Spatial infrastructure disparities: Impacts on economic efficiency across diverse urban–rural geographic regions

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Abstract---Spatial infrastructure gaps in roads, energy, digital connectivity, and public services increase regional inequalities and reduce economic efficiency in both urban and rural areas. Research examines how the imbalance in infrastructure affects economic efficiency on 2150 observations in 2018-2025. Road density, transport connectivity, electricity coverage, broadband penetration, and public service accessibility are the independent variables, whereas economic efficiency (EE) (per capita income, industrial output and employment rate) is the dependent variable. One of the control variables is population density. Research utilizes descriptive statistical analysis through the International Business Machines Statistical Package for the Social Sciences (IBM SPSS), Version 26.0, to come up with spatial variation and regional patterns, which are analyzed through correlation analysis to determine the initial association between the variables. To examine the influence of infrastructure inequalities on economic efficiency, panel regression equations, such as Ordinary Least Squares (OLS) and fixed-effects regression, are used. Given the spatial dependence of regions, spatial econometric models, such as the Spatial Lag Model (SLM) and Geographically Weighted Regression (GWR), can be used to represent local spatial heterogeneity in infrastructure-economy relationships. The findings show that urban areas that are better connected through infrastructure have much higher economic efficiency, and regions with low urban infrastructure have ongoing productivity discrepancies. OLS findings indicate that road density contributes a great deal to economic performance ($\beta = 0.48$, $t = 8.00$). The interaction effects indicate that transport and digital infrastructure complement each other and help to lessen the inequalities between regions.

Keywords---Spatial Infrastructure, Economic Efficiency, Urban–Rural Disparities, Spatial Econometrics, Regression Analysis.

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1. Introduction

Spatial infrastructure is an important factor influencing and defining the efficiency of a region's economy in terms of its accessibility and connectivity and distribution of resources across urban and village sceneries [1]. Inequality in infrastructure like road networks, power, internet connections, and community amenities is also directly related to socioeconomic disparity as they reduce mobility, access to jobs, and a market in underdeveloped areas [2]. The countryside tends to have a more difficult time getting to work, have less access to services, and have limited economic prospects, whereas cities enjoy a high level of concentration, which results in enduring economic productivity differences [3]. Trade across regions, labor mobility and integration of local economies are made easier by transportation infrastructure, especially road density, and connectivity, which induces a positive spillover effect on other regions. Digital infrastructure such as broadband and access to the internet facilitates innovation, transmission of knowledge and industrial output, which also enhances economic performance [4]. Although the research on such aspects continues to expand, most studies are conducted on the specific infrastructure type or solely on the economic growth, employment, or accessibility without evaluating the combination of multiple infrastructure components and economic efficiency indicators in full, like the per capita income, industrial output, and employment rate. In addition, the past literature tends to ignore the regional spillover effect and local spatial heterogeneity, which constrains the knowledge regarding the effect of improvements in infrastructure in one region on its neighboring regions. This demonstrates the importance of a complex, spatially sensitive analysis that includes both the direct and indirect effects of infrastructure inequalities [5]. The gap covered in the present research is that it incorporates the major economic efficiency measurements and various infrastructure measures, and the spatial econometric models are used to examine the urban-rural differences and spatial relations, making practical contributions to the equitable regional development.

Table 1 summarizes key prior studies that examine the association among infrastructure development, digital inclusion, and regional income disparities. It highlights the objectives, datasets, major findings, and limitations identified in earlier research.

Table 1. Summary of Previous Studies on Infrastructure Inequality and Regional Economic Disparities

Reference	Objective	Data	Result	Limitation
[6]	Study urban–rural integration and topography impact	Regional infrastructure data (China)	Negative effect on infrastructure (−0.18, −0.17; p < 0.001)	Focus mainly on topography
[7]	Measure urban infrastructure gaps	Census data and satellite night lights (South Africa, India)	Higher inequality in South Africa at a coarser spatial scale	Limited regional scope
[8]	Analyze digital financial inclusion impact	Regional economic and financial data (China)	Reduces income gaps (p < 0.01) with spatial spillover	Country-specific analysis
[9]	Examine infrastructure inequality in urbanizing regions	Road density and electricity coverage data	Large regional differences (mean = 42.6 km/100 km²; electricity = 89.5)	Focus on limited infrastructure indicators
[10]	Evaluate digital infrastructure and income disparity	Data from 285 cities in China	Increases city–regional income disparities by 8–12	Limited to an urban productivity context

