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Original Research

How Does the International Transport Network Affect Corporate Green Innovation: Evidence from the China-Europe Railway Express

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Abstract

Leveraging the inauguration of the China-Europe Railway Express (CRE) as a natural experiment, this study employs a multi-period difference-in-differences (DID) model using data from China's listed manufacturing firms spanning 2011 to 2021. The findings reveal that the CRE has significantly enhanced the green innovation capabilities of manufacturing enterprises, with a notably stronger impact on substantive green innovation than strategic green innovation. These results are further reinforced through rigorous robustness checks, including instrumental variable approaches, propensity score matching combined with difference-in-differences (PSM+DID) regression, and variable substitution. The study identifies two primary mechanisms driving the CRE's positive impact on corporate green innovation: alleviating financial constraints and facilitating cross-border innovation resource flows. Heterogeneity analysis indicates that the CRE's benefits are particularly pronounced among non-state-owned enterprises, firms with lower degrees of internationalization, and smaller firms. Regionally, the impact is most substantial in the central regions, followed by the eastern regions, while the western regions show limited effects due to structural challenges. Industry-level analysis reveals a hierarchical impact, with high-tech manufacturing deriving the greatest benefit, followed by medium-tech and traditional manufacturing sectors. This study contributes theoretical insights and offers actionable policy recommendations to maximize the CRE's potential in fostering green innovation, addressing regional inequalities, and advancing sustainable international trade and logistics.

Keywords: China-Europe railway express, green innovation, substantive green innovation, strategic green innovation

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Introduction

The China-Europe Railway Express (CRE) is a flagship project in a major national strategy of the Chinese government known as the "Belt and Road Initiative (BRI)". This governmental initiative is aimed at expediting infrastructure development and economic prosperity of countries along the historic Silk Road [1]. It plays an extremely significant and sometimes decisive role in reforming cross-regional transport systems and various related fields such as trade, technology, and education [2-6]. According to data from the China "Belt and Road" website, the number of China-Europe Railway Express trains has steadily increased annually since its inception. As of March 2024, the China-Europe Railway Express (CRE) had operated over 87,000 cumulative trips, reaching 222 cities across 25 European countries [7]. As the "Belt and Road" initiative continues to unfold, the China-Europe Railway Express has demonstrated strong growth in its transportation business on a macro level and profoundly influenced enterprises' operational models, market strategies, and investment decisions.

Against the backdrop of intensifying global demands for sustainable development, it becomes imperative to assess not only the macroeconomic benefits of the China-Europe Railway Express (CRE) but also its influence on firm-level green innovation along its routes. Of particular interest is whether the CRE promotes meaningful improvements in innovation quality—especially in terms of substantive green innovation that reflects long-term, technology-driven efforts rather than merely strategic compliance with regulatory pressures. Moreover, what are the underlying mechanisms that drive this potential impact? These questions are especially salient as infrastructure-led development is increasingly expected to contribute to environmental and technological transitions. This study aims to systematically explore the extent and transmission channels through which the CRE affects corporate green innovation, thereby bridging the gap between macro-level transport policy and micro-level innovation behavior.

Two primary strands of literature inform this study: one examining the impact of the China-Europe Railway Express (CRE) on innovation performance and the other focusing on the environmental effects of large-scale transportation infrastructure, particularly domestic high-speed railway (HSR) openings. As for the innovation outcomes, numerous macro-level analyses have demonstrated that the CRE's establishment has significantly stimulated urban innovation systems and fostered the growth of related activities [8-11]. Furthermore, HSR development is anticipated to contribute to environmental sustainability by reducing pollution emissions [12-14], improving air quality [15-16], and decreasing energy consumption [17]. While prior work focuses on the general innovation impact, we aim to investigate how the opening of the China-Europe Railway influences the substantive green innovation and strategic green innovation of companies along its route. These two major categories can be traced to Delmas and Montes-Sancho [18], who found that most of the literature was on innovation intensity and quantity, ignoring the impact of innovation quality under different motivations. Building upon this theoretical foundation, Lian et al. [19] extended this analytical framework to the domain of green innovation and explicitly conceptualized Substantive Green Innovation and Strategic Green Innovation, as shown in Table 1.

As for the mechanism analysis, the existing literature has primarily emphasized infrastructure improvement, technological spillover effects, and cost reduction. For instance, infrastructure-centric studies highlight CRE's role in enhancing connectivity and logistics efficiency, thereby reducing energy-intensive transportation modes [5]. Technological spillover mechanisms are often linked to knowledge diffusion through high-value cargo transported via CRE. Cost reduction effects are typically attributed to economies of scale in multimodal transport and policy-driven subsidies [20-21]. Notably, most prior studies overlooked firm-level mechanisms, thereby limiting their ability to fully capture the intricate dynamics shaping organizational green innovation behavior. We find two critical mechanisms for filling the gap: financing limitations and innovation component mobility. First, regarding the financing limitations mechanism, CRE's operational efficiency and policy support (e.g., subsidies, trade facilitation) can alleviate financial barriers for firms by reducing trade-related transaction costs and improving cash flow predictability [22]. For example, streamlined logistics reduce inventory holding costs, freeing capital for green investments [23]. Additionally, CRE's role in expanding export

Table 1. Definition of substantive green innovation and strategic green innovation.

Dimensions	Substantive Green Innovations	Strategic Green Innovations
Motivation	Technology-driven, pursuing long-term sustainability	Compliance-driven, seeking short-term legitimacy
Technical Level	High (invention patents)	Low (utility model patents)
Environmental Impact	Indirect (life-cycle optimization)	Direct (end-of-pipe treatment)
Financial Impact	Enhances performance	Weakens performance
Policy Response	Proactive innovation	Reactive compliance

markets may enhance firms' creditworthiness, enabling access to cheaper external financing for sustainable technologies [24]. Second, for the innovation component mobility mechanism, CRE facilitates cross-border flows of skilled labor, R&D resources, and green technologies, fostering innovation ecosystems [22, 25]. By connecting firms to global value chains, CRE enables access to specialized inputs and collaborative networks, accelerating the adoption of environmentally friendly practices [22, 25-27]. Reverse knowledge spillovers from high-value exports (e.g., electronics, advanced machinery) may also drive indigenous green innovation, particularly in resource-intensive regions [28]. These firm-level mechanisms remain underexplored in the current research.

Our dataset covers 2011 to 2021, and the model employs a multi-period difference-in-differences (DID) approach. We use this model according to Acemoglu et al. [29] and Zhang [30] for similar research designs. Several key findings yield that the CRE significantly boosts green innovation, with its effects being particularly pronounced in substantive green innovation by easing financial constraints and enhancing the mobility of innovative resources. Heterogeneity analysis revealed distinct patterns. The CRE exerts a stronger influence on non-state-owned enterprises and firms with lower levels of internationalization, reflecting their greater dependency on improved logistics and expanded market access. Smaller firms also derive more pronounced benefits from leveraging their flexibility to seize CRE-driven opportunities, whereas larger firms exhibit comparatively muted responses due to institutional inertia. Regionally, the CRE's impact is most substantial in the central regions, followed by the eastern regions, while the effects are minimal in the west, underscoring regional disparities in industrial capacity and resource allocation. Across industries, high-tech manufacturing reaps the greatest benefits from the CRE, with medium-tech and traditional industries following suit.

