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Can Transportation Infrastructure Construction Improve the Urban Green Development Efficiency? Evidence from China

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Abstract: As an important policy tool for urban economic development, transportation infrastructure development can influence the environmental loads and economic performances of cities. Naturally, the following questions arise. In China, has the transportation infrastructure development improved the urban green development efficiency (UGDE)? Is the effect heterogeneous across cities? In this study, we constructed a theoretical model that included the residential utility and transportation infrastructure to analyze the influence path of the transportation infrastructure on the UGDE. Based on the panel data of China's 268 prefecture-level cities covering the period 2011–2017, we adopted the all-factor nonradial directional distance function (TNDDF) method to measure the UGDE, and we then applied the panel data to investigate the impact of the transportation infrastructure on the UGDE. Overall, the increase in the traffic infrastructure remarkably enhanced the UGDE. Furthermore, the impact was heterogeneous across cities. The larger the city, the more obvious the promotion effect of the transportation infrastructure on the UGDE. The research conclusion of the study reminds us that we should make efforts on the supply side when building cities, placing transportation infrastructure construction on the same level as ecological environmental protection to achieve high-quality urban development.

Keywords: transportation infrastructure; urban green development; efficiency; TNDDF

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1. Introduction

As China's economy enters the stage of "high-quality development", the effective transformation of economic development from "growth speed" to "quality of development" has become a necessary path for sustainable economic development. Although the traditional extensive-economic-development mode has led to fast economic growth in China, it has caused many ecological and environmental problems, which not only makes it difficult to sustain long-term stable economic growth but also seriously endangers the quality of life and health of the people. According to the Global Environmental Performance Index 2020 report (https://epi.yale.edu accessed on 1 January 2022), China is ranked 120th out of 180 countries (regions) in terms of air quality. Due to environmental problems, China's annual economic loss has reached 10% of GDP according to World Bank (https://www.worldbank.org accessed on 1 January 2007) estimates. Undoubtedly, the contradiction between economic increase and environmental protection has become a key factor that is limiting China's sustainable socioeconomic development, and it is imperative to promote the green transformation of economic development.

"The essence of green development efficiency is to achieve the maximum economic benefits with the minimum resource consumption and the lowest environmental cost" [1,2]. As a valuable embodiment of sustainability, green development efficiency has become an important criterion for formulating economic and environmental development policies in many regions, and China is no exception [2,3]. As an important policy tool for regional

economic development, transportation infrastructure construction has played a key role in the rapid and sustained growth of China's economy [4–6]. Duan et al. [7] showed that transportation infrastructure construction has a positive influence on economic growth. However, the rapid development of urbanization has brought about a dramatic increase in the urban population, which has caused a series of problems, such as traffic congestion, due to the relative lag in urban infrastructure construction [8], which makes urban air pollution more serious [9]. Increasing the urban infrastructure can lead to better air quality in cities [10]. However, transportation infrastructure itself is a resource-consuming industry with a high demand for energy. Inevitably, transportation infrastructure construction also increases the emissions of polluting gases and intensifies environmental pollution. Therefore, with limited resources and environmental constraints, can transportation infrastructure promote urban green development efficiency? Is the effect heterogeneous across cities? These questions deserve to be explored in depth.

In recent years, with the continuous promotion of ecological civilization construction, green-development-related research has gradually become the focus of scholars' attention. At present, the research on green development in Chinese urban areas focuses on the following three aspects: (1) The connotation definition and theoretical support of green development [11,12], the research of which focuses on defining the theoretical connotation and practical relevance of green development from the conceptual level. However, staying at the level of qualitative analysis makes the relevant research lack operability, and it is difficult to directly use it to measure the urban green development efficiency (UGDE) level in China; (2) The measurement and evaluation of the green development, which mainly focuses on how to assess the harmony between the socioeconomic development, resources, and environment [13,14]. Some researchers have measured the level of regional green development by building comprehensive evaluation index systems, but with different emphases (e.g., macroeconomics, ecological environment, energy consumption, etc.). These researchers have not yet reached a consensus on the accurate measurement of green development. Some studies have used data envelopment analysis (DEA) to measure the green development level from the perspective of efficiency and productivity [15–18]. Moreover, the traditional DEA fails to consider that the research data are all sample data rather than overall data, and the existence of sampling errors makes the calculation results biased so that they cannot truly portray the current state of China's green development; (3) The study of the influence factors of green development, of which some scholars have analyzed the industrial agglomeration [19] economic level [20], and technological level [2]. In the above research, some of the factors (e.g., the economic level and urbanization rate) are related to transportation infrastructure construction. However, few studies directly discuss the impact of transportation infrastructure on green development.

As social overhead capital, transportation infrastructure plays an important role in enhancing the UGDE. On the one hand, transportation infrastructure can improve the urban environment. Especially in China, urban development increases the demand for transport and logistics, commuting, and other transportation aspects, which, in turn, stimulates the upgrading of the urban transportation infrastructure [21]. According to the data (Calculated based on original data from the "China Urban Statistical Yearbook"), from 2013 to 2017, the average annual increase rate of China's motor vehicle ownership was 16.6%, while the urban road area was 6.1%. The rate of road growth is obviously lower than the rate of vehicle growth, which substantially increases the traffic flow on the roads, resulting in slow speeds, or even congestion, which lead to the incomplete combustion of fuel in the vehicles, and from a two- to three-fold increase in the emissions of harmful air pollutants [9]. Moreover, one of the major sources of urban pollution is exhaust emissions from vehicles [22,23]. According to Colvile et al. [24] and Ghose et al. [25], the transportation department is the largest producer of man-made pollutant emissions in the urban environment. More seriously, in China's megacities, such as Beijing and Guangzhou, "motor vehicles emit greater than 80% of carbon monoxide and about 40% of nitrogen oxide" [22]. The renovation and upgrading of the transportation infrastructure not only

promote the travel conditions of citizens but also enable the coordinated growth of motor vehicle ownership and road areas, easing the exhaust pollution caused by traffic congestion while improving road accessibility [10]. On the other hand, transportation infrastructure can promote economic growth. Most of the transportation infrastructure construction is led by the government, and government investment can drive the development of related industries through the investment multiplier effect, thereby promoting economic growth. Moreover, the network characteristics of transportation facilities can increase the communication between the region and the outside, which can lead to a decrease in transaction costs and can have a "spatial effect" [26]. Transportation infrastructure development has played a pivotal role in economic growth [27–29]. Lucas [27] and Aschauer [28] were the earliest scholars to agree that transportation infrastructure development is an essential condition for economic growth. Subsequently, some researchers found that transportation infrastructure can act as a magnet for regional economic growth by attracting resources from other regions [29–32]. Transportation infrastructure can not only contribute to improving environmental quality, but it can also promote economic growth.

