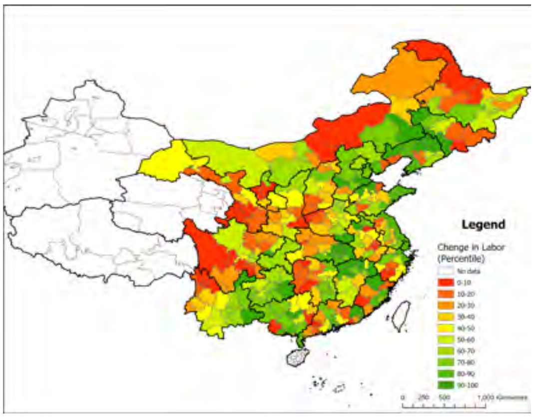
(f) Provincial Highway and Centrality

Figure 10: Model Replication of Stylized Facts

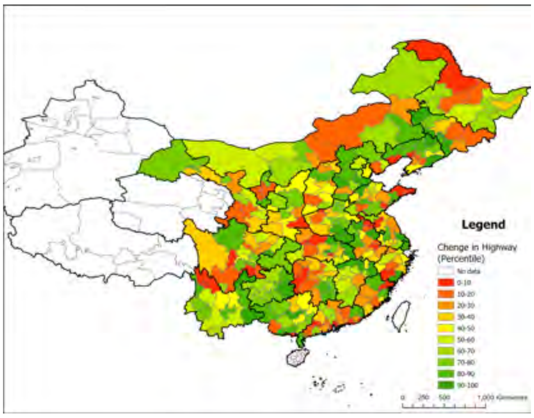
Note: This figure presents six panels illustrating how the baseline model replicates stylized facts in Section (3). Aligned with the data, the model predicts that (a) highways are positively correlated with income, (b) tunnel-to-highway ratio is positively correlated with average bilateral elevation to the rest of the regions, highways are positively correlated with tunnels from (c) national planning and (d) provincial planning, and highways are positively correlated with centrality within the jurisdiction at the (e) national level and (f) provincial level.



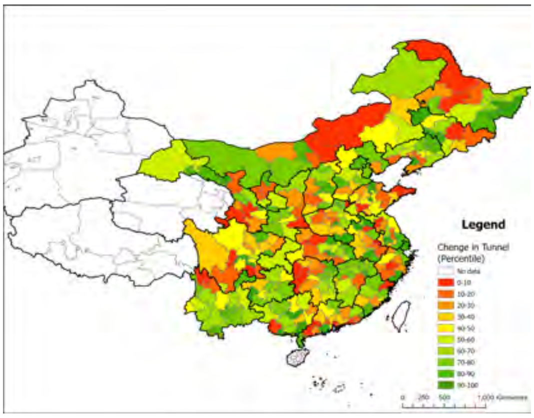
(a) Real Wage



(b) Labor



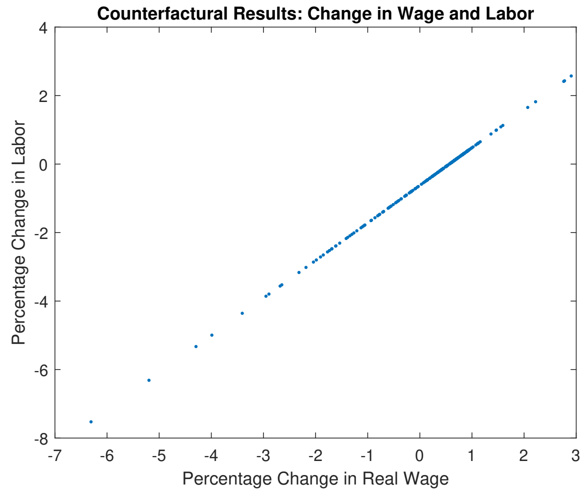
(c) Highway



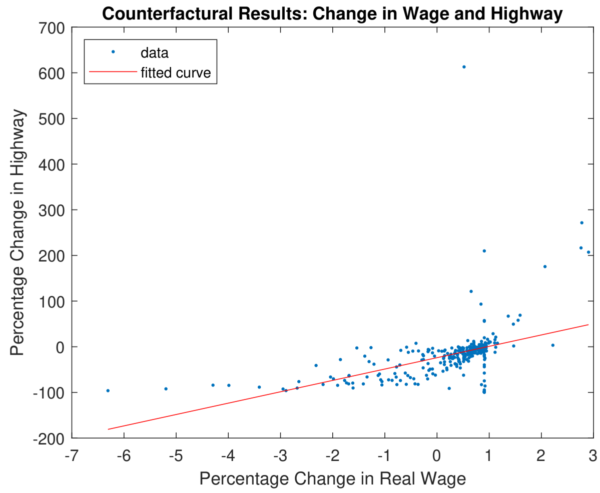
(d) Tunnel

Figure 11: Counterfactual Result: Distribution of Changes Under Complete Centralization