This study contributes to the literature by providing empirical evidence on how transportation infrastructure influences corporate green innovation at the microeconomic level, thereby expanding theoretical boundaries through its micro-level analysis of the China-Europe Railway Express (CRE) as a novel lens for examining green governance under the Belt and Road Initiative. Moreover, it advances mechanistic understanding by examining the internal pathways linking the CRE to differential green innovation outcomes (substantive vs. strategic). It establishes a new theoretical framework for analyzing infrastructure's role in fostering sustainability-oriented organizational behavior. Furthermore, the study pioneers a multi-dimensional heterogeneity analysis approach that uncovers how firm-specific characteristics moderate the CRE-green innovation relationship, thereby enriching the methodological toolkit for infrastructure-economic outcome research and enhancing the generalizability of its findings.

The remainder of this paper is organized as follows: Section 2 develops the theoretical framework and posits research hypotheses. Section 3 details the empirical strategy, including data sources, variable operationalization, and the multi-period DID model specification. Section 4 reports the regression results, accompanied by robustness tests and heterogeneity analysis. Sections 5 through 8 present the summary of findings, discussion, policy implications, and research limitations, respectively.

Theory and Hypothesis

To gain a deeper understanding of how exactly the impact mechanism is functioning, we present our theoretical analysis and key hypotheses in Fig. 1.

Hypothesis 1: The influence of CRE on corporate green innovation has both direct and indirect effects, with the latter being mediated through two main intermediary variables, including alleviation of financial constraints and facilitation of cross-border innovation resource flows.

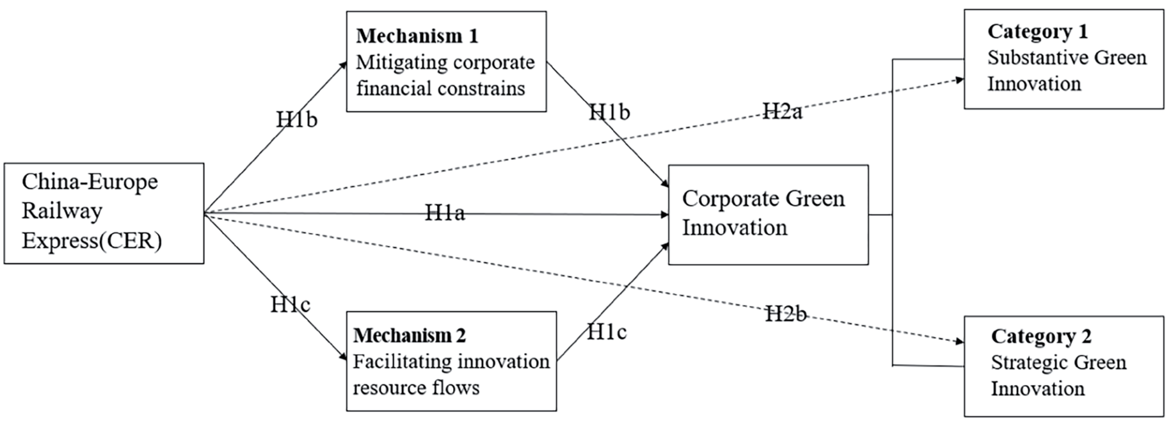

Fig. 1. Mechanisms of CRE promoting corporate green innovation.

Hypothesis 1a: The CRE directly improves corporate green innovation along its route.

Unlike conventional innovation, green innovation focuses on developing and implementing environmentally friendly technologies to minimize resource usage and environmental damage during production [31]. The CRE promotes international exchanges and cooperation by offering a broader market and more collaboration opportunities for green innovation [10]. Additionally, the efficient transportation model of the CRE facilitates the rapid circulation of green innovative products, helping enterprises respond to market demands more quickly and commercialize the results of green innovation. Lastly, opening the CRE will also assist in constructing green supply chains and encourage enterprises to adopt green practices in raw material procurement, production processes, and product distribution. By optimizing supply chain management, enterprises can reduce resource waste and environmental impacts, thereby enhancing green innovation's overall level and effectiveness.

Hypothesis 1b: The CRE significantly improves corporate green innovation by mitigating corporate financial constraints.

The operation of the CRE significantly alleviates financing constraints faced by enterprises, providing the necessary R&D capital for green innovation activities [10]. Enterprises require consistent financial flow to fund their ongoing innovation due to the high risk and lengthy nature of innovation activities, as well as the issue of information imbalance [32]. Adequate funding is crucial for promoting project investment and innovative activities [10, 33]. The "Belt and Road" initiative has received a positive response from the capital market, financial institutions, and government departments [11]. These departments have significantly assisted affiliated businesses by increasing bank lending, providing loan rate reductions, implementing tax cuts, and offering financial assistance. The launch of the CRE sends a positive signal of implicit government support to the outside world. This not only helps businesses acquire advanced green technologies but also promotes the spread of green concepts and the unification of green standards.

Hypothesis 1c: The CRE significantly improves corporate green innovation by facilitating cross-border innovation resource flows.

The inauguration of the CRE is anticipated to facilitate the mobility of innovative elements, thereby promoting corporate green innovation [10-11]. The launch of the CRE has significantly increased international exchanges and cooperation, breaking down regional barriers and promoting the efficient flow of key factors of production, as well as resources such as capital, technology, labor, and information [11]. This initiative not only improves cross-border factor mobility and resource allocation but also provides strong support for cross-border innovation capital and technology circulation. Furthermore, it is expected to increase transportation efficiency [34], further enhancing corporate market competitiveness and providing a more favorable external environment for green innovation.

Hypothesis 2: Compared to strategic green innovation, the CRE has a greater enhancing effect on the substantive green innovation of manufacturing enterprises along its route.

Innovation can be categorized into two distinct forms: substantive and strategic innovation [35-37]. Substantive innovation primarily involves invention patents with high technological intensity and difficulty in implementation, making it a high-level technological innovation project [35]. In contrast, strategic innovation often refers to utility model patent technology, with relatively lower technological content and implementation hurdles. It is generally perceived as a less advanced form of innovation, often carried out in response to government policies and regulatory demands. Studies indicate that strategic innovation may not necessarily bolster firms' profitability and could even result in "patent bubbles" [38].