According to the abovementioned effects of transportation infrastructure on environmental and economic development, transportation infrastructure has a certain influence on the UGDE. However, the existing research mainly focuses on the relationship between transportation infrastructure construction and the urban economy and environment. Few studies directly examine the impact of transportation infrastructure on the UGDE, which lays the foundation for the current research. Considering the limitations of the existing studies, in this study, we attempted to explore a new way to promote the UGDE from the perspective of transportation infrastructure. The main contributions of this study lie in the following three aspects: (1) we took 268 prefecture-level cities in China as the research object, and we adopted the TNDDF method to measure the UGDE by combining the governance model with Chinese characteristics; (2) we enriched the theoretical study by incorporating the residential utility, transportation infrastructure, and green development efficiency into a framework to construct a theoretical model and analyze the theoretical mechanisms of transportation infrastructure that affect the urban green development effects; (3) we explored the influence of the transportation infrastructure on the UGDE, which provides a new direction for urban governance.

2. Theoretical Analysis

In this study, we measured the UGDE according to the methods of Zhang et al. [33] (see Section 3 of this paper for details), and we analyzed its outputs from two perspectives: the desired output, GDP, and the undesired output, environmental pollutant emissions. Thus, we concentrated on analyzing the impact of transportation infrastructure on the UGDE through the theoretical mechanisms of economic growth (i.e., GDP) and environmental pollution.

2.1. Model Specification

2.1.1. Household Consumption

At $\forall t > 0$, there are "young people born at time (t), and older people at time($t-1$"), with the subscripts $1,t$ and $2,t$, respectively. In this study, we assumed that the young obtained their incomes by working and that the income makes consumption and savings or investment and inheritance the surplus capital after production. "The elderly holds full capital at the beginning of the period and lease the capital to young people for production to obtain rental income to purchase goods." We assumed that the population remained in a steady state (i.e., the number of people per generation was constant, denoted by the normalization 1 (i.e., $L_t = 1$).

Consumers buy general goods (C) and cars (V). Drawing on Grossman's [34] theoretical model of demand for health and general goods, the residential utility is affected by the

environment. We introduce air pollution (A) into the residential utility function. The utility obtained by the consumer (i) at time (t) is as follows:

$$U_{i,t} = u_{A_{i,t}}(\ln C_{i,t} + \varphi(H_t) \ln V_{i,t}) \tag{1}$$

$$u_{A_{i,t}} = (1/tra_{i,t})^b (1/A_{i,t})^c, b > 0,\ c > 0. \tag{2}$$

where $i = 1, 2$. H_t is the roads, and the nonnegative function ($\varphi(H_t)$) portrays the impact of the roads on the residents' consumption. $\varphi'(H_t) > 0$, $\varphi''(H_t) < 0$, and $\varphi(H_t)$ converges to φ_0: $\lim_{H_t \to \infty} \varphi(H_t) = \varphi_0 > 0$ (that is, more roads increase the utility that residents obtain from vehicle consumption, but with diminishing marginal returns to the roads). $U_{i,t}$ emphasizes the pull of the roads on the car consumption, and it portrays the impact of the transportation infrastructure on the consumption. $u_{A_{i,t}}$ is the air pollution function, where tra denotes the degree of traffic accessibility and is equal to the difference between the actual time ($traac$) and potential time ($traop$) for residents to travel a unit distance by car (that is, $tra = traac - traop$). Usually, the residential utility will be inversely proportional to the difference in the travel time and air pollution. Our model is an extension of the existing literature.

The utility maximization problem for a resident born at time (t) is as follows:

$$U_t = U_{1,t} + \beta U_{2,t+1} \tag{3}$$

where β is the discount factor.

2.1.2. Firm Department

The firm needs to use capital (K), labor (L), and road infrastructure (H) to produce the product, and the production function of the total output is as follows:

$$Y_t = H_t^{\alpha} L_t^{\alpha} K_t^{1-\alpha} \tag{4}$$

where the roads are public goods, which are expended by government departments, and the firms need to provide labor wages (ω_t) and capital rents (r_t). The firms' maximization profit can be written as follows:

$$\max \pi = Y_t - \omega_t L_t - r_t K_t \tag{5}$$

Let $y_t = \frac{Y_t}{H_t L_t} = \left(\frac{K_t}{H_t L_t}\right)^{1-\alpha} = k_t^{1-\alpha}$. Because $L_t = 1$ and $k_t = \frac{K_t}{H_t}$, we can express the total capital corresponding to each unit of road and determine the capital road density.

Assuming that the depreciation rate of the capital is δ_k, and the new investment is I_t, "the accumulation of capital stock" is satisfied:

$$K_{t+1} = I_t + (1 - \delta_k) K_t \tag{6}$$

2.1.3. Government Department

We assumed that only the local government offers transportation infrastructure and sets the tax rate ($\tau \in [0, 1]$) to obtain the fiscal revenue; thus, the transportation infrastructure construction in maintaining the break-even point is T_t (that is, $T_t = \tau Y_t$).

Assuming that the infrastructure depreciation rate is δ_h, and the road construction is satisfied:

$$H_{t+1} = T_t + (1 - \delta_h) H_t \tag{7}$$

2.2. Model Equilibrium

We expressed the end product in four dimensions (i.e., general consumer goods (C_t), vehicles (V_t), savings or investments (I_t), and transportation infrastructure construction (T_t)). Thus, the resource constraint in the economy satisfies $Y_t = C_t + V_t + I_t + T_t$.