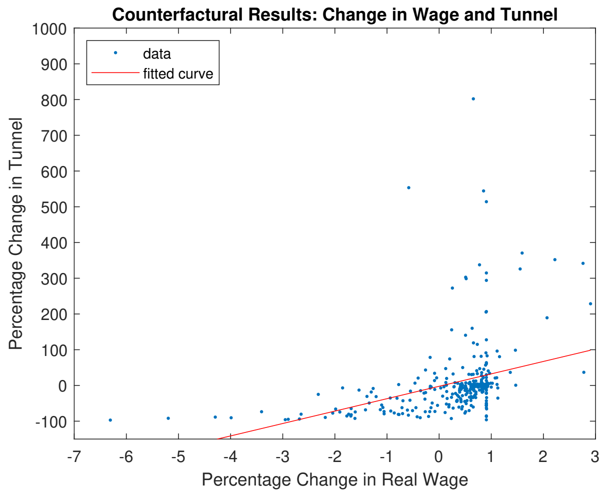
Note: This figure illustrates the distributional impacts of complete centralization in infrastructure planning across four key variables: (a) real wage, (b) labor, (c) highway, and (d) tunnel.



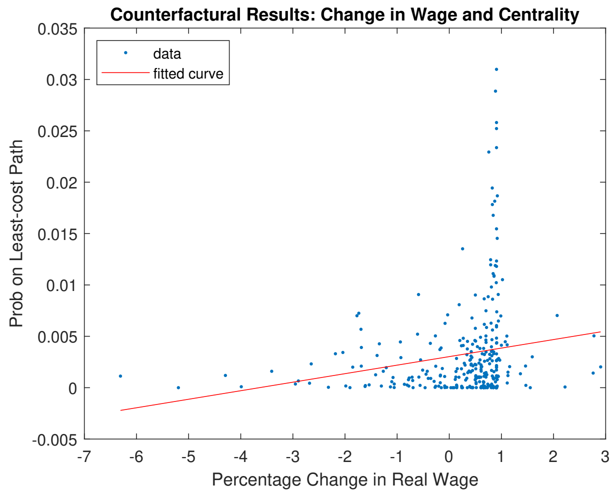
(a) Wage and Labor



(b) Wage and Highway



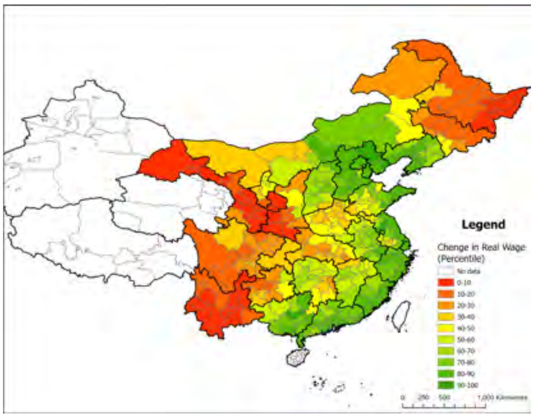
(c) Wage and Tunnel



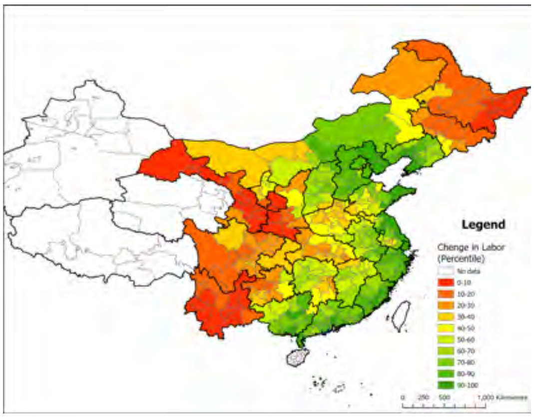
(d) Wage and Centrality

Figure 12: Counterfactual Result: Relationship of Changes Under Complete Centralization