Compared to strategic green innovation, the CRE has a greater enhancing effect on substantive green innovation in manufacturing enterprises along its route. This is because the CRE promotes deeper technological innovation through several interrelated mechanisms. First, it reduces logistics costs and enhances supply chain efficiency, thereby creating economic incentives for firms to engage in resource-saving and environmentally friendly innovation. Second, by facilitating the international exchange of technology and expertise, the CRE enables enterprises to access and absorb advanced green technologies from abroad, accelerating the development of high-quality green inventions. Third, expanding overseas markets increases competitive pressure, encouraging firms to develop more differentiated and sustainable products to meet global environmental standards. Lastly, heightened regulatory expectations along transnational trade corridors further incentivize firms to invest in substantive innovation to maintain compliance and enhance their environmental legitimacy.

Hypothesis 2a: The CRE improves the strategic green innovation of corporates along its route.

Hypothesis 2b: The CRE improves the substantive green innovation of corporates along its route.

Materials and Methods

Data

To validate the aforementioned hypotheses, the dataset was chosen from manufacturing firms listed on the stock market between 2011 and 2021, forming the initial sample pool. During the sampling process, entities designated as ST (Special Treatment), PT (Particular Transfer), or those with irregular financial conditions and lacking essential data were excluded. This is in line with the research objectives and the availability of data. After this stringent screening, a refined sample of 21,292 firm-year observations was selected for analysis. We chose these manufacturing enterprises based on the following considerations. Firstly, from the perspective of patent applications, the patent application volume of manufacturing listed companies is significantly higher than the average level of industrial enterprises and the entire listed industry. This indicates that manufacturing enterprises play a central role in promoting innovation-driven development. Secondly, from the perspective of sample representativeness, the data of manufacturing enterprises reflects the dynamics of innovation activities and green development within the industry in a more comprehensive way.

We collect data on green innovation patents from China's National Intellectual Property Administration, which is retrieved through an online tool named "Green Inventory of International Patent Classification", introduced by the World Intellectual Property Organization (WIPO) in 2010. It categorizes green patents into seven primary domains based on the United Nations Framework Convention on Climate Change. These domains encompass transportation, waste management, energy conservation, alternative energy production, regulatory management, design, agriculture and forestry, and nuclear power. Based on these classification criteria, our research quantifies the annual amount of green innovation patents of each corporation in the initial sample pool and classifies patents into green invention patents and green utility patents so that green innovation efforts can be evaluated. We also obtain other data from multiple sources, including the China Belt and Road website, the CRE website, official government websites, and relevant media reports. All financial data was acquired from the CSMAR database. To reduce the impact of outliers on analytical results, this study has implemented a Winsorization technique on all continuous variables at the 1% and 99% percentiles.

Variables

Independent Variable: The launch of the CRE (Treatment * Post). Two important variables were created to assess the impact of policy changes on the CRE: the policy dummy variable (Treat) and the time dummy variable (Post). These variables indicate whether different prefecture-level cities in China served as the starting point for the railway express between 2011 and 2021. The policy dummy variable (Treat) is defined as follows: if a listed firm is located in a city where the CRE has been implemented, it is assigned a value of 1 as part of the treatment group. Otherwise, it will be assigned a value of 0 as part of the control group. The time dummy variable (Post) is based on each city's initial year of the CRE. For the year of initiation and all subsequent years, this variable is set to a value of 1. In this study, we consider the possibility that certain locations may have initiated multiple routes of the CRE at the same time. To ensure a consistent reference point for the express launch, we use the opening time of the first route. Furthermore, it should be noted that introducing certain routes towards the end of the year may not have a significant impact on innovation immediately. As a result, modifications were made to the temporal effect setting as described by Wang et al. [11]. The adjustment method is as follows: if the express was launched in September or earlier in the year, the Post variable is assigned a value of 1 from that year; for example, Chongqing (launched in March 2011) and Zhengzhou (launched in July 2013); if the launch was after September of that year, the Post variable is assigned a value of 1 from the following year, for example, Wuhan (launched in October 2012) and Yiwu (launched in November 2014).

Dependent Variable: Corporate green innovation encompasses the creation and implementation of novel technologies, processes, or products that advance environmental sustainability by curbing emissions, conserving natural resources, and improving energy efficiency [38]. This study delineates green innovation into three categories for analysis: substantive green innovation, strategic green innovation, and the total scope of green innovation. Substantive green innovation signifies groundbreaking technological advancements underpinned by substantial R&D investments, offering enduring environmental benefits [38]. Strategic green innovation centers on incremental adaptations designed to address external pressures, such as regulatory requirements or market dynamics [39]. Total green innovation captures the overall extent of a firm's green-oriented innovation activities, measured by the total number of green patent applications. This study's evaluation of green innovation leverages patent data, which is widely acknowledged as a robust proxy for innovation [40]. Substantive green innovation is quantified by the number of green invention patents granted (Greeninn_inv), as these patents often signify profound technological progress and underscore a firm's commitment to intensive R&D in green technologies. Strategic green innovation is assessed by the number of green utility model patents granted (Greeninn_uti), which better capture incremental modifications in response to external mandates. Total green innovation is measured by the total number of green patent applications (Greeninn), which provides a comprehensive indicator of a firm's overall green innovation activities, including both substantive and strategic innovations. This classification aligns with established innovation theories distinguishing radical and incremental innovation. An illustrative example of substantive green innovation is hydrogen fuel cell technology advancement. Toyota's pioneering work in fuel cell vehicles, marked by substantial R&D investments, has resulted in numerous invention patents in areas such as hydrogen storage and energy efficiency, exemplifying technological breakthroughs with far-reaching sustainability impacts. In contrast, strategic green innovation can be typified by retrofitting diesel engines to comply with stricter emissions standards. For instance, a Chinese logistics company upgraded its fleet by incorporating cost-effective, energy-efficient technologies to meet regulatory demands, leading to utility model patents for enhanced exhaust systems. These patents illustrate a tactical response to external pressures rather than transformative technological advancements.

Control Variables: In this study, when analyzing the impact of the CRE on corporate green innovation, we consider the potential impact of macroeconomic market factors on micro-level corporate behavior. Therefore, a series of financial and macroeconomic indicators have been introduced as control variables to guarantee the accuracy and reliability of the analysis. Specifically, firm size (Size) is quantified by the natural logarithm of total assets to account for the scale effect of the firm. The asset-liability ratio (Lev) is calculated by dividing the total liabilities by the total assets, providing insight into the firm's level of financial leverage. Profitability (ROA) is calculated by the return on assets, indicating the firm's efficiency in generating profits. The firm value (Tobin's Q) is evaluated using Tobin's Q value, which encompasses the market's assessment of the firm's overall worth. To mitigate the impact of macroeconomic factors, the following macroeconomic indicators are used: regional economic development (GDP), measured by the natural logarithm of the city's gross domestic product; industrial structure (Ind), quantified by the proportion of secondary industry in the city's gross domestic product; and the level of infrastructure construction (Facility), measured by the ratio of fixed asset investment to gross domestic product in the city.