Research gap: Most previous research focuses on individual infrastructure types and does not integrate multiple infrastructure indicators with overall economic efficiency. They also overlook spatial heterogeneity, urban–rural differences, and spillover effects on neighboring regions. Therefore, this research addresses these gaps by analyzing the combined effects of multiple infrastructures, spatial variations, and interaction effects between urban and rural areas.

Research objective: This research aims at studying the impacts of the infrastructure differences on the EE of the region involving the interaction impacts and geographical spillovers in urban and rural regions. Some of these differences are density of roads, transportation connectivity, access to electricity, internet penetration and access to public services.

Research organization. The research is organized into six sections. Section 1 introduces the research context and highlights urban–rural infrastructure gaps. Sections 2 and 3 describe the research objectives, hypotheses, contributions, and methodology, including descriptive statistics, panel regression, and spatial econometric models. The results and analysis of disparities, interaction effects, and spatial spillovers are presented in Section 4, significant outcomes, legislative consequences, and additional investigation approaches are presented in the concluding part.

2. Hypothesis development

The research analyzes how infrastructure factors road density (RD), transport connectivity (TC), electricity coverage (EC), broadband penetration (BP), and public service accessibility (PSA) influence economic efficiency (EE). EE is measured using per capita income (PCI), industrial output (IO), and employment rate (ER), while also considering the interaction between BP and transport connectivity and the spatial spillover effects of regional infrastructure development, which are shown in figure 1.

H1: RD → EE. Higher RD significantly improves regional EE (PCI, IO, ER) by facilitating goods movement, labor mobility, and market accessibility.

H2: TC → EE. Greater TC positively influences regional EE (PCI, IO, ER) by improving logistics efficiency and inter-regional trade.

H3: EC → EE. Expanded EC enhances EE (PCI, IO, ER) by supporting industrial activity, service delivery, and productivity.

H4: BP → EE. Higher BP significantly improves EE (PCI, IO, ER) through digital access, innovation, and information flow.

H5: PSA → EE. Improved PSA positively affects EE (PCI, IO, ER) by enhancing human capital development and workforce participation.

H6: TC × BP → EE. The interaction between TC and BP significantly reduces urban–rural economic disparities and enhances regional EE.

H7: RID → EE. Infrastructure development in one region generates positive spatial spillover effects that improve EE in neighboring regions.
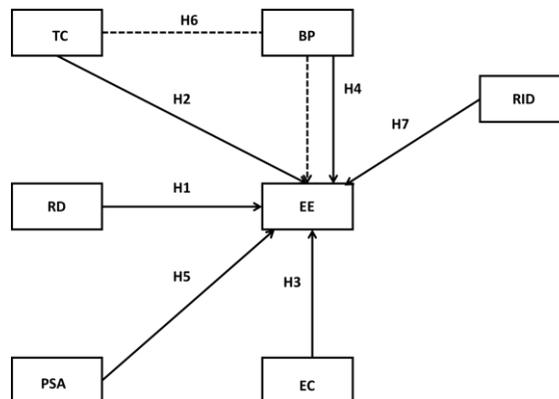
Figure 1. Conceptual framework of spatial infrastructure effects on regional economic efficiency