"Competitive market equilibrium": Given a government tax rate, a group of factor prices, the allocation of consumption, the allocation of labor, and the allocation of "capital stock", the firm maximizes profits and the residents maximize utility, and the following market-clearing specifications are satisfied: $Y_t = C_t + V_t + I_t + T_t$, where $C_t = C_{1,t} + C_{2,t}$, and $V_t = V_{1,t} + V_{2,t}$.

According to the above model, the budget constraints for the young and old are expressed as Equations (8) and (9), respectively:

$$(1-\tau)\alpha Y_t = C_{1,t} + I_t + V_{1,t} \tag{8}$$

$$(1-\tau)(1-\alpha)Y_{t+1} = C_{2,t+1} + A_{2,t+1} \tag{9}$$

To solve the equilibrium of the model, we used the Lagrange multiplier to solve the resident-utility-maximization problem to obtain:

$$\frac{\varphi(H_{t+1})}{\varphi(H_t)}\frac{V_{1,t}}{V_{2,t+1}} = \frac{C_{1,t}}{C_{2,t+1}} = \frac{k_{t+1}^{\alpha}}{\beta(1-\tau)(1-\alpha)^2} \tag{10}$$

When there is equilibrium, we have $k_{t+1} = k_t = k^*$, and then the equilibrium condition is as follows:

$$(1-\tau)\alpha(k^*)^{-\alpha} + 1 - \delta_K = \left[\tau(k^*)^{1-\alpha} + 1 - \delta_H\right]\left(1 + \frac{1}{\beta(1-\alpha)}\frac{1+\varphi(H_t)}{1+\varphi(H_{t+1})}\right) \tag{11}$$

2.3. Qualitative Analysis

2.3.1. Road Investment and Economic Development

Similar to other types of infrastructure development, the purpose of road investment is economic development. From the equilibrium condition of the model ($k = k^*$), the output at equilibrium is also constant (i.e., $y^* = f(k^*)$). Thus, the rate of economic growth at equilibrium is as follows:

$$g = \frac{Y_{t+1}}{Y_t} - 1 = \frac{H_{t+1}}{H_t} - 1 = \tau k^{1-\alpha} - \delta_H \tag{12}$$

The economic-growth rate (g) will increase with the growth rate of the transportation infrastructure, as seen in Equation (12).

In Equation (11), the capital road density ($k^* = K_t/H_t$) at equilibrium is negatively related to the tax rate (τ) set by the government so that the economic growth rate is a function of the tax rate (τ):$g = \tau[k(\tau)]^{1-\alpha} - \delta_{\mathrm{H}}$. Then, we have:

$$\frac{\partial g}{\partial \tau} = [k(\tau)]^{1-\alpha} + (1-\alpha)\tau[k(\tau)]^{-\alpha}\frac{\partial k}{\partial \tau} \tag{13}$$

Because $\frac{\partial k}{\partial \tau} < 0$(derived from Equation (11)), the right-hand side of Equation (13) contains two terms of opposite signs: the first term is positive, and it decreases with the increase in the tax rate (τ); the second term is negative, and its absolute value increases with the increase in the tax rate (τ). When $\tau = 0, \frac{\partial g}{\partial \tau} = [k(0)]^{1-\alpha} > 0$, and when $\tau \to 1, k(\tau) \to 0$; thus, $\frac{\partial g}{\partial \tau} < 0$. Therefore, if $\tau \in [0,1]$, then the rate of economic development increases before it decreases.

Combined with the multiplier and crowding-out effects of infrastructure construction, the overall impact of roads on economic growth is as follows: The economic growth and road growth rates are positively correlated. When the tax rate is low, the road investment is low. Currently, the crowding-out effect is low, and the road investment has a positive externality. As a result, the economic growth rate increases with the tax rate, and when the tax rate is high, the crowding-out effect of the road investment on private capital is

larger, which leads to a decrease in the rate of economic development with the increase in public investment.

2.3.2. Road Investment and Environmental Pollution

We determined the potential time to travel a unit distance by the vehicle ownership and transportation infrastructure of the corresponding city so that it follows that:

$$traop = \phi(V_{j,t}, H_{j,t}) = (V_{j,t})^m (H_{j,t})^n, m > 0, n < 0 \quad (14)$$

where $V_{j,t}$ represents the vehicle ownership in the city (j), and $H_{j,t}$ represents the transportation infrastructure. Equation (14) shows the relationship between the potential travel time, vehicle ownership, and level of transportation infrastructure. The better the level of transportation infrastructure and the lower the vehicle ownership in the city, the shorter the potential travel time (i.e., $m > 0$, $n < 0$).

In this study, we did not consider the effects of uncertain factors, such as weather, and we mainly related the actual time that residents spend traveling on the road to the degree of traffic flow. Therefore, we also determined the difference between the actual and potential time by the vehicle ownership and transportation infrastructure, which can be expressed as follows:

$$tra_{j,t} = f(V_{j,t}, H_{j,t}) \quad (15)$$

Urban pollution involves many influencing factors, which are not only related to traffic emissions but also other factors (such as the economic level and industrial structure, etc.) that can directly or indirectly affect air quality. For simplicity, we just considered the traffic emissions:

$$A_{j,t} = (traac)^{\eta} \quad (16)$$

where $\eta > 0$ indicates the coefficient of the influence of the actual travel time on the air quality.

From the maximization resident utility, and by combining Equations (2), (14) and (16), we can obtain:

$$A_{j,t} = \left(\frac{\eta c}{b + \eta c} (V_{j,t})^m (H_{j,t})^n \right)^{\eta} \quad (17)$$

Taking the logarithms of both sides of Equation (17), we can obtain the linear equation in the form of Equation (18):

$$\ln A_{j,t} = \eta \ln \frac{\eta c}{b + \eta c} + m\eta \ln V_{j,t} + n\eta \ln(H_{j,t}) \quad (18)$$

From $n < 0$, $\eta > 0$, we can know that $n\eta < 0$ combined with Equation (18) shows that the transportation infrastructure construction has an inhibitory effect on the air pollution.

Combined with the above theoretical analysis, transportation infrastructure construction may enhance green development. Therefore, in this study, we further tested the results through empirical analysis.