Empirical Models

To accurately identify the impact of the CRE on corporate green innovation, this study adopts a multi-period difference-in-differences (DID) model. Given the staggered launch of the CRE policy across different prefecture-level cities, the multi-period DID framework allows us to fully leverage the temporal and spatial variation in policy implementation. This model is particularly suitable for capturing policy effects in settings where treatment timing is not uniform across units [41]. Compared to traditional two-period DID models, the multi-period approach enables the estimation of dynamic and heterogeneous treatment effects, thereby enhancing identification accuracy. The Tobit regression method is used to estimate the model, taking into account the left-censored distribution characteristic of green innovation data. The model is structured in the following manner:

$$\mathrm{Greeninn}_{i,t} = \beta_0 + \beta_1 \mathrm{Treat}_i * \mathrm{Post}_t + \mathrm{Control} + \mu_i + \gamma_t + \varepsilon_{i,t} \quad (1)$$

In model (1), the variable "Greeninn" is used to quantify the extent of corporate green innovation. The variables i and t indicate the prefecture-level city and year, respectively, and this notation is consistently used throughout the text. The variable Treat is a dummy policy variable that takes a value of 1 when the listed company's domicile city implements the CRE and 0 otherwise. The variable Post is a binary variable that holds the value of 1 for years after the launch of the CRE in each location and 0 for years before. The interaction term coefficient between Treat and Post shows the contrasting effect of the CRE launch on the treatment group (areas where the express is introduced) compared to the control group (areas where it is not introduced) in relation to green innovation. If the introduction of the CRE positively impacts corporate green innovation, the coefficient is expected to show a positive value. The set of control variables, referred to as "Control", encompasses various control aspects. μ_i and γ_t are used to account for unobservable heterogeneity by representing city and year-fixed effects, respectively. The stochastic disturbance term, denoted by $\varepsilon_{i,t}$, represents the random fluctuation in the system. The model includes an interaction term between provincial dummy variables and temporal fixed effects to minimize the impact of time-varying factors at the provincial level on the estimation. Furthermore, this work uses clustered robust standard errors clustered at the business level to account for potential issues with serial correlation and heterogeneity.

$$\mathrm{Greeninn\_inv}_{i,t} = \beta_0 + \beta_1 \mathrm{Treat}_i * \mathrm{Post}_t + \mathrm{Control} + \mu_i + \gamma_t + \varepsilon_{i,t} \quad (1\text{-}1)$$

$$\mathrm{Greeninn\_uti}_{i,t} = \beta_0 + \beta_1 \mathrm{Treat}_i * \mathrm{Post}_t + \mathrm{Control} + \mu_i + \gamma_t + \varepsilon_{i,t} \quad (1\text{-}2)$$

In model (1), we substitute the dependent variable Greeninn with two distinct variables: substantive green innovation (Greeninn_inv) and strategic green innovation (Greeninn_uti). We then conducted separate regression analyses to create models (1-1) and (1-2) to verify Hypothesis 2. If the regression coefficient of the explanatory variable in model (1-1) is significantly greater than the corresponding coefficient in model (1-2), it will support Hypothesis 2, which suggests that the launch of the CRE has a stronger impact on substantive green innovation compared to strategic green innovation.

Results

Descriptive Statistics

As shown in Table 2, the descriptive statistical findings reveal that the mean value of corporate green innovation (Greeninn) is 0.1527, with a standard deviation of 0.6983. The minimum value is 0, while

Table 2. Results of descriptive statistics.

Variable	Obs	Mean	Std.dev.	Min	Max
Greeninn	21292	0.1527	0.6983	0	6
Greeninn_inv	21292	0.1689	0.8026	0	6
Greeninn_uti	21292	0.1137	0.5631	0	4
Treat*Post	21292	0.2899	0.4537	0	1
Size	21292	21.9749	1.1777	19.5550	27.1464
Lev	21292	0.3862	0.1960	0.0510	0.9719
ROA	21292	0.0660	0.1404	-0.8763	0.3696
Tobin'q	21292	2.1205	1.3724	0.8558	9.7412
GDP	21292	18.0333	1.0519	15.4607	19.8843
Ind	21292	0.4273	0.1024	0.1583	0.6341
Facility	21292	0.6926	0.4294	0.1698	2.1469

the maximum value is 6. This highlights the significant disparity in implementing environmentally friendly innovation initiatives among different organizations. Substantive green innovation (Greeninn_inv), which refers to the number of green invention patents, has a mean of 0.1689 and a standard deviation of 0.8026, indicating a significant dispersion in companies' investment and outcomes in substantive green innovation. Strategic green innovation (Greeninn_uti) has a mean of 0.1137 and a standard deviation of 0.5631. It ranges from a minimum value of 0 to a maximum value of 4, which is generally lower than substantial green innovation. The dummy variable representing the launch of the CRE (Treat*Post) has an average value of 0.2899 and a standard deviation of 0.4537. This suggests that around 29% of the companies in the sample are located in prefecture-level cities where the CRE was introduced during the sample period. The average business size (Size) is 21.9749, with a standard deviation of 1.1777. The range of firm sizes in the sample spans from a minimum of 19.5550 to a maximum of 27.1464. This suggests that the distribution of company sizes in the sample is fairly concentrated. The average regional GDP is 18.0333, with a standard deviation of 1.0519. This shows an uneven distribution of economic development levels. The statistical findings from other control factors align with prior research.

Parallel Trends Test

This study conducted a parallel trend test to examine the trends in green innovation before and after

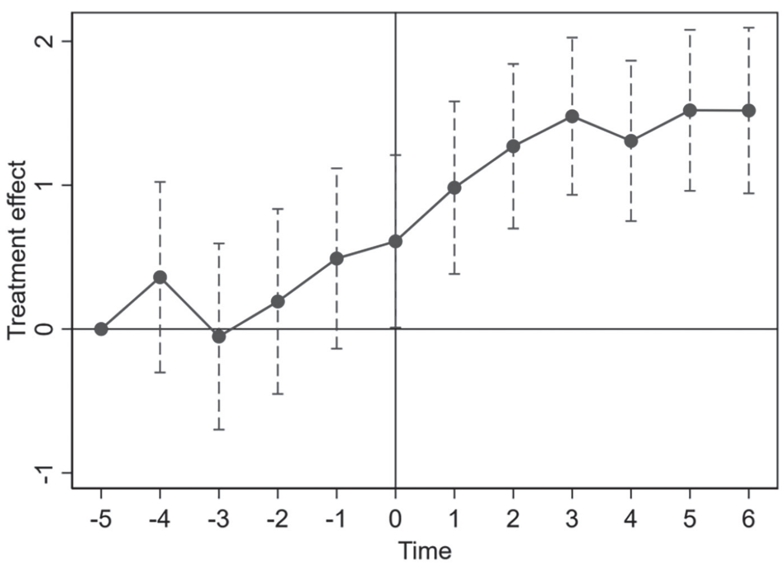

Fig. 2. Parallel trends test.