3. Methodology

Research uses 2,150 urban and rural observations (2018–2025) to examine the impact of infrastructure on regional economic efficiency. The quantitative analysis was used with descriptive statistics and correlation analysis, followed by panel regression and spatial econometric models to capture regional differences and spatial spillover effects and the overall research structure and process are illustrated in Figure 2.
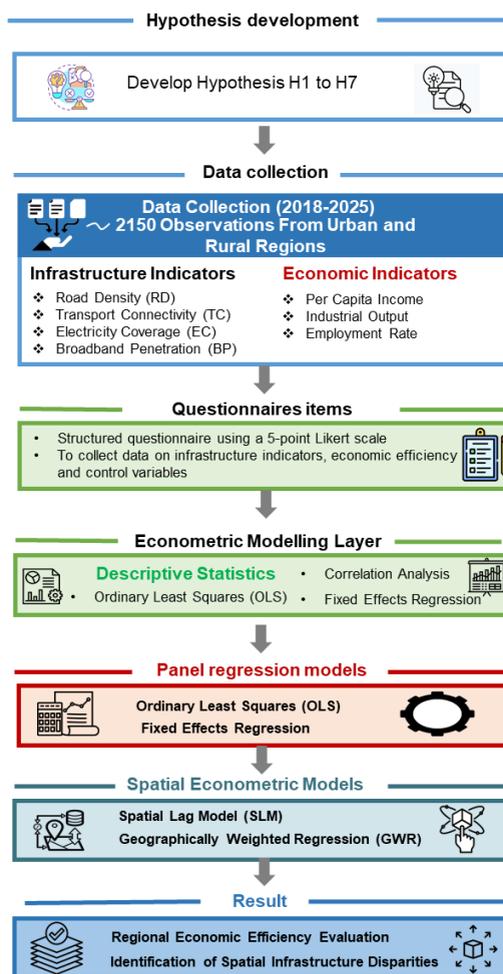
Figure 2. Research methodology workflow for analyzing the impact of spatial infrastructure disparities on regional economic efficiency

3.1. Data Collection

Research utilizes panel data of 2,150 observations in 2018-2025 in the urban and rural areas, based on national statistical, infrastructure, and geographical databases. The dataset has the infrastructural indicators: RD, TC, EC, BP and PSA. EE are assessed by means of PCI, IO, and ER. Control variables consider regional factors such as population density, the level of urbanization, land-use structure and topography.

3.2 Questionnaires items

To measure the association between infrastructure development and the efficiency of the regional economy, a structured questionnaire was designed using the major infrastructure and economic indicators. The questionnaire was created to gather data in the context of RD, TC, EC, BP, and the presence of necessary services in urban and rural areas of PSA. The questions concerning economic efficiency indicators, including per capita income (PCI), industrial output (IO), and employment rate (ER), in EE and demographic and geographic features, such as population density, urbanization level, land-use structure, and topography, were also present in the questionnaire. A five-point Likert scale (1 = extremely low to 5 = very high) was used to gauge respondents' perceptions as shown in table 2.

Table 2. Questionnaire Items for Infrastructure and Economic Efficiency Assessment

Variable	Questionnaire Item	Scale
RD	How adequate is the road density in your region for transportation and mobility?	1–5
TC	How effective is the transport connectivity between urban and rural areas in your region?	1–5
EC	How reliable is the electricity coverage available in your area?	1–5
BP	How accessible and reliable is broadband internet service in your region?	1–5
PSA	How easily can residents access public services such as healthcare, education, and government facilities?	1–5
PCI	To what extent has infrastructure development improved per capita income in your region?	1–5
IO	How has infrastructure development influenced industrial output in your region?	1–5
ER	How has infrastructure development affected employment opportunities in your region?	1–5

Scale: 1 = Very Low, 2 = Low, 3 = Moderate, 4 = High, 5 = Very High.

3.3. Data analysis of Econometric Models

Descriptive, correlation, analyses were conducted using IBM SPSS 26.0, while panel regression and spatial econometric methods have been combined to comprehensively assess the impact of spatial variations in infrastructure on the economic efficiency of regions. Although taking into consideration local characteristics and temporal influences, this multi-level approach ensures that the global tendencies and the local deviations are also accounted for.

