



Digital Innovation Effects of Cross-Border Transport Infrastructure: A Case Study of the China-Laos Railway

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Abstract. This study analyzes the impact of the China-Laos Railway on regional digital innovation using panel data from 29 Chinese provinces from January 2018 to December 2023. The multi-period DID, propensity score matching, and event study analysis demonstrate the railway's significant positive effect on digital infrastructure development, especially 5G and fiber network expansion. The results indicate digital infrastructure fully mediates the relationship between the railway's opening and digital innovation growth, supported by robustness checks including placebo tests and sensitivity analyses.

Keywords: Cross-border Transport Infrastructure, Digital Infrastructure, Digital Innovation.

1 Introduction

Transportation infrastructure connectivity along the Belt and Road has risen. A paradigm centred on intelligent upgrading now guides regional links in China. Empirical evidence shows that this paradigm alleviates constraints of traditional corridors^[13]. Embedded technological innovation enlarges the functions of conventional facilities, fosters regional integration and synergy.

Infrastructure milestones include the Youyiguan-Youyi Cargo Port system that realises continuous unmanned customs inspection. The Chancay Port in Peru employs automatic ship-loading and intelligent scheduling to shorten operations from days to hours and lower maritime costs. The China-ASEAN Information Harbor strengthens regional data processing and enables large-scale cross-border e-commerce through a multi-node cloud computing center.

The China-Laos Railway illustrates full-cycle application of digital and intelligent technologies completed on 3 December 2021. This railroad from Kunming, China to Vientiane, Laos is 1,035 kilometers long, which stands as an important Belt and Road project^[8]. The entire project construction process makes extensive use of digital and intelligent technology, which improves the efficiency of project implementation and

also changes the knowledge and understanding of railroad development in the traditional way.

BIM delivers end-to-end data integration in railway electrification and supports a unified O&M platform with real-time monitoring, data visualisation and fault forecasting [2,7,11,12]. BeiDou positioning and infrared scanning create an automated cabling measurement system that improves construction accuracy and efficiency through shared data [3,9,15]. Station management uses face recognition and machine-readable travel documents to integrate verification and raise safety and efficiency [13]. The international multimodal off-station management system on the China-Laos Railway has prompted several provinces to operate passenger and freight services between Kunming and Vientiane [4]. These advances illustrate the benefits of digital upgrades to cross-border transport infrastructure. However, there is a lack of systematic, empirical research into the impact of such projects on regional digital innovation capacity. This study uses the China-Laos Railway as a case study to address this issue.

As for operational management, station facilities have undergone a process of digital upgrading. This upgrading encompasses the integration of facial recognition technologies and machine-readable travel document systems. This technological configuration facilitates integrated verification procedures. In doing so, it enhances both operational efficiency and security protocols.

In a related development, the implementation of the China-Laos Railway's international intermodal "out-of-station" management system has led to a situation where multiple provinces have initiated dedicated freight services along the railway corridor (see Figure 1). This phenomenon reflects a broader shift that points toward the adoption of more intelligent and streamlined logistics operational models.

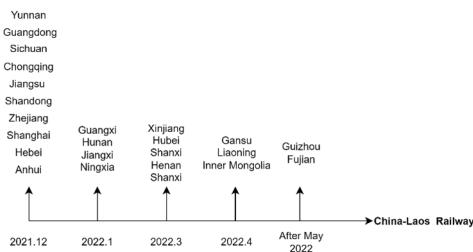


Fig. 1. China-Laos Railway Domestic Train Timeline

The body of existing literature has tended to concentrate its attention on two primary domains of inquiry. These domains revolve around the technological impacts and economic consequences of cross-border infrastructure development. When it comes to technological applications, scholarly investigations into the digital upgrading of transportation infrastructure have spanned a diverse array of fields [6]. These fields include the application of BIM [7], the deployment of drone surveillance technology [1], and the implementation of cloud computing applications [10]. Turning to economic effects, research efforts to date have examined this issue from multiple analytical perspectives. Yuan and Yang (2022) [16], for instance, have underscored the significant role that cross-border infrastructure plays in facilitating regional economic development. In a similar

vein, Wendt et al. (2021) ^[14] have highlighted the critical function of transport infrastructure in enhancing connectivity within border regions. Within the sphere of research focused on innovation-driven effects, cross-border transportation infrastructure has been recognized as a key catalyst for regional innovation ^[8].