establishing the CRE. The purpose was to confirm the initial assumption of the model, which states that in the absence of external shocks caused by the CRE, the levels of green innovation in both the treatment group (cities where the CRE was introduced) and the control group (cities where it was not introduced) should remain relatively stable or show convergence. Fig. 2 shows that prior to establishing the CRE, indicated by the horizontal axis value of -1, the annual trends in green patents for both the treatment and control groups varied around the vertical axis value of 0, with their trends converging. This suggests that prior to introducing the CRE, there were no notable disparities in the level of green innovation performance between the two cities. This supports the assumption of parallel trends in the DID model. After the CRE was established, there was a significant shift in the annual trend of green patents between the two groups of cities. Starting from a horizontal axis value of 0, the introduction of the CRE likely had a significant impact on the green innovation of cities in the treatment group, while cities in the control group did not see a similar impact. This discovery supports the logic of conducting further research using the Difference-in-Differences (DID) model. It suggests that establishing the CRE may have caused an external shock, leading to changes in the level of green innovation in cities that were part of the treatment group. The findings provide initial empirical evidence supporting the DID hypothesis's validity.

DID Regression Results

In this study, we empirically tested the impact of the CRE launch on corporate green innovation through a multi-period difference-in-differences (DID) model. Table 3 presents the regression results, with detailed results as follows:

The regression results show a significant positive relationship between the CRE launch and corporate green innovation (Greeninn). Specifically, the interaction term's Treat*Post coefficient is 1.8563 ($p<0.01$), suggesting that the CRE launch significantly enhances corporate green innovation. This outcome supports the idea that the CRE, as a crucial international transportation channel for promoting regional economic development, positively impacts corporate green innovation activities.

Further analysis shows that the China-Europe Railway launch has a significant impact on substantive green innovation (Greeninn_inv), with a coefficient of 1.4873 ($p<0.01$). This indicates that the launch of the China-Europe Railway not only promotes overall corporate green innovation but also particularly strengthens activities in substantive green innovation. As for strategic green innovation (Greeninn_uti), the coefficient is 1.0815 ($p<0.01$), indicating a significant positive effect on strategic green innovation, albeit to a lesser extent than substantive green innovation. This confirms Hypothesis 2 of the paper.

The regression results for the control variables are as follows: Across all regression analyses, it is clear that firm size (Size) has a substantial and positive impact on green innovation (Greeninn). This implies that larger companies are more likely to participate in green innovation due to their superior resources and skills for research and development. The asset-liability ratio (Lev) exhibits a notable positive correlation with green innovation (Greeninn), suggesting that increased financial leverage enables enterprises to access more funds, hence promoting green innovation. A firm's profitability (ROA) has a significant positive impact on green innovation (Greeninn), suggesting that organizations with higher profitability are more likely to allocate resources towards green innovation. This is because they have the capability to take on the risks associated with research and development activities and reap the rewards that come with it. Regional Gross Domestic Product (GDP) and Industrial Structure (Ind) have a significant positive impact on green innovation (Greeninn). This suggests that regions with higher levels of economic development and industrial concentration are more favorable for corporate green innovation. The extent of infrastructure development (Facility) has no significant impact on green innovation (Greeninn), indicating that while infrastructure is crucial for business activities, its direct impact on green innovation may be minor.

Robustness and Endogeneity Checks

This section aims to verify that the conclusions drawn from this study remain valid under various robustness tests. This study conducted four robustness tests: Instrumental Variable (IV), PSM+DID, Treatment Group Redefinition, and Dependent Variable Replacement, as shown in Table 4.

Instrumental Variable Method

The instrumental variable (IV) method is a robust statistical technique employed to estimate causal relationships in the presence of potential endogeneity. In this study, endogeneity arises from the deliberate selection of specific provinces or cities as starting points for the China-Europe Railway Express (CRE) under the framework of the "Belt and Road Initiative" (BRI). This purposeful selection introduces policy endogeneity, which can bias the treatment effect estimation. To address this issue, the study employs the IV approach, ensuring that the chosen instrument is highly correlated with the endogenous explanatory variable (Treat) while remaining uncorrelated with the error term. The instrumental variable is derived from regions historically traversed by the ancient Silk Road, an approach grounded in prior research, such as the works of Mao et al. [10] and Wang et al. [11], which underscore the alignment of the BRI with the routes of the historical Silk Road.

Table 3. DID regression results.

Variables	Greeninn	Greeninn_inv	Greeninn_uti
Treat*Post	1.8563***	1.4873***	1.0815***
	(4.07)	(3.98)	(4.05)
Size	2.7661***	2.3824***	1.2675***
	(9.19)	(9.80)	(8.58)
Lev	4.4480***	3.0273***	3.1917***
	(3.87)	(3.16)	(4.76)
ROA	5.3741***	3.9992***	3.0818***
	(4.85)	(4.27)	(4.72)
Tobin'q	-0.1352	0.0311	-0.1967**
	(-1.02)	(0.28)	(-2.56)
GDP	2.3974***	1.7311***	1.3152***
	(4.12)	(3.26)	(3.51)
Ind	0.0366***	0.0131***	0.0213***
	(3.57)	(3.51)	(5.01)
Facility	0.3007	0.2575	0.3753
	(1.07)	(0.98)	(1.02)
Constant	-47.5111	-91.3331	-42.5442
	(-0.64)	(-1.50)	(-0.88)
Firm	Control	Control	Control
Year	Control	Control	Control
Province*Year	Control	Control	Control
Observations	21,292	21,292	21,292
Pseudo R2	0.0404	0.05	0.0428

Note: ***, **, * are used to denote statistical significance at the 1%, 5%, and 10% levels, respectively, with the corresponding t-values indicated in parentheses. This notation will be employed throughout the subsequent text.

Table 4. Robustness checks.