- **Descriptive Statistics -** All variables that comprised controls, the economic efficiency indicators and the infrastructure indicators were performed with descriptive statistics to bring out city-regional differences and give a preliminary overview. The means, standard deviations, minimums, and maximums provide data variation and aid further correlation, regression, and spatial econometric analysis.
- **Correlation analysis -** The relationships between infrastructure indicators and economic efficiency were analyzed by correlation coefficients with the help of Pearson coefficients (−1 +1) to identify multicollinearity and have an initial idea before regression and spatial analysis.
- **Panel regression models -** They used panel regression models to examine how the variables of infrastructure affect the efficiency of a region's economic across space and time. This method captures both cross-sectional and temporal variability in the data. The two methods applied in the panel regression are OLS and the Fixed-Effect regression model which are represented in equations (1-2) are shown in table 3.

Table 3. Econometric Models Used for Infrastructure Impact Analysis

Model	Equation	Description
OLS Regression Model	$Z = \beta_0 + \sum_{i=1}^{O} \beta_i w_i + \varepsilon$ (1)	The Z stands for the dependent variable (economic efficiency), β_0 for the intercept term, β_i for the regression coefficients, w_i for the independent variables, and ε for the error term. This model provides baseline estimates of the effects of infrastructure factors on economic efficiency.
Fixed-Effects Panel Model	$URI_{j,s} = \alpha_0 + \alpha_1 DEI_{j,s} + \sum_l \alpha_l\, Control_{j,s} + \delta_j + \eta_s + \varepsilon_{js}$ (2)	Where the dependent variable for region j in time period s is represented by $URI_{j,s}$, the intercept term is represented by α_0, the regression coefficients are indicated by α_1 and α_l, the key explanatory variable is represented by $DEI_{j,s}$, and the control variables are shown by $Control_{j,s}$. The region-specific and time-specific fixed effects are represented by the terms δ_j and δ_j, respectively, and the error term is denoted by ε_{js}.

3.4. Data analysis of Spatial Econometric Models

Spatial econometric models were used to capture regional variation and spatial dependence in the relationship between the indicators of infrastructure and economic efficiency. The models help in establishing the possible impacts of infrastructure development in a single location on the economic performance in surrounding areas and other geographical regions. The spatial econometric analysis of this research employs two methods, namely, GWR and SLM.

- **Spillover Analysis via SLM -** SLM incorporates spatial dependence and spillover effects and is used to demonstrate the impact of infrastructure and economic efficiency in a region on adjacent areas, giving a clearer picture of the disparity within regions.
- **Local Heterogeneity Analysis via GWR -** The local heterogeneity between the variables of infrastructural variables and economic efficiency was investigated through GWR. GWR can also produce variations in regional affiliations among the variables since it estimates location-specific parameters. The standard form of the GWR model is equation (3).

$Z_j = \beta_{j0} + \sum_1^O \beta_{jl} w_{jl} + \varepsilon_j$

$$(3)$$

Here w_{jl} stands for the explanatory variables, ε_j represents the unexplained variation, β_{j0} represents the local intercept, β_{jl} represents the location-specific coefficients, and Z_j represents the dependent variable of position j. This model aids in capturing regional spatial differences in how infrastructure development affects economic efficiency.

4. Results and Discussion

The analysis conducted using IBM SPSS 26.0 shows that urban areas that have a greater RD, TC, EC, BP, and PSA have much higher EE, whereas rural areas are lagging. Correlation and panel regressions verify that all the infrastructure variables exert positive and significant effects, with RD and EC producing the most. Spatial econometric models set emphasis on significant spatial spillovers and local heterogeneity, whereby improvements in one region have an effect on the neighboring places, and the effects of infrastructure vary depending on the area. Path analysis also reveals the transport connectivity and broadband penetration interaction.

4.1. Descriptive Statistics for Infrastructure and Economic Performance Variables

The statistical characteristics for the research elements are displayed in Table 4. The results indicate that there exist regional disparities in infrastructure indicators like accessibility to public services, energy

availability, road density, transportation connection and internet adoption. Similarly, differences can be observed in the economic effectiveness indicators of employment rate, industrial production and the PCI between Metropolitan and non-metropolitan areas. These transitions are the basis of further regression and spatial econometric studies and they show that there are inequities of spatial infrastructure.