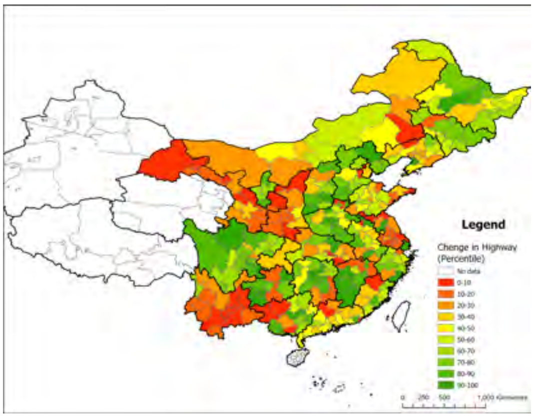
This figure presents the relationship between real wage changes and various key variables (labor, highway, tunnel, and centrality) under the complete centralization scenario. Panel (a) shows that, after the counterfactual change, labor is migrated to the regions with higher changes in real wages. Panel (b) and (c) explain the mechanism of change in real wage: Regions that experienced a greater increase in infrastructure investment see greater rises in real wage. Panel (d) further explains the distributional pattern of the changes: Regions with a greater probability of being on the least path experience the most substantial changes in the real wage.



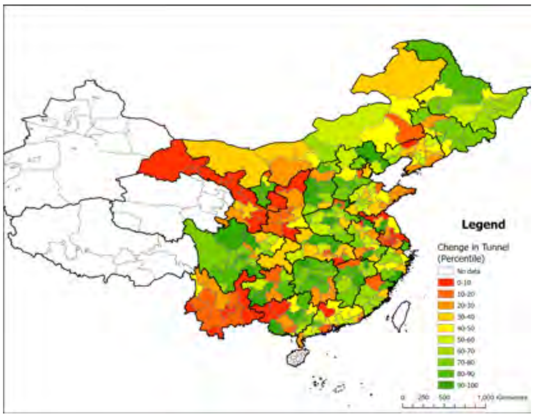
(a) Real Wage



(b) Labor



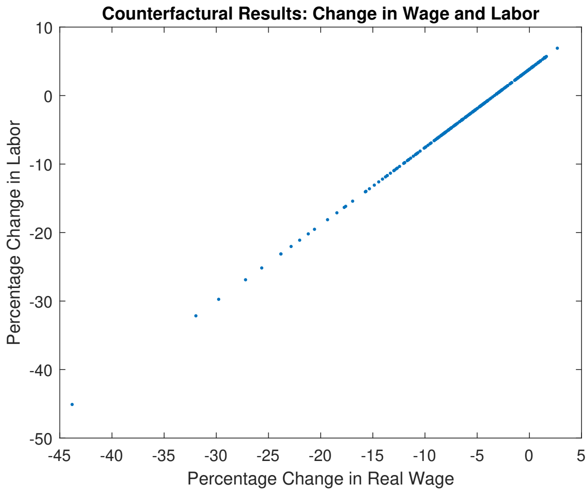
(c) Highway



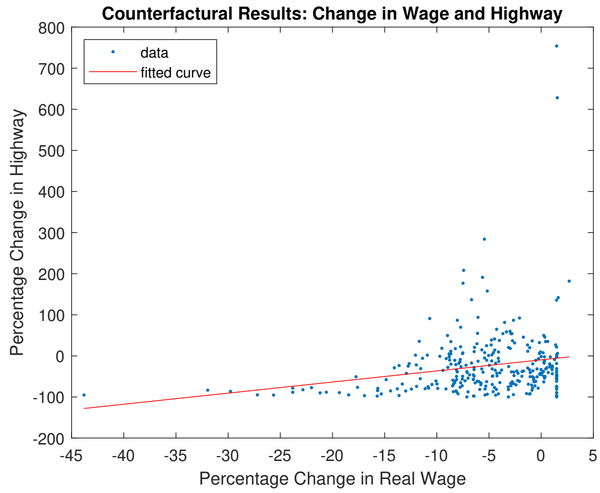
(d) Tunnel

Figure 13: Counterfactual Result: Distribution of Changes Under Complete Decentralization