Method	Operationalization	Problem Addressed
Instrumental Variable (IV)	Using historical Silk Road regions as instrumental variables, two-stage least squares (2SLS) estimation was applied	To address policy endogeneity. Government strategies influenced CRE route selection, while the historical Silk Road introduced randomness, satisfying instrumental variable relevance and exogeneity. Validity was verified via the Sargan test and first-stage F-statistic, ruling out weak instrument bias
PSM+DID	The Logit model estimated CRE launch probability, followed by 1:1 nearest-neighbor matching to balance treatment and control groups, with subsequent multi-period DID regression	To reduce non-random selection bias. CRE implementation may correlate with urban economic/industrial characteristics, creating systematic group differences. PSM balances covariates pre-policy, enhancing DID reliability
Treatment Group Redefinition	All prefecture-level cities in provinces with "regular operation cities" (≥2 weekly direct trains) were included in the treatment group instead of just origination cities	To test sensitivity to the treatment group definition. CRE's "hub-and-spoke" effect may influence surrounding areas. Significant results after expansion indicate spatial spillover effects, strengthening conclusion generalizability
Dependent Variable Replacement	Green patent authorizations (Greeninn2) replaced green patent applications (Greeninn) in regression analysis	To ensure the robustness of the measurement approach. Applications may include unwarranted cases, whereas authorizations reflect realized innovation. Consistent results validate CRE's genuine promotion of green innovation

The validity of the instrumental variable is underpinned by its fulfillment of two essential conditions: relevance and exogeneity. From a relevance standpoint, the explicit strategy of the Chinese government to revive historic trade routes and foster regional economic integration under the modern framework of the CRE reflects a strong alignment with the ancient Silk Road. This historic trade corridor has indelibly shaped regional development and infrastructure, making it a logical determinant for the CRE's route selection. Regions historically linked to the Silk Road are demonstrably more likely to be prioritized as CRE starting points, providing a solid theoretical basis for the instrument's relevance. From an exogeneity perspective, the ancient Silk Road is a historical variable with no direct influence on contemporary corporate green innovation activities. Its role is confined to shaping policy decisions regarding the CRE's routes, thus ensuring that its impact is mediated and indirect. The significant temporal gap between the Silk Road's historical prominence and modern green innovation activities eliminates the possibility of a direct causal pathway. Instead, the influence of the instrument is exclusively channeled through the designation of CRE starting points, subsequently affecting corporate behavior. This indirect mechanism aligns with the theoretical framework of instrument validity.

The instrumental variable (IV) is assigned a value of 1 for prefecture-level cities located in provinces historically connected to the Silk Road and 0 otherwise. The endogenous variable Treat is represented as an interaction term, Treat*Post, with its corresponding instrument being IV*Post. The regression results confirm the validity of the instrument. In the first stage (Table 5, first column), the IV*Post coefficient is positive and statistically significant, demonstrating a strong correlation between the CRE operational regions and their historical connection to the Silk Road. In the second stage (Table 5, second column), the Treat*Post coefficient remains positive and statistically significant, indicating that the CRE exerts a robust and positive influence on corporate green innovation even after accounting for endogeneity. To further validate the instrument's exogeneity, a Sargan test for overidentification was performed. The test produced a p-value of 0.28, supporting the null hypothesis that the instrument is exogenous. Additionally, the first-stage F-statistic significantly exceeded the critical threshold of 10, affirming the strength of the instrument and mitigating concerns about weak instrument bias. These results, combined with theoretical justification, provide strong evidence for the causal relationship between the CRE and corporate green innovation.

PSM+DID

We employ a PSM-DID approach to further address potential selection bias and unobservable confounding. This method is particularly effective in quasi-experimental settings where treatment assignment is not random. This methodology consists of two essential steps: The opening of the CRE is first analyzed using a Logit model to determine its probability. Then, cities that have not yet opened (control group) are selected based on their similarity in propensity scores to match the opened cities (treatment group). This procedure employs nearest-neighbor matching techniques, specifically 1:1 nearest-neighbor matching with replacement, to ensure no substantial disparities in important covariates between the treatment and control groups before the start of the CRE. This effectively eliminates selection bias and potential endogeneity concerns. Furthermore, using the collected sample data, a multi-period difference-in-differences (DID) model is employed to evaluate the impact of the initiation of the CRE on corporate green innovation. The findings of this study, displayed in the third column of Table 5, confirm the positive impact of the CRE on increasing corporate green innovation skills. The coefficient of the interaction term aligns with the baseline regression results, providing further evidence of the positive effect.

Changing the Method for Designating the Treatment Group

Given the CRE's "hub-and-spoke" operational structure, we test the robustness of our results by redefining the treatment group. Cities such as Chongqing, Chengdu, Zhengzhou, Wuhan, Suzhou, Jinhua, Changsha, Hefei, Shenyang, Dongguan, Xi'an, and Lanzhou are considered the primary sources of commodities. We refer to these cities as "regular operation cities", as they guarantee a minimum of two direct point-to-point trains each week and efficiently manage the scheduling of return trains. The CRE, with its "hub-and-spoke" organizational structure, significantly impacts surrounding areas as these cities operate in a stable manner and radiate their influence [6, 12]. Thus, this study classifies all prefecture-level cities within the provinces of these consistently functioning cities as the treatment group, while other prefecture-level cities are classified as the control group [6]. The regression results from the robustness test show that even after changing the definition method of the treatment group, the impact of the CRE launch on corporate green innovation (Greeninn) remains statistically significant. This outcome suggests that introducing the CRE has a positive impact not only on cities where it operates regularly but also has the potential to expand its reach to a wider region through a ripple effect.

Replace the Dependent Variable

To address concerns about potential measurement error and indicator sensitivity, we conduct a robustness test by replacing the main dependent variable with an alternative measure – namely, the number of green patent

Table 5. Robustness test results.

	IV		PSM+DID	Replace the Independent Variable	Replace the Dependent Variable
Variables	Treat*Post	Greeninn	Greeninn	Greeninn	Greeninn2
IV*Post	0.7058***	-	-	-	-
	(25.54)	-	-	-	-
Treat*Post	-	2.6613*	1.6999***	-	0.6364***
	-	(1.76)	(3.65)	-	(2.94)
Treat*Post2	-	-	-	1.9606***	-
	-	-	-	(3.70)	-
Size	-0.0054*	2.7701***	2.7305***	2.7681***	1.4389***
	(-1.89)	(27.94)	(8.80)	(9.21)	(13.18)
Lev	0.0196	4.4330***	4.2586***	4.4597***	0.4221
	(1.17)	(7.17)	(3.53)	(3.88)	(0.67)
ROA	0.0822***	5.3088***	5.3813***	5.4444***	0.9789
	(4.00)	(6.78)	(4.59)	(4.91)	(1.59)
Tobin'q	0.0014	-0.1364	-0.1390	-0.1429	-0.1269
	(0.67)	(-1.63)	(-0.98)	(-1.08)	(-1.60)
GDP	1.8724***	1.8861***	1.1214***	0.8971***	1.3152***
	(3.26)	(3.91)	(3.12)	(3.86)	(3.51)
Ind	0.0298***	0.0213***	0.0411***	0.0163***	0.0213***
	(2.96)	(3.41)	(4.15)	(5.13)	(5.01)
Facility	0.0971	0.1215	0.0981***	0.2811	0.2141
	(1.12)	(0.86)	(3.02)	(1.12)	(0.62)
Firm	Control	Control	Control	Control	Control
Year	Control	Control	Control	Control	Control
Province*Year	Control	Control	Control	Control	Control
Constant	-12.6832***	-37.5456	-21.3122	-18.7984	-39.2798
	(-7.98)	(-0.61)	(-0.27)	(-0.25)	(-0.88)
Sargan P-value	0.28		-	-	-
Observations	21,292	21,292	15,863	21,292	21,292
Pseudo R2	-	-	0.0408	0.0402	0.0883

authorizations. Patent data are widely used in innovation research for their objectivity and comparability across regions. The dependent variable in the regression analysis presented in the fifth column of Table 5 is the number of green patent authorizations. The results align with the initial regression analysis, providing further evidence that introducing the CRE has a significant and beneficial impact on corporate green innovation. The consistent findings indicate that the introduction of the CRE has a significant impact on promoting corporate green innovation, regardless of the method used.