Table 4. Descriptive Statistics of Variables used to Assess the Impact of Infrastructure on EE

Variable	Mean	Std. Deviation	Minimum	Maximum
RD	42.6	15.3	12.4	78.5
TC	0.64	0.18	0.21	0.91
EC	89.5	8.7	63.2	99.1
BP	56.8	14.2	22.6	85.4
PSA	71.4	11.5	38.9	90.2
EE	15840	4820	6200	28400
RID	0.68	0.12	0.42	0.88

4.2. Correlation Analysis

The positive correlation analysis relationship indicates that infrastructure metrics and economic efficiency are associated. The relationships between broadband penetration and transport connectivity and other infrastructure factors are relatively high. In Table 5, the regional infrastructure development is positively correlated with the economic efficiency as well; thus, it can be concluded that the better the infrastructure, the better the regional economic performance.

Table 5. Correlation Analysis of Infrastructure Indicators and Economic Efficiency

Variable	RD	TC	EC	BP	PSA	EE	RID
RD	1						
TC	0.62**	1					
EC	0.58**	0.60**	1				
BP	0.55**	0.63**	0.59**	1			
PSA	0.51**	0.57**	0.54**	0.60**	1		
EE	0.49**	0.52**	0.50**	0.48**	0.46**	1	
RID	0.56**	0.59**	0.55**	0.53**	0.50**	0.62**	1

4.3. OLS-Based Analysis of Economic Efficiency and Fixed-Effects Regression Analysis

The infrastructural indicators all increased economic efficiency (the largest impacts were on road density (β=0.48, t = 8.00) and electricity coverage (β=0.42, t = 8.40). The positive contribution was also made by TC, BP. The OLS model estimates the baseline estimates of these effects regionally. The detailed regression results have been given in Table 6 and Figure 3 (a). The output of the Fixed-Effects regression model is in table 6 and figure 3 (b). The fixed-effects model adjusted by region and time-specific factors attests that all the variables of infrastructure increase the efficiency of economies, with the strongest impact on RD (β=0.51, t=9.00). The model demonstrates the infrastructure robustness effects that consider unobserved regional and temporal variation.

Table 6. Combined OLS and Fixed-Effects Regression Results for Infrastructure Indicators and Economic Efficiency

Variable	OLS Parameter Estimate (β)	Standard Error (SE)	t-statistic	Sig. (p)	Fixed-Effects Parameter Estimate (β)	Standard Error (SE)	t-statistic	Sig. (p)
RD	0.48	0.06	8.00	<0.001	0.51	0.05	9.00	<0.001
TC	0.35	0.05	7.00	<0.001	0.33	0.04	8.25	<0.001
EC	0.42	0.05	8.40	<0.001	0.45	0.05	9.00	<0.001
BP	0.28	0.04	7.00	<0.001	0.30	0.04	7.50	<0.001
PSA	0.25	0.05	5.00	<0.001	0.27	0.04	6.75	<0.001
Constant	5.12	1.20	4.27	<0.001	4.98	1.15	4.33	<0.001

(a)   (b)
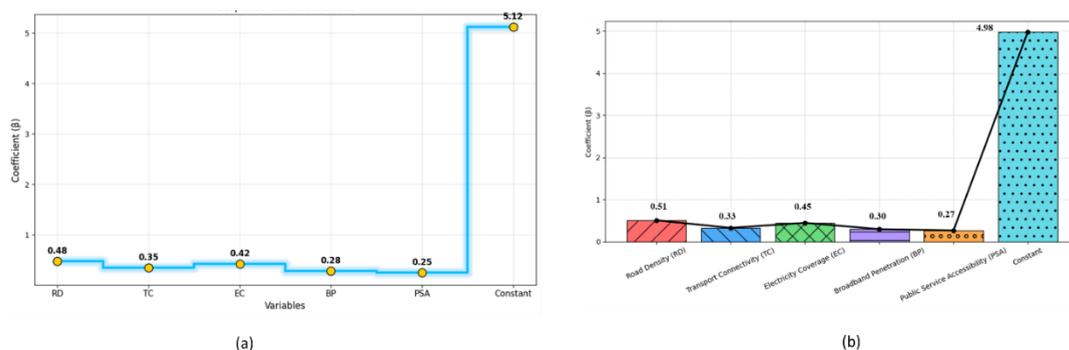
Figure 3. Presents the regression results (a) OLS regression coefficients and (b) fixed-effects regression coefficients.