Scholars working in this area have primarily made use of survey-based analyses, quantitative statistical methods, and text analytical approaches. Based on previous research, our research integrates the methodological rigor of established paradigms to construct a Multi-period Difference-in-Differences (DID) framework.

2 Research Design and Data Description

2.1 Model Setting

This paper analyzes the impact of the China-Laos Railway on digital innovation using a multi-period difference-in-differences (DID) model structured as follows:

$$\text{Dig}_{it} = \alpha_0 + \alpha_1(\text{treat}_i * \text{time}_t) + \beta X_{it} + \eta_{it} + \gamma_{it} + \varepsilon_{it} \quad (1)$$

Where i denotes the province, t indicates the month. Dig_{it} is the explanatory variable indicating the level of digital innovation; treat_i is a policy dummy variable, one for the province that opens the China-Laos Railway Special Train and zero otherwise; time_t is a time dummy variable, which is 1 if it is the province that opens the China-Laos Railway Special Train, or 0 otherwise; α_1 indicates the difference in the effect of the opening of the China-Laos railway on the treatment group and the control group. A significant positive α_1 indicates that the China-Laos Railway's opening fosters digital innovation.; X_{it} indicates a series of control variables; η_{it} controls for individual-specific effects, and γ_{it} controls for time-specific effects; ε_{it} indicates the error term.

2.2 Data Description

The dependent variable is the level of digital innovation (Dig). This study defines digital innovation as the development and application of new products, services, or processes driven by digital technologies such as artificial intelligence and blockchain. Digital technology patent applications are selected as the metric because they directly and objectively quantify a company's core technological output in this field. Therefore, this study uses the number of patent applications for digital technologies between January 2018 and December 2023 as an indicator of firms' digital innovation. Keywords related to digital technologies were extracted using Python software, based on the Chinese government's standardised digital economy industry classification (2021) and official administrative reports. The formula is as follows:

$$\text{TOT_words}_{it} = \sum\{\text{keywos}\} \quad (2)$$

Subsequently, the digital technology keywords were cross-referenced with Chinese patent literature to quantify patent applications related to digital innovations using IPC categorisation. Following data cleaning, the number of patents relating to digital

technology was derived by correlating the keywords with the IPC codes of invention and utility model patents of listed companies in the CNRDS database.

The core explanatory variables captured by the double difference (DID) refers to provinces that have launched direct international freight trains on the China-Laos Railway following its inauguration. These provinces are directly connected to the China-Laos Railway via the railway network, enabling their goods to reach Laos and Southeast Asia via this route. As of December 2023, dedicated China-Laos Railway freight trains have commenced operations in 24 provinces (including autonomous regions and municipalities directly under the central government). Provinces providing active services are assigned a policy dummy variable value of 1; comparison provinces (Qinghai and Tibet excluded due to developmental disparities and geographical isolation) are coded as 0. The time indicator is valued at 1 in the month following the launch of railway services and 0 in all other months.

To address the potential impact of other factors on the estimation results, the following control variables were selected for this study: Economic development (GDP): given that GDP data is provided on a quarterly basis, it was converted to monthly data using quadratic interpolation in the Eviews statistical software. (ii) Government financial support (sup): measured by the ratio of local government general budget expenditure to regional GDP. (iii) Industrial structure (ind): measured by the ratio of secondary industry output to GDP. (iv) Social consumption level (con): This reflects the population's living standards and purchasing power, which directly impact market demand and the potential for cross-border e-commerce. In this study, it is measured by the ratio of the total retail sales of consumer goods to GDP. Level of financial development (deposits): A well-developed financial system provides adequate financial support for cross-border e-commerce, as well as convenient payment and settlement services and effective risk management tools. This variable is expressed as the ratio of loans from financial institutions to GDP. (vi) Capital accumulation (fixed): Regions with higher levels of capital accumulation are more likely to invest in areas such as technology, R&D, supply chain management, and marketing. This enhances their competitiveness in cross-border e-commerce. This is measured by the cumulative growth rate of fixed asset investment. (vii) Openness: This is measured by the total value of exports and imports, reflecting the extent to which a region interacts with the global market.