Mechanism Testing

Financing Constraints

The aforementioned analysis mentioned two important mechanistic pathways through which the opening of the CRE affects corporate green innovation. Initially, we investigated how financial restrictions (SA) affect the relationship between CRE establishment and corporate green innovation (Greeninn). Initially, we derived Models (2) and (3) from Model (1). In Model

(2), the dependent variable is financing limitations, and the impact of the CRE is represented by the interaction term “Treat*Post”. In Model (3), the dependent variable, green innovation, includes both financial limitations and the interaction term “Treat*Post”, which is linked to the opening of the CRE. If the coefficient of financing limitations in Model (2) is significant and the association between financing constraints and green innovation in Model (3) is also statistically significant, this would provide evidence of a mediating influence. Suppose the relationship between financing constraints and green innovation in Model (3) is significant, and the impact of the CRE on financing constraints in Model (2) is also significant. In that case, it suggests that the mediating effect model exhibits a partial mediating effect. On the other hand, if the CRE no longer significantly impacts financing constraints, then the mediating effect model would demonstrate a full mediating effect. Within this framework, funding restrictions (SA index) are established based on the research conducted by Hadlock and Pierce [42]. The SA index serves as a measure of a negative relationship.

$$SA_{i,t} = \beta_0 + \beta_1 Treat_i * Post_t + Control + \mu_i + \gamma_t + \varepsilon_{i,t} \quad (2)$$

$$Greeninn_{i,t} = \beta_0 + \beta_1 Treat_i * Post_t + \beta_2 SA_{i,t} + Control + \mu_i + \gamma_t + \varepsilon_{i,t} \quad (3)$$

Table 6 reports the mediating effect of financing constraints between the opening of the CRE and corporate green innovation in the first and second columns. In Model (2), the coefficient for financing constraints (SA) is 0.0256 ($p<0.01$), indicating a significant positive impact of the CRE opening on financing constraints. In Model (3), the relationship coefficient between financing constraints (SA) and green innovation (Greeninn) is 1.6358 ($p<0.01$), demonstrating a significant positive correlation between financing constraints and green innovation. The interaction term Treat*Post for the CRE opening in Model (3) is 0.0071 ($p<0.01$), indicating a significant positive impact on green innovation, which remains substantial after considering financing constraints. Green innovation activities typically require substantial upfront investment, often accompanied by high uncertainty and risk. Enterprises may struggle to secure sufficient funds to support their green innovation projects in an environment with stringent financing constraints. The opening of the CRE helps to improve logistics efficiency and reduce transportation costs, which can assist enterprises in reducing operational costs, thereby enhancing their financial status and cash flow and alleviating financing constraints. For example, Mao et al. [10] provide evidence that the CRE significantly improves regional credit environments by reducing export costs and stabilizing enterprise revenue streams, thereby increasing firms’ access to external capital. The results of the mechanism test confirm the earlier analysis, indicating that establishing the CRE indirectly stimulates green innovation by improving financial conditions.

Innovation Factor Mobility

Factor mobility refers to the ability of factors of production, such as labor and capital, to move freely between different sectors or regions within an economy. Innovation factor mobility specifically focuses on the movement of innovative ideas, technologies, and knowledge between industries. Expanding on Model (1), Models (4) and (5) were created to examine the mediating influence of innovation factor mobility. The construction technique for innovation factor mobility is based on a study conducted by Wei and Geng [43]. In Model (4), the dependent variable is innovation factor mobility, and the impact of the CRE opening is represented by the interaction term Treat*Post. In Model (5), the dependent variable is green innovation, which includes both innovation factor mobility and the interaction term Treat*Post, which is related to the inauguration of the CRE. If the coefficient for innovation factor mobility in Model (4) is significant and the association between innovation factor mobility and green innovation in Model (5) is also significant, this would provide evidence of a mediating impact.

$$Flow_{i,t} = \beta_0 + \beta_1 Treat_i * Post_t + Control + \mu_i + \gamma_t + \varepsilon_{i,t} \quad (4)$$

$$Greeninn_{i,t} = \beta_0 + \beta_1 Treat_i * Post_t + \beta_2 Flow_{i,t} + Control + \mu_i + \gamma_t + \varepsilon_{i,t} \quad (5)$$

In Model (4), the coefficient for the flow of innovation factors (Flow) is 8.4407 ($p<0.01$), indicating that establishing the CRE greatly enhances the movement of innovation components. In Model (5), the correlation coefficient between the flow of innovation factors (Flow) and green innovation (Greeninn) is 1.7882 ($p<0.01$), indicating a statistically significant and positive association between the two variables. The interaction term Treat*Post coefficient in Model (5) is 0.0152 ($p<0.01$), suggesting a statistically significant and positive effect on green innovation. This effect remains significant even after taking into account other innovation determinants. The CRE serves as a logistics conduit that enables the transfer of technology, talent, and information across borders, facilitating innovation flow between China and Europe. This mobility enables firms to gain new knowledge and technology, boost creative thinking, and foster environmentally friendly innovation. For instance, since 2020, the Xi’an International Trade and Logistics Park – one of the key hubs of the China-Europe Railway Express – has attracted several European technology firms, particularly

Table 6. Results of mechanism testing.