3. Methodology and Data

3.1. Econometric Model

Based on the above theoretical analysis, we constructed an empirical model to further examine the impact of transportation infrastructure construction on the UGDE. The specific form is as follows:

$$GDI_{j,t} = \alpha_0 + \alpha_1 Road_{j,t} + \alpha_n \sum X_{j,t} + \eta_j + \varepsilon_{j,t} + year_t \quad (19)$$

Where $GDI_{j,t}$ denotes the green development efficiency of the city (j) in the period (t); $Road_{j,t}$ denotes the transportation infrastructure; $X_{j,t}$ represent a set of control variables; $\varepsilon_{j,t}$ is the error term; η_j and $year_t$ are the city and year fixed effects, respectively.

3.2. Variables and Data

3.2.1. Measuring the UGDE

Based on the work of Liu and Du [35] and Zhang et al. [33], we measured the UGDE by using the TNDDF method.

Suppose that each urban area inputs capital stock (K), labor (L), and energy (E) to produce the desired output (Y) and undesired output (P). Then, we can express the multiple-output production technology as follows:

$$S = \{(K, L, E, Y, P) : (K, L, E) \text{ can produce } (Y, P)\} \tag{20}$$

where S is usually assumed to satisfy the production theory [33] (i.e., nonproduction exists), and a finite number of inputs can only produce a finite number of outputs. In addition, the undesired outputs are weakly disposable, while the inputs and desired outputs are freely disposable. These two assumptions can be expressed as follows: (1) if $(K, L, E, Y, P) \in S, 0 \leq \theta \leq 1$, then $(K, L, E, \theta Y, \theta P) \in S$; (2) if $(K, L, E, Y, P) \in S, P = 0$, then $Y = 0$. According to the "weak disposability" assumption, diminishing emissions are expensive for the same percentage of energy reduction. Pollutants need to be reduced at the expense of the city's GDP, and the only way to eliminate pollution is to end production.

Following Zhou et al. [36], we express the nonradial direction distance function as follows:

$$\vec{D}(K, L, E, Y, P; g) = \sup\left\{w^{\mathrm{T}}\beta : (K, L, E, Y, P + g \times \mathrm{diag}(\beta)) \in S\right\} \tag{21}$$

where $g = (-g_K, -g_L, -g_E, g_Y, -g_P)^{\mathrm{T}}$ is the explicit directional vector that will scale the combination of inputs and outputs. $w = (w_K, w_L, w_E, w_Y, w_P)^{\mathrm{T}}$ denotes the normalized weight vector that is associated with the numbers of inputs and outputs. $\beta = (\beta_K, \beta_L, \beta_E, \beta_Y, \beta_P)^{\mathrm{T}} \geq 0$ denotes the ratio vector of the input-to-output inefficiencies. Then, according to Lin and Du [35], let $g = (-K, -L, -E, Y, -P)^{\mathrm{T}}$ and $w = (1/9, 1/9, 1/9, 1/3, 1/3)^{\mathrm{T}}$. We obtain the optimal solution through Equation (20), and the uniform efficiency index is:

$$UEI = \frac{\frac{1}{4}[(1-\beta_K^*) + (1-\beta_L^*) + (1-\beta_E^*) + (1-\beta_P^*)]}{1+\beta_Y^*} = \frac{1 - \frac{1}{4}(\beta_K^* + \beta_L^* + \beta_E^* + \beta_P^*)}{1+\beta_Y^*}. \tag{22}$$

In Equation (22), the UEI is between 0 and 1, and the higher its value, the more efficient the urban green development. We used the global environment DEA method to estimate the efficiency level of each decision unit for each year. We achieved the TNDDF value through the below DEA model:

$$\begin{aligned}
&\vec{D}(K, L, E, Y, P; g) = \max(w_K\beta_K + w_L\beta_L + w_E\beta_E + w_Y\beta_Y + w_P\beta_P) \\
&\text{s.t.} \sum_{t=1}^{T}\sum_{n=1}^{N} z_{n,t}K_{n,t} \leq K - \beta_K g_K \\
&\sum_{t=1}^{T}\sum_{n=1}^{N} z_{n,t}L_{n,t} \leq L - \beta_L g_L \\
&\sum_{t=1}^{T}\sum_{n=1}^{N} z_{n,t}E_{n,t} \leq E - \beta_E g_E \\
&\sum_{t=1}^{T}\sum_{n=1}^{N} z_{n,t}Y_{n,t} \leq Y + \beta_Y g_Y \\
&\sum_{t=1}^{T}\sum_{n=1}^{N} z_{n,t}P_{n,t} \leq P - \beta_P g_P \\
&z_{n,t} \geq 0, n = 1, 2, \cdots, N, t = 1, 2, \cdots, T, \beta_K, \beta_L, \beta_E, \beta_Y, \beta_P \geq 0
\end{aligned} \tag{23}$$

We calculated the UGDEs of the sample cities by the TNDDF, and we present the trends of the UGDEs from 2011 to 2017 in Figure 1. The UGDEs obtained from the urban industrial SO_2 and industrial wastewater emissions as undesired outputs decreased in 2015, while the UGDEs obtained from the urban industrial dust and industrial total pollutant emissions as undesired outputs decreased slightly in 2014. Overall, although the UGDEs were on the rise, the average values of the UGDEs in China were between 0.422 and 0.557, which indicates that the urban green development was relatively low.