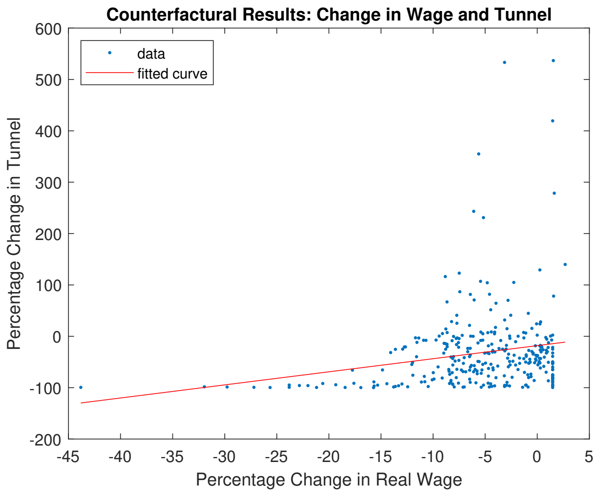
Note: This figure illustrates the distributional impacts of complete decentralization in infrastructure planning across four key variables: (a) real wage, (b) labor, (c) highway, and (d) tunnel.



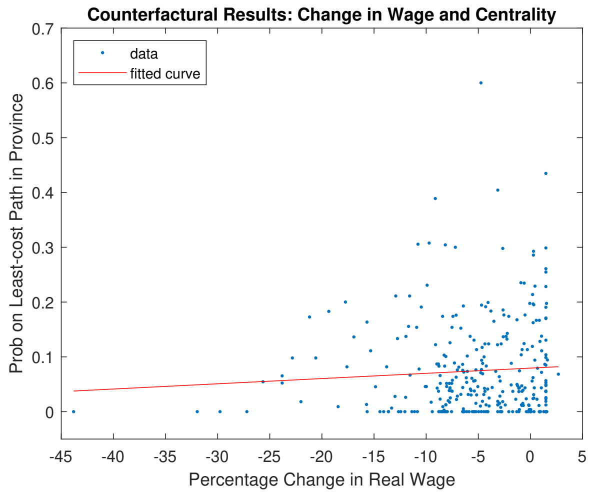
(a) Real Wage and Labor



(b) Real Wage and Highway



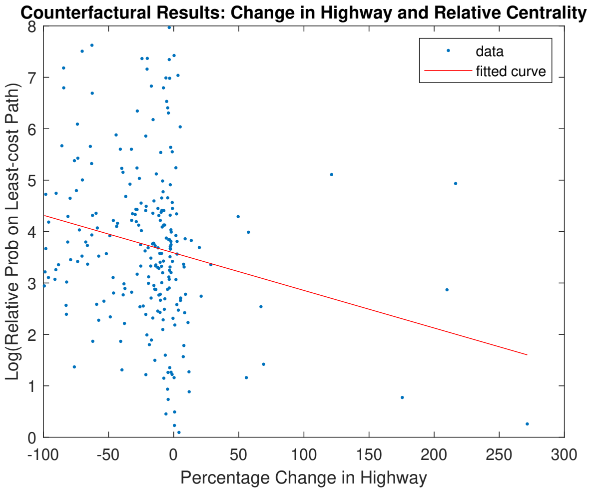
(c) Real Wage and Tunnel



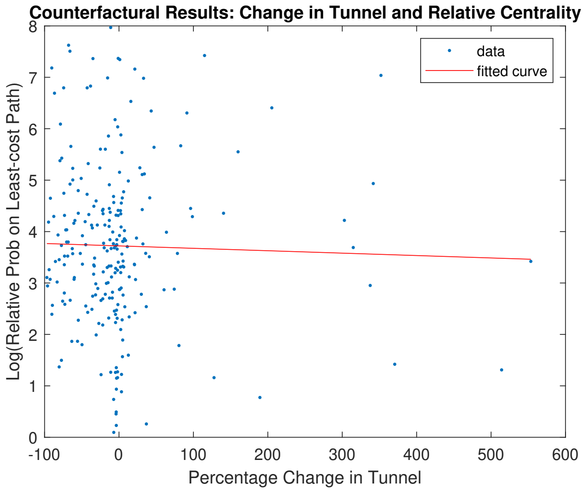
(d) Real Wage and Centrality

Figure 14: Counterfactual Result: Relationship of Changes Under Complete Decentralization