2.3 Data Sources

This study uses balanced panel data collected monthly from 29 Chinese provinces between January 2018 and December 2023 ($N = 2,088$ observations). This extended spatio-temporal coverage enhances the study's empirical robustness. The dependent variables are compiled from detailed, monthly, aggregated customs records at provincial level, which are provided by China's General Administration of Customs. The control variables are based on authoritative references from multiple sources, including provincial statistical yearbooks of local indicators, China's National Statistical Yearbook of Standardised Indicators and coordinated economic time series from the EPS database. Table 1 provides a full set of descriptive statistics for all variables.

Table 1. Descriptive statistics of the variables involved in the model from 2018 to 2023

VARIABLES	(1)	(2)	(3)	(4)	(5)
	N	mean	sd	min	max
did	2,016	0.276	0.447	0	1
Indig	2,088	7.456	1.277	3.784	10.57
gdp	2,088	2,944	2,470	111.1	14,220
fixed	2,088	4.871	15.58	-82.80	284.8
imp	2,088	795.4	1,343	0	8,293
sup	2,088	0.238	0.0803	0.105	0.465
con	2,088	0.379	0.0665	0.180	0.504
ind	2,088	37.56	7.530	14.90	53.98
deposit	2,088	1.689	0.386	0.980	2.770
Number of id	29	29	29	29	29

3 Research Design and Data Description

3.1 Benchmark Regression Results

The results of the multi-period DID benchmark regression (see Table 2, columns 1–2) show that the coefficient of the DID interaction term is statistically significant at $p < 0.01$ after covariate adjustment. This indicates that the China-Laos Railway's dedicated freight services stimulate digital innovation by facilitating cross-border trade, logistics, and tourism activities. This generates demand for smart logistics systems, e-payment solutions, and cross-border e-commerce platforms.

Table 2. The result of the benchmark regression

VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)	(7)
did	0.337*** (0.0241)	0.361*** (0.0258)	0.269*** (0.0528)	0.360*** (0.0405)	0.364*** (0.0257)	0.1065*** (0.0026)	0.0111*** (0.00269)
gdp		-1.21e-05 (1.25e-05)	5.17e-05 (3.83e-05)	-3.63e-05** (1.62e-05)	-1.46e-05 (1.25e-05)		-1.79e-06 (1.12e-06)
sup		-0.435 (0.455)	0.256 (0.891)	-2.359*** (0.692)	-0.456 (0.454)		0.293*** (0.0501)
con		-0.0866 (0.376)	4.110*** (1.290)	0.515 (0.522)	-0.0578 (0.376)		0.282*** (0.0416)
ind		-0.00753 (0.00467)	0.0543*** (0.0153)	-0.00224 (0.00609)	-0.00715 (0.00466)		- (0.000515)
deposit		-0.211*** (0.0692)	0.919*** (0.211)	-0.285*** (0.0801)	-0.181*** (0.0700)		-0.0476*** (0.00764)

Table 2. The result of the benchmark regression

fixed	0.00111*** (0.000372)	0.000843 (0.00108)	0.00189*** (0.000732)	0.00107*** (0.000372)			0.000179*** (3.69e-05)
imp	3.32e-06 (6.07e-06)	0.00011*** (3.18e-05)	1.60e-06 (8.77e-06)	3.92e-06 (6.06e-06)			-2.38e-06*** (6.62e-07)
diddig				-0.0846*** (0.0313)			
Constant	6.942*** (0.0389)	7.723*** (0.328)	1.221 (1.067)	7.875*** (0.422)	7.660*** (0.328)	0.2797*** (0.0013)	0.280*** (0.0359)
Observations	2,016	2,016	412	1,044	2,016	2,016	2,016
R-squared	0.776	0.779	0.803	0.822	0.780	0.948	0.953
Number of id	29	29	11	29	29	29	29

Note: Robust standard errors are reported in parentheses (with adjustments made for heteroscedasticity during calculations). ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively (this criterion is tailored to the sample size characteristics of the present study).