4.4. Spatial Lag Model (SLM)

The spatial spillovers of SLM outcomes are high, as the improvement of infrastructure in one area is beneficial to the adjacent areas. The spatial lag (β=0.45, z = 6.43) and the regional infrastructure development (β=0.33) demonstrate that there are strong interregional impacts. The indicators of all infrastructure performed well and it showed that the investments within a single location have regional effects. Table 7 shows detailed SLM results and their effects.

Table 7. SLM Results: Impact of Infrastructure on Economic Efficiency

Predictor	Parameter Estimate (β)	SE	z-statistic	Sig. (p)
RD	0.42	0.06	7.00	<0.001
TC	0.31	0.05	6.20	<0.001
EC	0.39	0.05	7.80	<0.001
BP	0.27	0.04	6.75	<0.001
PSA	0.24	0.05	5.80	<0.001
RID	0.33	0.05	6.60	<0.001
Spatial Lag (ϱ)	0.45	0.07	6.43	<0.001

4.5. Geographically Weighted Regression

GWR emphasizes the heterogeneity of effects of infrastructure locally. The highest local influences are RD and EC (β=0.32,0.33) and the least but significant are BP and accessibility of government services.

These findings highlight the fact that the effects of infrastructure are diverse and differ depending on the places and urban-rural settings. Comprehensive GWR local coefficient information is displayed in Table 8.

Table 8. Spatial Variation in GWR Local Coefficients

Predictor	Minimum β	Maximum β	Mean β	Std. Deviation
RD	0.32	0.61	0.48	0.07
TC	0.25	0.44	0.34	0.05
EC	0.33	0.56	0.42	0.06
BP	0.20	0.38	0.29	0.05
PSA	0.18	0.36	0.26	0.04
RID	0.28	0.46	0.35	0.05

4.6. Path analysis

Table 9 provides an analysis of interaction, which indicates that the interaction between TC and BP significantly lowers the urban-rural disparities, and regional infrastructure development has positive spillovers to the neighbor regions ($\beta = 0.33$, t= 5.02). In general, the planning of integrated transport, energy, and digital infrastructure is needed to improve the economic performance and equity in regions.

Table 9. Path Analysis of Infrastructure Indicators on Economic Efficiency

Hypothesis	Structural Path	Effect Type	Standardized Coefficient (β)	t-value	p-value	R²	Decision
H1	RD → EE	Direct	0.42	7.86	< 0.001	0.58	Supported
H2	TC → EE	Direct	0.51	9.14	< 0.001	0.58	Supported
H3	EC → EE	Direct	0.47	8.21	< 0.001	0.58	Supported
H4	BP → EE	Direct	0.39	6.72	< 0.001	0.58	Supported
H5	PSA → EE	Direct	0.36	6.10	< 0.001	0.58	Supported
H6	TC × BP → EE	Moderated	0.28	4.63	< 0.001	0.58	Supported
H7	RID→ EE	Spatial Spillover	0.33	5.02	< 0.001	0.58	Supported

5. Conclusion

Research analyzed the impact of spatial infrastructure inequalities using 2,150 observations of 2018-2025 on the regional economic performance measured by per capita income, industry production, and employment. The major metrics were road density (42.6 ± 15.3 km/100 km²), transport connectivity (0.64 ± 0.18), electricity coverage ($89.5\% \pm 8.7$), broadband penetration (56.8 ± 14.2), and the availability of the services of the government (71.4 ± 11.5). Descriptive statistics, correlation, panel regressions, and spatial econometric model analyses indicate that all the infrastructure factors are significantly ($p < 0.001$) efficient, with road density and electricity being the strongest. The interrelationships and spillovers decrease the urban-rural differences. Further studies need to be based on micro-level data and other types of infrastructure.

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