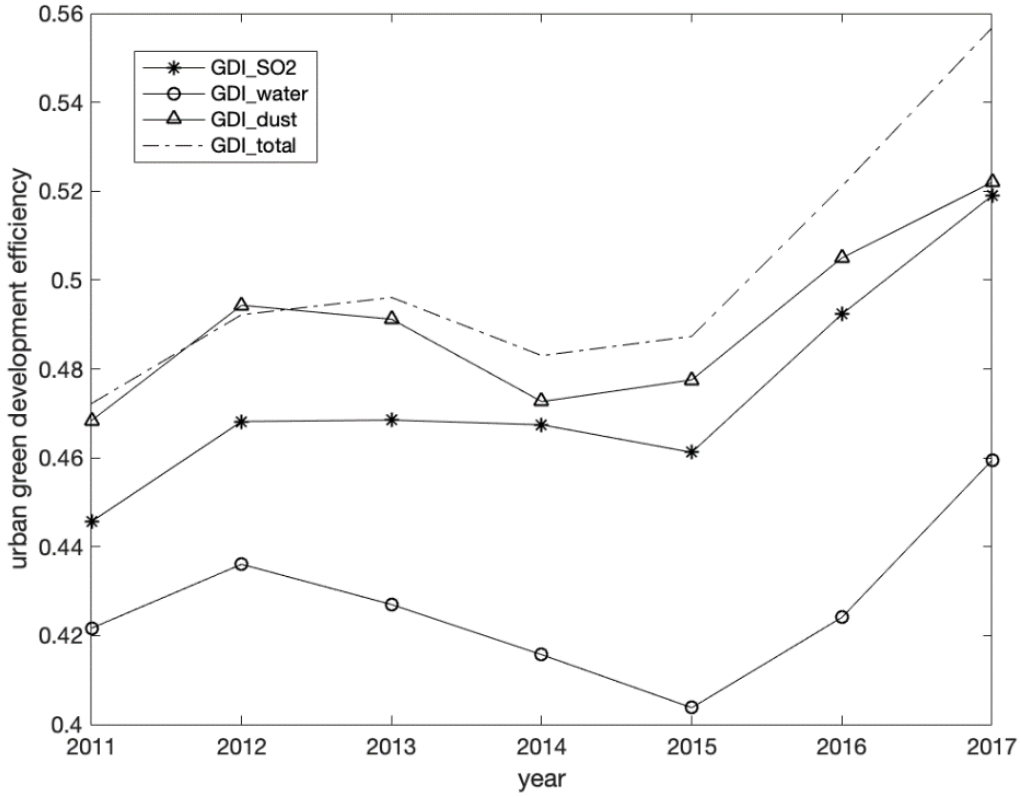


Figure 1. Average UGDEs in China. Notes: GDI_so_2, GDI_water, GDI_dust, and GDI_total denote the UGDEs obtained by using the emissions of sulfur dioxide, wastewater, dust, and total pollutants from urban industries, respectively, as the undesired outputs.

3.2.2. Explanatory Variable

The urban transportation infrastructure is the explanatory variable. In the existing studies, the measurement indicators of the transportation infrastructure mainly include the public input and stock of the transportation infrastructure. Transportation infrastructure does not consist of public inputs only but also includes more private investments, and the public inputs of the transportation infrastructure are not a stock but a flow, and they are prone to systematic errors in processing. Therefore, we referred to Luo et al. [22] and used the road densities of the sample cities to measure the transportation infrastructure.

3.2.3. Control Variables

In addition to the explained and explanatory variables, we selected the following control variables in combination with the existing studies, the urban industrial level, technological innovation, foreign investment effect, government support, and economic development level. More specifically, *indus* indicates the ratio of the secondary industry to the GDP; *inno* represents the urban innovation capacity, which can be obtained from the China Urban and Industrial Innovation Research Report [37]; the foreign investment effect (fdi) is expressed by the foreign investment as a percentage of the city's GDP; *gove* indicates the government support, which is measured as the ratio of the fiscal spending to

the GDP; gdp indicates the economic development, which is measured by the logarithm of the city's GDP per capita. In addition, researchers usually use the GDP per capita quadratic term (gdp^2) to examine the "EKC" curve. Therefore, we further added the quadratic term of the economic level to analyze the "inverted U-shape" between economic development and UGDE.

3.3. Data Source

Given the availability of the data, we selected the panel data of 268 Chinese cities above the prefecture level from 2011 to 2017 as the research sample. We collected the UGDE data from the China Statistical Yearbook on Environment and China City Statistical Yearbook. We collected the transportation infrastructure data from the China Traffic Yearbook. We collected the other sample data from the China Statistical Yearbook, China City Statistical Yearbook, and Wind database. We processed the data in this paper as follows: we excluded some cities with large missing data, and we filled in the rest of the missing data by interpolation. We present the summary statistics of the variables in Table 1.

Table 1. Summary statistics of variables.

Variable	Definition	Obs.	Mean	Std. Dev	Min	Max
GDI_so_2	UGDE using urban industrial SO_2 emissions as undesired output (GDI)	1876	0.474	0.137	0.168	1.000
GDI_water	Green development efficiency using urban industrial wastewater emissions as undesired output	1876	0.427	0.118	0.233	1.000
GDI_dust	Green development efficiency using urban industrial dust emissions as undesired output (GDI)	1876	0.490	0.151	0.159	1.000
	Green development efficiency using total urban industrial pollutant emissions as undesired output	1876	0.500	0.152	0.191	1.000
$Road$	Urban road area	1876	7.070	0.962	3.951	9.846
$indus$	Secondary industry/GDP	1876	0.485	0.097	0.000	0.758
$inno$	Technology innovation	1876	16.014	65.942	0.005	1153.167
fdi	Foreign investment/GDP	1876	10.192	1.755	1.098	14.941
$gove$	Fiscal spending/GDP	1876	0.583	0.247	0.027	2.665
gdp	Logarithm of city's GDP per capita	1876	10.642	0.562	8.841	13.055
gdp^2	Quadratic term of GDP (in log) per capita	1876	113.541	12.064	78.173	170.451

4. Empirical Analyses

4.1. Impact of Transportation Infrastructure on UGDE

We present the impact of the transportation infrastructure on the UGDE from the undesired outputs, such as the urban "industrial sulfur dioxide", "industrial wastewater", "industrial dust", and "total pollutant emissions" in Table 2. The coefficient of the effect of the transportation infrastructure on the UGDE was significantly positive at the 5% level, regardless of which undesired output of the UGDE was used, which indicates that transportation infrastructure construction is conducive to improving the UGDE. The development of China's cities has increased the demand for transportation and logistics, commuting, and other transportation aspects, which, in turn, has stimulated the upgrading of the urban transportation infrastructure [21]. Traffic congestion increases urban pollution [9]. The increase in transportation infrastructure construction will reduce environmental pollution, thereby improving the UGDE.

Table 2. Impact of transportation infrastructure on urban green development efficiency.