3.2 Parallel trend testing

This study used the event study framework to test the dynamic effects of the treatment and control groups over time and to test the parallel trend hypothesis. The model was constructed as shown in equation (3).

$$Dig_{it} = \alpha_0 + \sum_{N=-8}^M \alpha_1 (M_{it} * DID_{it}) + \beta X_{it} + \eta_{it} + \gamma_{it} + \varepsilon_{it} \quad (3)$$

Where N and M represent the number of months before and after the opening of the China-Laos Railway dedicated trains, respectively. The results, shown in Figure 2, indicate that in the first 8 months before the opening of the dedicated trains, the interaction term coefficients did not pass the significance test, which supports the parallel trends assumption. After the opening of the China-Laos Railway, the interaction term coefficients were significant at the 1 percent level and positive, exhibiting a marked increasing trend thereafter.

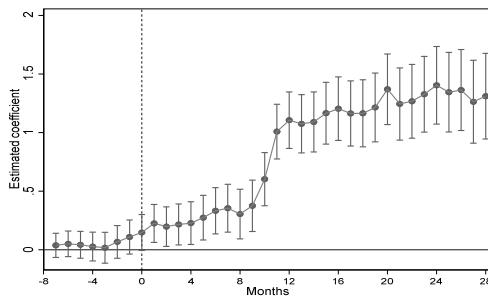


Fig. 2. Parallel trend test

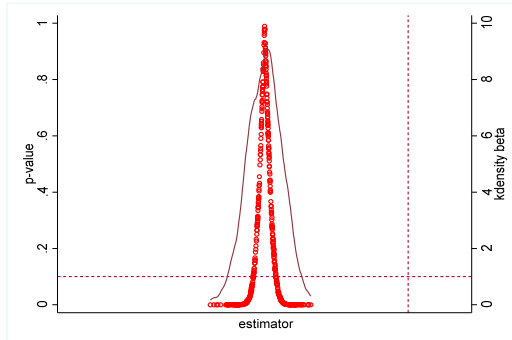


Fig. 3. Placebo test

3.3 Placebo Test

To mitigate the potential bias arising from unobservable characteristics that change over time, this study conducts a placebo test to assess the robustness of the empirical results. The placebo test generally involves random assignment of control and treatment groups, random assignment of policy implementation timings, and re-estimating the model. In this study, we employ the random assignment of control and treatment groups for the placebo test. A virtual policy dummy variable is randomly created, and a random shock is applied to 29 sample cities 1,000 times.

The results of the placebo test, as shown in Fig.3, indicate that the kernel density distribution shows a pronounced peak near zero, while most p-values exceed the 0.1 threshold., which presents a significant deviation from the core regression estimates. This suggests that the conclusion that the opening of the China-Laos Railway promotes the level of digital innovation is robust.

3.4 Robustness Testing

PSM-DID.

Utilizing Propensity Score Matching (PSM), this research minimizes observable differences between treatment and control cohorts. First, a Logit model is used to estimate the propensity scores. Then, the analysis employs two matching techniques: 1-to-2 nearest neighbor pairing and caliper-based radius matching with a caliper of 0.03 to match samples with similar characteristics (see fig.4).

The empirical results of the PSM-DID method are presented in Column (3) of Table 2. The policy implementation variable (DID) shows a significant positive effect on the dependent variable, confirming that the above conclusions are robust.

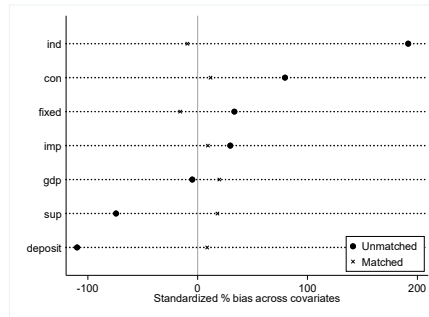


Fig. 4. PSM results

Removing the Effects of the Epidemic.

As an unprecedented global health emergency, the COVID-19 pandemic has had a significant impact worldwide, including supply chain disruptions, logistics delays, and the hindrance of traditional offline industries. To ensure the robustness of the research conclusions and eliminate the potential confounding effects of the pandemic, this study excludes the observational samples from 2020 to 2022 and conducts a re-estimation. The results, presented in Column (4) of Table 2, show that the effect remains significantly positive, with both the direction and significance consistent with the previous analysis, further confirming the robustness of the empirical findings.

Removing the Effects of Other Policies.

To promote the flow of digital economy factors and the coordination of new production relations, China established National Digital Economy Innovation and Development Pilot Zones in 2019. To control for this policy effect, this study re-ran the regression with the designation as a National Digital Economy Innovation and Development Pilot Zone as a dummy variable. As shown in Column (5) of Table 2, the DID coefficient is significantly positive at the 5% level, reaffirming the original conclusion.