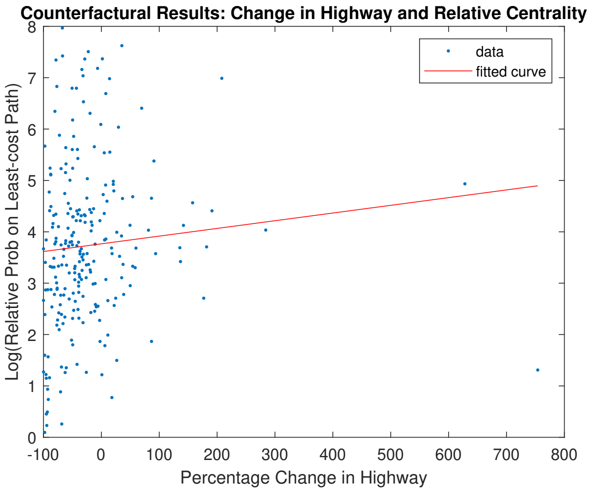
This figure presents the relationship between real wage changes and various key variables (labor, highway, tunnel, and centrality) under the complete decentralization scenario. Panel (a) shows that, after the counterfactual change, labor is migrated to the regions with higher changes in real wages. Panel (b) and (c) explain the mechanism of change in real wage: Regions that experienced a greater increase in infrastructure investment see greater rises in real wage. Panel (d) further explains the distributional pattern of the changes: Regions with a greater probability of being on the least path in the province experience the most substantial changes in the real wage.



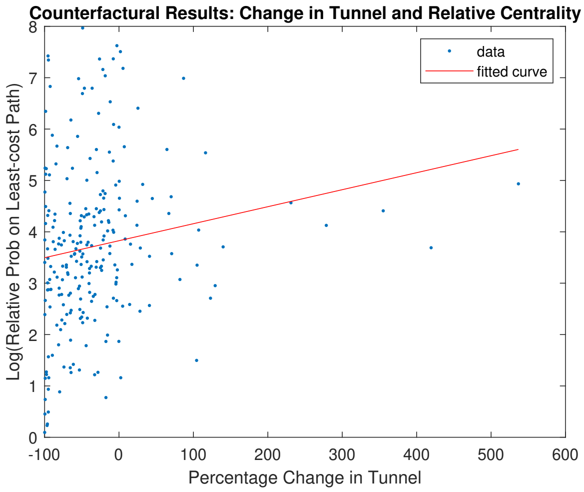
(a) Highway



(b) Tunnel



(c) Highway



(d) Tunnel

Table 10: Counterfactual Result: Change in Wage and Relative Centrality

Note: In the tables, the variable on the x-axis is the percentage change in infrastructure in counterfactual 1 (Panels (a) and (b)) and in counterfactual 2(Panels (c) and (d)). The variable on the y-axis is the log of relative probability on the least-cost path (the probability of being on the least-cost path within a province divided by the probability of being on the least-cost path within the whole country).

Province	Data Hwy	Baseline Hwy	Data Tnnl	Baseline Tnnl
Hebei	8267.29	6202.63	1116.69	145.44
Shanxi	4040.14	3236.02	1929.72	101.58
Inner Mongolia	5897.23	4118.59	335.27	115.04
Liaoning	3683.21	3870.97	489.56	98.33
Jilin	2913.39	2498.48	174.23	58.01
Heilongjiang	4520.96	3375.11	87.58	88.87
Jiangsu	5786.74	8305.14	133.81	145.28
Zhejiang	2591.06	4441.09	1664.34	93.42
Anhui	4743.06	4619.54	410.70	90.36
Fujian	2172.65	4033.64	2467.07	103.66
Jiangxi	5815.31	3728.85	473.70	97.85
Shandong	6092.25	6187.10	126.47	152.35
Henan	7212.01	6120.22	252.10	163.28
Hubei	6477.43	5771.93	1210.98	143.05
Hunan	6359.01	5066.10	611.99	125.54
Guangdong	7337.19	7116.51	1169.30	149.83
Guangxi	5136.53	7180.51	430.06	245.64
Sichuan	8254.74	9328.63	3620.87	311.23
Guizhou	3662.50	4407.69	877.20	167.92
Yunnan	5302.60	4644.63	1232.28	137.73
Shaanxi	3676.85	3606.02	2512.54	103.78
Gansu	3590.03	2194.73	1169.54	60.08
Ningxia	1558.98	602.34	69.72	14.97

Table 11: Calibration fit: infrastructure lengths by province

This table provides a detailed overview of the lengths of highways and tunnels across various provinces in China, comparing actual data (Data Hwy and Data Tnnl) with baseline model predictions (Baseline Hwy and Baseline Tnnl). The unit is in kilometers.