Variable	*GDI_SO*$_2$	*GDI_water*	*GDI_dust*	*GDI_total*	*GDI_SO*$_2$	*GDI_water*	*GDI_dust*	*GDI_total*
Road	0.053 ***	0.025 ***	0.031 ***	0.060 ***	0.032 ***	0.022 ***	0.015 **	0.033 ***
	(7.34)	(3.74)	(4.59)	(7.58)	(4.51)	(3.11)	(2.05)	(4.14)
indus					0.134 ***	0.265 ***	0.119 **	0.157 ***
					(2.90)	(5.85)	(2.55)	(3.09)
inno					0.021 *	0.036 ***	0.045 ***	0.047 ***
					(1.72)	(3.00)	(3.68)	(3.42)
fdi					0.064 ***	0.043 *	0.061 ***	0.060 **
					(2.71)	(1.84)	(2.58)	(2.28)
gove					−0.016	−0.014	−0.024	−0.014
					(−1.10)	(−1.04)	(−0.17)	(−0.82)
gdp					0.035 ***	0.015 ***	0.029 ***	0.037 ***
					(8.45)	(3.55)	(3.78)	(7.95)
gdp^2					−0.057 ***	−0.024	−0.072 ***	−0.097 ***
					(−2.96)	(−1.30)	(−3.78)	(−4.53)
cons	0.099 *	0.245 ***	0.264 ***	0.074	0.051	0.069	0.198 ***	0.096
	(1.95)	(5.05)	(5.27)	(1.33)	(0.79)	(1.15)	(3.19)	(1.39)
City FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Obs.	1876	1876	1876	1876	1876	1876	1876	1876
R^2	0.312	0.111	0.221	0.341	0.137	0.112	0.100	0.118

Notes: (): t-values; *Obs*.: sample size; R^2: determination coefficient. "*, ** and *** denote significance at the 10%, 5%, and 1% levels", respectively.

According to the estimated results of the control variables, the estimated coefficients of the urban industrialization level on the UGDE are all positive, which indicates that the improvement in the urban industrialization level promotes urbanization development, which is conducive to the construction of urban industrial parks, which then promotes the improvement in the UGDE. The coefficients of the effects of technological innovation and foreign investment on the UGDE are significantly positive, which indicates that technological innovation can enhance the UGDE by changing production methods, reducing energy consumption and pollution, and increasing output. The foreign investment to enhance the UGDE may expand the level of openness to the outside world that is introduced with advanced technology and production equipment, which is advantageous to promoting the transformation of the city's industrial structure and UGDE. If the estimated coefficient of the economic development level is significantly positive at the 1% level, then the city's economic development is positively related to its UGDE, which is because, on the one hand, the increase in the urban economic level promotes the increase in the residents' income, which increases the quality of life and requires the relevant government departments to manage the environment, etc. On the other hand, it increases the government's public investment and introduces high-tech production enterprises, thereby promoting the UGDE. The estimated coefficient of the quadratic term of the economic development level is significantly negative, which indicates that there is an "environmental Kuznets" curve effect on the UGDE.

4.2. Robustness Analysis

4.2.1. Endogenous Test

Considering the possible endogenous problems, we used the slope index as an "instrumental variable" for the urban transportation infrastructure index because, in the field of urban road engineering planning, the urban slope is an important index that affects urban road construction. The urban slope is not only a city-specific geographic information attribute; it also has good exogenous characteristics, satisfying the assumption of the exogeneity of valid instrumental variables. However, the slope index is urban cross-sectional data in the data dimension, and both the endogenous and explanatory variables contain panel data with city and time information. Therefore, referring to the processing method

of Angrist and Keueger [38], in this study, we introduced the cross term of the slope and annual dummy variables into the model as instrumental variables. Moreover, the long construction cycle of transportation infrastructure may have a time lag in its impact on the UGDE. Therefore, we regressed the lags of the UGDE variables.

We present the results of the instrumental variables using two-stage least squares (2SLS) and the dependent variables with a one-period lag in Table 3. According to the results of the instrumental-variable regressions, the F-statistic of the first stage is well above the empirical value of 10, which indicates that the slope index is highly correlated with the endogenous explanatory variables, and the weak instrumental variable can be excluded. We performed instrumental-variable-overidentification tests, and none of the results of the Sargan–Hansen statistic test were significant. Thus, we rejected the original hypothesis that all the variables are exogenous, which indicated that our choice of instrumental variables was relatively valid. According to the regression results of the second stage, the coefficients of the *GDI* are still significantly positive, and these results are consistent with the regression results of the benchmark model in the direction, which verifies that there is an improvement effect of road construction on the UGDE. However, all the estimated coefficients of the *GDI* in the instrumental-variable regressions are larger than the results of the baseline regression in Table 2, which suggests that, due to potential endogeneity issues, we may have somewhat underestimated the improvement effect of the urban transportation infrastructure development on the UGDE. According to the regression results of the one-period-lag UGDE, the regression coefficient of the transportation infrastructure on the UGDE was still significantly positive.

Table 3. Transportation infrastructure construction on urban green development efficiency: instrumental variable regression and urban green development efficiency one-period-lag robustness tests.

Variable	Instrumental Variable Regression				Urban Green Development Efficiency Lags by One Period			
	GDI_SO$_2$	*GDI_water*	*GDI_dust*	*GDI_total*	*GDI_SO*$_2$	*GDI_water*	*GDI_dust*	*GDI_total*
Road	0.046 ***	0.028 ***	0.027 ***	0.048 ***	0.037 ***	0.025 ***	0.023 ***	0.035 ***
	(4.26)	(2.67)	(2.48)	(4.01)	(5.33)	(3.74)	(3.26)	(4.65)
cons					0.099 *	0.087	0.111 *	0.063
					(1.95)	(1.54)	(1.80)	(0.98)
controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
First stage F-statistics	699.336	699.336	699.336	699.336				
Second-stage F-statistics	209.423	209.423	209.423	209.423				
Sargan–Hansen test	0.376	0.300	0.195	0.116				
(*p*-value)	(0.539)	(0.583)	(0.658)	(0.733)				
City FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Obs.	1876	1876	1876	1876	1608	1608	1608	1608
R^2	0.762	0.546	0.184	0.201	0.103	0.601	0.523	0.362.