Mechanism Testing.

As an important corridor connecting China and Laos, the China-Laos Railway has facilitated regional connectivity and cross-border trade efficiency, driving the integration of digital technologies such as smart logistics systems and cross-border electronic payments. This has accelerated the upgrade of communication networks along the railway, including the installation of 5G base stations and fiber optic networks, thereby expanding the demand for digital innovation in the relevant regions. Furthermore, the growth of the tourism industry and the influx of investments driven by the railway have further stimulated smart services such as online bookings and digital settlements, energizing the vitality of digital innovation. These changes have created a positive feedback loop of "transportation driving the economy, and the economy driving digitalization," through which the China-Laos Railway has contributed to the development of digital innovation by promoting regional digital infrastructure construction.

To verify the mechanisms through which the China-Laos Railway promotes digital innovation, this study constructs the following mediation model:

$$Lev_{it} = \beta_0 + \delta_1 DID_{it} + \beta X_{it} + \eta_{it} + \gamma_{it} + \varepsilon_{it} \quad (4)$$

In this model, cross-border infrastructure is represented as a key variable. Considering that digital infrastructure is built on next-generation digital technologies and network sharing, this study uses proxy variables for digital infrastructure construction sourced from government work reports and relevant institutions. Drawing on the research by Chen et al.(2023)^[5], four dimensions are selected to measure digital infrastructure: internet broadband access rate, mobile phone penetration rate, the extent of fiber-optic cable infrastructure and the count of registered internet domains. The construction level of digital infrastructure is measured using the entropy method. As shown in Column (6) -(7) of Table 2, the results of the digital infrastructure mediation effect test indicate that digital infrastructure plays a sufficiently significant mediating role in the relationship between the operation of the China-Laos Railway and the development of digital innovation.

4 Conclusion

Based on the evidence presented, this study employs a DID framework to examine the China-Laos Railway's role in augmenting the digital innovation capacities of connected regions. The analysis extends beyond a simple impact assessment to specifically dissect the mechanisms through which cross-border infrastructure development fosters these innovative capabilities. A principal finding is that such infrastructure projects significantly advance regional digital innovation, an effect transmitted chiefly through the concurrent enhancement of digital infrastructure. This observation corroborates a well-established stream of scholarship that identifies infrastructure as a foundational pillar for innovation ecosystems, a principle of acute relevance within the context of developing economies. This research connects to and extends a body of literature exploring infrastructure's influence on economic and technological progress. Much of the preceding work has concentrated on how physical networks, including transportation and logistics, serve as catalysts for innovation by improving physical connectivity and facilitating the seamless flow of goods and services.

Our analysis contributes to this conversation by re-centering the analytical focus onto digital infrastructure. Such a pivot is essential, reflecting a contemporary economic landscape where digital technologies are increasingly integral to development. In contrasting our approach with existing studies, a comparison with the work of Chakraborty and Pal (2020)^[4] is illustrative. While their research provides valuable insights into the direct economic returns of infrastructure investments, it gives less consideration to the parallel strengthening of technological capacities. This study, by directly probing the nexus between cross-border transport systems and digital innovation, illuminates a critical indirect benefit that the capacity of such projects to catalyze the digital transformation of regional economies.

These findings suggest clear implications for policy formulation, indicating that decision-makers should account for the wider effects of cross-border transport initiatives, including their proven capacity to spur digital innovation. A crucial takeaway for strategic planning is the amplified value derived from investing in digital infrastructure concurrently with physical development. To maximize the contribution of these large-scale endeavors to regional innovative strength, governments and international organizations should prioritize the expansion of digital connectivity as a core, integrated component of cross-border infrastructure projects.

The analytical scope of this research is, however, focused on the China-Laos Railway, which naturally raises questions about the generalizability of these findings. The extent to which these observed effects can be extrapolated to other regions, presents a clear avenue for future inquiry. Subsequent research could productively broaden this investigation to other cross-border infrastructure projects, with an especially fruitful approach involving a comparative analysis of regions characterized by varying degrees of pre-existing digital development. Such a methodology would foster a more granulated understanding of how infrastructure development interacts with digital innovation across diverse geographic and economic settings.

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