Province	**Data NTL Hwy**	**Baseline NTL Hwy**	**Data NTL Tnnl**	**Baseline NTL Tnnl**
Hebei	6866.22	5880.61	770.10	131.55
Shanxi	3573.85	2738.00	985.80	80.15
Inner Mongolia	3886.37	3494.52	116.18	91.86
Liaoning	3501.73	2985.45	397.65	78.53
Jilin	2115.29	1806.12	63.82	41.03
Heilongjiang	3321.06	1907.07	14.55	40.10
Jiangsu	3813.13	6191.39	85.76	108.29
Zhejiang	2898.61	2767.55	941.55	45.25
Anhui	3578.97	3045.25	340.16	44.97
Fujian	3266.66	2946.78	1665.21	85.25
Jiangxi	4010.67	3501.51	245.03	89.60
Shandong	4393.43	4146.51	100.89	98.18
Henan	3963.66	4342.59	101.52	87.56
Hubei	4033.83	4056.18	576.84	81.69
Hunan	4089.22	3127.89	313.53	74.89
Guangdong	5623.73	3675.68	750.24	72.27
Guangxi	4045.46	6822.33	349.04	236.90
Sichuan	7632.02	5980.67	2916.63	182.14
Guizhou	1707.62	4392.35	357.11	163.47
Yunnan	2405.06	3900.66	534.27	106.35
Shaanxi	4892.26	2869.08	2500.26	73.46
Gansu	3348.98	1726.11	1017.38	40.83
Ningxia	1348.68	362.12	34.03	8.13

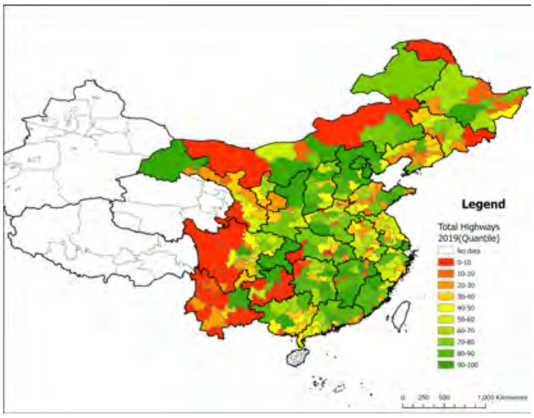
Table 12: Calibration fit: national infrastructure lengths by province

This table provides a detailed overview of the lengths of highways and tunnels in the National Expressway network across various provinces in China, comparing actual data with baseline model predictions. The unit is in kilometers.

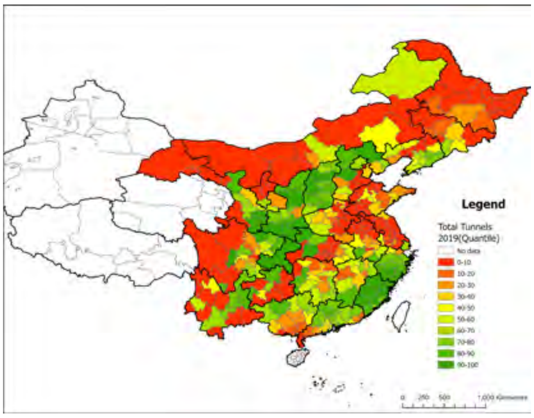
Province	Data Prvn Hwy	Baseline Prvn Hwy	Data Prvn Tnnl	Baseline Prvn Tnnl
Hebei	2517.76	322.01	346.59	13.89
Shanxi	2396.01	498.02	943.92	21.43
Inner Mongolia	1023.35	624.07	0.00	23.18
Liaoning	671.04	885.52	91.91	19.80
Jilin	531.40	692.35	37.38	16.98
Heilongjiang	846.55	1468.05	0.00	48.76
Jiangsu	2107.43	2113.75	48.06	36.98
Zhejiang	1356.80	1673.54	722.79	48.17
Anhui	1574.79	1574.30	70.55	45.39
Fujian	1373.06	1086.87	801.86	18.41
Jiangxi	2278.33	227.34	228.66	8.25
Shandong	1825.30	2040.58	25.58	54.16
Henan	3059.53	1777.64	77.55	75.72
Hubei	1449.95	1715.74	269.00	61.37
Hunan	2440.85	1938.21	225.43	50.64
Guangdong	2882.76	3440.84	419.06	77.57
Guangxi	1521.12	358.18	81.02	8.74
Sichuan	2920.81	3347.97	485.15	129.09
Guizhou	627.45	15.34	154.95	4.45
Yunnan	161.49	743.97	40.75	31.38
Shaanxi	347.57	736.95	12.29	30.32
Gansu	67.46	468.62	6.10	19.25
Ningxia	280.02	240.23	35.69	6.84