Notes: (): t- or z- values; *Obs*.: sample size; R^2: determination coefficient. "*, and *** denote significance at the 10%, and 1% levels", respectively.

4.2.2. Further Discussion on Robustness

To ensure the reliability of the research results, we used the urban road area to replace the road density to measure the transportation infrastructure. In addition, considering that the core variables may have endogenous biases, we did not rule out the possibility that the control variables had endogenous problems. Therefore, we further regressed the control variables with a one-period lag. We present the results in Table 4. The estimated coefficients and significance of the core variables did not substantially change, which confirms that the findings of this paper are robust.

Table 4. Transportation infrastructure construction on urban green development efficiency: replacement transportation infrastructure metrics and control-variable one-period-lag robustness tests.

Variable	Road Area Instead of Road Density				Control-Variable One-Period Lags			
	GDI_SO$_2$	*GDI_water*	*GDI_dust*	*GDI_total*	*GDI_SO*$_2$	*GDI_water*	*GDI_dust*	*GDI_total*
Road	0.033 ***	0.006	0.023 **	0.034 ***	0.024 ***	0.023 ***	0.009	0.026 ***
	(3.40)	(0.60)	(2.36)	(3.13)	(2.79)	(2.74)	(1.13)	(2.69)
cons	0.236 ***	0.222 ***	0.278 ***	0.298 ***	0.098	0.052	0.271 ***	0.183 **
	(6.82)	(6.60)	(8.03)	(7.70)	(1.33)	(0.73)	(3.68)	(2.18)
controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Obs.	1876	1876	1876	1876	1568	1568	1568	1568
R^2	0.133	0.186	0.218	0.344	0.197	0.172	0.163	0.176

Notes: (): t-values; *Obs.*: sample size; R^2: determination coefficient. "** and *** denote significance at the 10%, 5% and 1% levels", respectively.

4.3. Regional Heterogeneity Test

According to the above analyses, urban transportation infrastructure construction can significantly drive green development efficiency. However, is there a difference in the influence of the urban transport infrastructure construction on the UGDE for different levels of cities? In view of this, we classified the cities by cluster analysis through indicators such as the GDP, population, per capita disposable income, actual utilization of foreign capital, fiscal revenue, loans for RMB capital utilization by financial institutions, the average wage of employees, greening-rate coverage of the built-up area, and the number of colleges and universities. We divided the 268 cities in this paper into four groups of cities (see Appendix A for details) to further test the urban heterogeneity. Because the sample size of the first-tier cities was small, we put "first-tier and second-tier" cities together for the regression. We present the regression results in Table 5.

Table 5. Heterogeneous analysis.

Variable	"First- and Second-Tier" Cities				"Third-Tier" Cities			
	GDI_SO$_2$	*GDI_water*	*GDI_dust*	*GDI_total*	*GDI_SO*$_2$	*GDI_water*	*GDI_dust*	*GDI_total*
Road	0.051 ***	0.103 **	0.087 **	0.138 ***	0.030 **	0.018 *	0.024 *	0.061 ***
	(4.43)	(2.18)	(2.02)	(2.82)	(2.37)	(1.73)	(1.91)	(4.95)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
cons	0.067	−0.142 ***	−0.681	−0.520	0.204 **	0.162 *	0.091	0.045 **
	(0.27)	(−3.29)	(−1.50)	(−1.03)	(2.13)	(1.75)	(0.81)	(2.51)
City FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Obs.	231	231	231	231	896	896	896	896
R^2	0.453	0.197	0.275	0.162	0.187	0.128	0.149	0.131

Variable	"Fourth-tier" Cities			
	GDI_SO$_2$	*GDI_water*	*GDI_dust*	*GDI_total*
Road	0.019 *	0.032 ***	0.013 ***	0.029 **
	(1.72)	(3.18)	(3.33)	(2.48)
Controls	Yes	Yes	Yes	Yes
cons	0.329 ***	0.095	0.369 ***	0.272 ***
	(3.90)	(1.21)	(4.05)	(2.60)
City FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Obs.	749	749	749	749
R^2	0.151	0.131	0.151	0.183

Notes: "*, ** and *** denote significance at the 10%, 5% and 1% levels", respectively. (): t-values; *Obs.*: sample size; R^2: determination coefficient.

The estimated coefficients of the transportation infrastructure construction on the UGDE are 0.051, 0.103, 0.087, and 0.138 for the "first- and second-tier" cities, 0.030, 0.018, 0.024, and 0.061 for the "third-tier" cities, and 0.019, 0.032, 0.013, and 0.029 for the "fourth-tier" cities. Therefore, regardless of which undesired output is used for the green development efficiency (industrial sulfur dioxide, wastewater, dust, or total pollutants), transportation infrastructure contributes more to the green development efficiency in the "first- and second-tier" cities than in the "third- and fourth-tier" cities, which may be for the following reasons: (1) large cities are more likely to exert "economic agglomeration" effects and are better able to use "information technology" to alter the urban governance mode, which is advantageous to the improvement in the UGDE; (2) large cities are more prone to traffic congestion, and the improvement in the transportation infrastructure construction is more advantageous to the improvement in the UGDE.

5. Conclusions

China's rapid economic development has also generated serious environmental problems. Environmental pollution problems have seriously threatened human physical and mental health and restricted sustainable economic and ecological development. Green economic development has become a global development consensus, which has far-reaching relevance for ecological and economic sustainability. Transportation infrastructure construction, as one of the policy instruments for urban development, plays a non-negligible role in enhancing the UGDE. However, the existing literature lacks systematic research on the role of the transportation–infrastructure–construction mechanism that affects the UGDE. Therefore, in this study, we constructed a theoretical model to demonstrate the intrinsic mechanism of the influence of the transportation infrastructure on the UGDE by combining the panel data of 268 Chinese cities from 2011 to 2017 to measure the UGDE of each city using the TNDDF method.