Table 13: Calibration fit: provincial infrastructure length by province

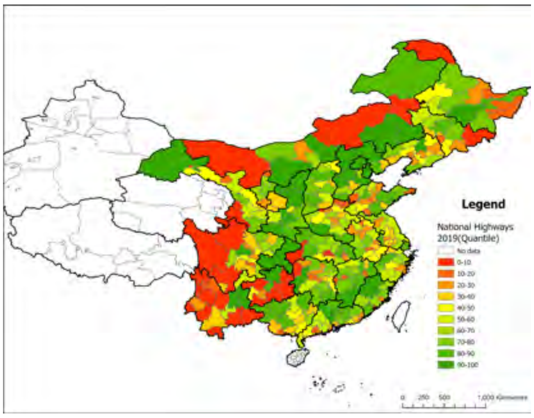
This table provides a detailed overview of the lengths of highways and tunnels in the Provincial Expressway network across various provinces in China, comparing actual data with baseline model predictions. The unit is in kilometers.



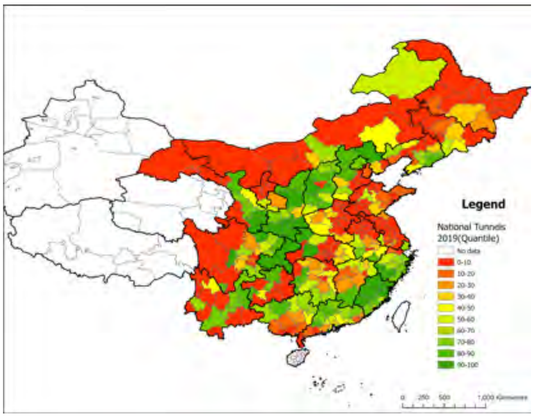
(a) Total Highway



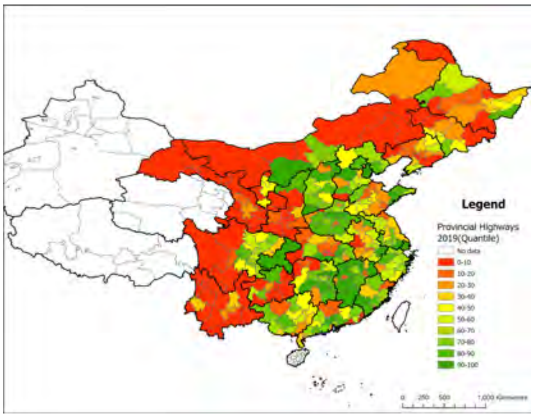
(b) Total Tunnel



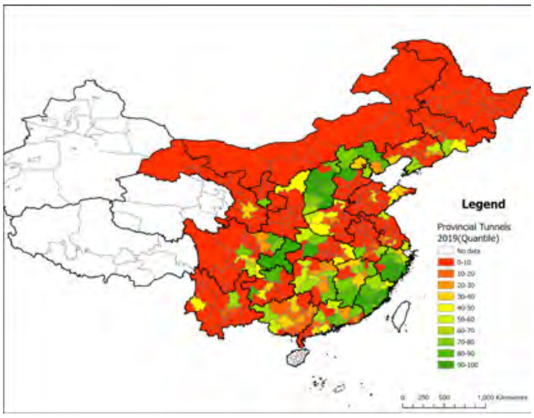
(c) National Highway



(d) National Tunnel



(e) Provincial Highway



(f) Provincial Tunnel

Figure 15: China's Highway and Tunnel Distribution 2019

This table provides the distribution of highways and tunnels in the National and Provincial Expressway network in 2019.