According to the results, the UGDE shows an increasing trend, but this is generally at a low level. Urban transportation infrastructure construction can substantially improve the UGDE. The impact of the transportation infrastructure construction on the UGDE is different at different city levels. The more developed the city, the greater the effect of the transportation infrastructure influence (i.e., the promotion effect of the transportation infrastructure on the green development efficiency in the "first-tier and second-tier" cities is greater than that in the "third-tier and fourth-tier" cities). In this study, we put transportation infrastructure construction and ecological environmental protection on the same level to explore new ways to solve urban environmental pollution problems; thus, urban-economic-development and ecological-environmental-protection work go hand in hand. At the same time, the research provides a clear answer to the mechanisms and effects of transportation infrastructure in the promotion of the UGDE. The research findings will help to build a long-term mechanism of urban green development driven by transportation infrastructure construction, improve the urban governance system, and promote sustainable urban development.

Based on these conclusions, we make the following policy recommendations. (1) The further strengthening of the transportation infrastructure construction. Currently, China's urbanization is still in the development stage, and the transportation infrastructure construction is not yet able to meet the speed of the increasing urban population. Therefore, the transportation infrastructure construction should be improved by, for example, increasing the area of roads and building new bridges so that they can match the number of motor vehicles and slow down the environmental pollution caused by traffic congestion. (2) The enhancement of the UGDE through the vigorous development of clean transportation, the acceleration of the technical innovation of public transportation, the strengthening of the construction of intercity trains, subways, BRT, and other public transportation, the encouragement of public transportation trips instead of motor vehicle trips, and a reduction in the energy consumption and pollutant emissions per unit of transportation. (3) We should adopt differentiated transportation-infrastructure-construction policies to promote

the balanced development of transportation infrastructure construction among the cities. For the "first-tier" and "second-tier" cities, the urban transportation infrastructure is better developed, and while it relieves the traffic congestion, it also creates a further concentration of the population, which, in turn, increases the urban vehicle density and leads to environmental pressure. To avoid the effect of diminishing marginal utility, the "first-tier" and "second-tier" cities should focus on the construction of high-capacity rail-transit-based transportation networks. At the same time, in terms of the "small and medium-sized" cities, we should pay attention to the development planning, strengthening the financial support for the transportation infrastructure, improving the transportation network mainly by bus, enhancing the accessibility and convenience of the transportation, and giving greater play to the role of transportation infrastructure in promoting the UGDE.

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Appendix A

City Classification

First-tier cities: Beijing, Guangzhou, Nanjing, Shanghai, Shenzhen, Tianjin, Chongqing.

Second-tier cities: Changzhou, Chengdu, Dalian, Dongguan, Foshan, Fuzhou, Harbin, Hangzhou, Hefei, Jinan, Kunming, Nanchang, Nanning, Ningbo, Qingdao, Xiamen, Shenyang, Shijiazhuang, Suzhou, Taiyuan, Wuxi, Xian, Changchun, Changsha, Zhengzhou.

Third-tier cities: Anqing, Anyang, Anshan, Bengbu, Baotou, Baoji, Baoding, Beihai, Benxi, Binzhou, Cangzhou, Changde, Chaozhou, Chenzhou, Chengde, Chizhou, Datong, Dandong, Deyang, Dezhou, Dongying, Erdos, Fushun, Ganzhou, Guiyang, Guilin, Haikou, Handan, Heyuan, Heze, Hohhot, Huludao, Huzhou, Huai'an, Huibei, Huainan, Huangshan, Huizhou, Jilin, Jining, Jiaxing, Jiangmen, Jiaozuo, Jinhua, Jinzhou, Jincheng, Jingdezhen, Jiujiang, Laiwu, Lanzhou, Langfang, Lishui, Lianyungang, Liaoyang, Liaocheng, Linyi, Liuzhou, Longyan, Loudi, Luzhou, Luoyang, Maanshan, Maoming, Meizhou, Mianyang, Nanping, Nantong, Ningde, Panzhihua, Panjin, Pingdingshan, Pingxiang, Putian, Puyang, Qinhuangdao, Qingyuan, Quzhou, Quanzhou, Rizhao, Sanming, Shangrao, Shaoguan, Shaoxing, Shiyan, Shuozhou, Songyuan, Taizhou, Tai'an, Taizhou, Tangshan, Tongling, Weihai, Weifang, Wenzhou, Urumqi Wuhu, Xining, Xiangtan, Xiangyang, Xinxiang, Xinyu, Xingtai, Suqian, Xuzhou, Xuchang, Xuancheng, Yantai, Yancheng, Yangzhou, Yangquan, Yibin, Yichang, Yingkou, Yuxi, Yueyang, Zaozhuang, Zhanjiang, Zhangjiakou, Zhangzhou Changzhi, Zhaoqing, Zhenjiang, Zhongshan, Zhoushan, Zhuhai, Zhuzhou, Zibo, Zunyi.

Fourth-tier cities: Ankang, Anshun, Bayanzhuoer, Bazhong, Baicheng, Baisan, Baise, Baoshan, Bozhou, Chaoyang, Chifeng, Chongzuo, Chuzhou, Dazhou, Dingxi, Ezhou, Fangchenggang, Fuzhou, Fuxin, Fuyang, Guangyan, Guangyuan, Guigang, Hanzhong, Hechi, Hezhou, Hebi, Hegang, Heihe, Hengshui, Hengyang, Hulunbeier, Huaihua, Huanggang, Huangshi, Jixi, Ji'an, Jiamusi, Jieyang Jinzhong, Jingmen, Jingzhou, Jiuquan, Kaifeng,

Laibin, Leshan, Lijiang, Liaoyuan, Lincang, Linfen, Liuan, Liupanshui, Luohe, Lvliang, Meishan, Nanchong, Nanyang, Neijiang, Pu'er, Qitaihe, Qiqihar, Qinzhou, Qingyang, Qujing, Sanmenxia, Shanwei, Shangluo, Shangqiu, Shaoyang, Shuangyashan, Siping, Suihua, Suizhou, Suining, Tonghua, Tongliao, Tongchuan, Weinan, Wuhai, Ulanqab, Wuzhou, Wuwei, Xianning, Xianyang, Xiaogan, Xinzhou, Xinyang, Cebu, Ya'an, Yan'an, Yangjiang, Yichun, Yichun, Yiyang, Yingtan, Yongzhou, Yulin, Yulin, Yunfu, Yuncheng, Zhangjiajie, Zhangye, Zhaotong, Zhoukou, Zhumadian, Ziyang, Zigong.

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