	Mediator Variable: Financing Constraints		Mediator Variable: Innovation Factor Mobility	
Variables	SA	Greeninn	Flow	Greeninn
Treat*Post	0.0256***	1.6358***	0.0071***	1.7882***
	(3.09)	(3.67)	(4.01)	(3.94)
SA	-	7.8302***	-	-
	-	(6.93)	-	-
Flow	-	-	-	8.4407***
	-	-	-	(3.13)
Size	-0.0096	2.7064***	-0.0083***	2.8306***
	(-1.61)	(9.86)	(-10.28)	(9.29)
Lev	-0.1158***	5.4017***	-0.0565***	4.9184***
	(-5.09)	(4.80)	(-8.98)	(4.29)
ROA	0.0259	5.0937***	-0.1533***	6.5686***
	(1.37)	(4.70)	(-17.20)	(5.64)
Tobin'q	0.0017	-0.1514	0.0091***	-0.2022
	(0.67)	(-1.18)	(10.22)	(-1.52)
GDP	1.2186***	0.9161***	1.1646***	0.9781***
	(4.01)	(3.52)	(3.63)	(3.17)
Ind	0.1271***	0.0979***	0.0513***	0.0819***
	(2.89)	(3.61)	(4.25)	(4.21)
Facility	0.0712	0.0818	0.0152	0.1643
	(1.09)	(0.56)	(3.16)	(1.11)
Firm	Control	Control	Control	Control
Year	Control	Control	Control	Control
Province*Year	Control	Control	Control	Control
Constant	-3.8158***	-13.2092	0.0061	-49.6716
	(-3.80)	(-0.18)	(0.01)	(-0.67)
Observations	21,292	21,292	21,292	21,292
R-squared/Pseudo R2	0.200	0.0464	0.280	0.0408

in the fields of precision machinery, environmental monitoring, and smart logistics. Some companies have engaged in joint R&D and personnel exchange programs with local manufacturers. Additionally, the China-Germany SME Cooperation Park in Chengdu, co-established by the Chengdu High-tech Zone and German Chambers of Commerce, has emerged as a key platform for cross-border flows of green technologies and innovation talent. These cases demonstrate that the CRE does not merely serve as a trade corridor but also as a dynamic platform that enhances cross-regional innovation ecosystems. The inauguration of the CRE has the potential to provide businesses along the route with cutting-edge European technology and management expertise, accelerating the process of environmentally friendly innovation through the transfer of technology and the exchange of skilled personnel.

Heterogeneity Test

This study conducts heterogeneity analyses across dimensions of ownership structure, degree of internationalization, firm size, regional differences, and industry characteristics. A summary of the empirical results is presented in Table 7, with detailed discussions provided in the subsequent sections.

Table 7. Summary of empirical findings from the heterogeneity analysis.

Heterogeneity Aspect	Operationalization	Conclusion
Property Rights	Subsample regression dividing SOEs and NSOEs with a DID model	NSOEs show significant green innovation improvement (coefficient 2.2191***), while SOEs show no significant effect (coefficient -0.3589)
Internationalization Level	Grouping by overseas revenue ratio (high vs. low internationalization)	The low-internationalization group shows significant improvement (coefficient 1.9111***), while the high-internationalization group shows no significant effect (coefficient 1.3461)
Firm Size	Division into large and small firms based on a provincial annual median size	Small firms show stronger improvement (coefficient 1.7377***) compared to large firms (coefficient 1.5232*)
Regional Disparities	Regression analysis for Eastern, Central, and Western regions separately	The central region shows the strongest effect (coefficient 4.5971***), followed by the eastern region (1.2745**), with no significant effect in the western region (0.8666)
Industry Heterogeneity	Comparative regression for high-tech, medium-tech, and traditional manufacturing sectors	High-tech manufacturing shows the strongest effect (coefficient 3.1125***), followed by medium-tech (2.1753***) and traditional manufacturing (1.1841**)

Heterogeneity Tests of Property Rights

According to Yang and Tsou [44], non-state-owned firms (NSOEs) are more inclined to engage in international trade and improve their ability to innovate independently in the current economic climate than state-owned enterprises (SOEs). Non-state-owned enterprises (NSOEs) frequently face credit discrimination when seeking financing, as documented by Aivazian et al. [45] and Cull and Xu [46]. This discrimination leads to more stringent financing limitations and further exacerbates the resource disparity between state-owned enterprises (SOEs) and NSOEs.

This heterogeneity test seeks to investigate whether establishing the CRE can mitigate the problem of resource misallocation due to unequal property rights. The property rights heterogeneity test allows us to better understand how the CRE affects the green innovation capabilities of enterprises with varying ownership structures. This provides empirical evidence to support effective resource allocation and improve overall economic efficiency. The sample is divided into state-owned and non-state-owned groups for separate regression analysis. The property rights heterogeneity test findings are displayed in the first and second columns of Table 8. Within the NSOE group, the interaction term "Treat*Post" coefficient for the opening of the CRE is 2.2191 ($p<0.01$), suggesting that the opening of the CRE has a significant positive effect on promoting green innovation in NSOEs. Within the SOE group, the coefficient of the interaction term "Treat*Post" for the opening of the CRE is -0.3589.

However, this coefficient is not statistically significant, indicating that the opening of the CRE does not significantly impact the green innovation of SOEs. This indicates possible inefficiencies in the allocation of resources for state-owned enterprises (SOEs) and their slow response to external market information. NSOs have superior resource allocation efficiency and flexibility in comparison to SOEs. The factors of production in non-state-owned enterprises (NSOEs) possess greater mobility and agility, allowing them to promptly adapt to market fluctuations. On the other hand, state-owned enterprises (SOEs) have limited skills to receive and adapt to external market information due to their internal institutional arrangements. Non-state-owned enterprises (NSOEs) show increased responsiveness to external market data and are better equipped to utilize this knowledge to enhance their capabilities and drive for environmentally friendly innovation. This disparity can affect businesses' innovative reactions when faced with external prospects, particularly in the realm of eco-friendly innovation, where businesses must quickly adopt and implement new technology and concepts to achieve sustainable growth. Moreover, NSOEs are often under greater competitive pressure and performance scrutiny in market environments, incentivizing them to pursue innovation proactively in order to maintain their competitive edge. The CRE reduces logistics costs and improves market accessibility, directly translating into stronger marginal returns for NSOEs seeking to expand into overseas markets or access foreign technologies. These firms are more likely to leverage the connectivity gains from the CRE to explore environmentally sustainable practices, adopt cleaner production processes, and engage in international green technology collaboration. In contrast, SOEs – often cushioned by state support – may lack such market-driven incentives to rapidly adjust their innovation strategies in response to infrastructural developments. This institutional inertia can significantly dampen their responsiveness to policy or logistical shocks, including the expansion of international transport corridors such as the CRE.

Degree of Internationalization

The degree of internationalization of a company is a crucial metric for evaluating its global strategic layout and international competitiveness. It reflects both a company's degree of participation in the global market and its ability to allocate resources, expand into new markets, and manage risks. As globalization continues to advance, the varying degrees of internationalization among enterprises have an increasingly significant impact on the diverse outcomes of policy results.

The China-Europe Railway Express (CRE), a crucial part of the "Belt and Road" initiative, has had a profound influence on commercial interactions among countries and businesses along its route. However, this impact is not evenly distributed among all companies but is instead influenced by the extent of their internationalization. Segmented regression analysis provides a more accurate identification and interpretation of this heterogeneity. Our measure of a company's degree of internationalization is the ratio of its sales revenue generated outside mainland China to its total sales revenue. This indicator precisely reflects the company's involvement in the global market and its capacity to successfully enter foreign markets. To examine the specific impact of internationalization on the green innovation effect of the CRE strategy, we standardized the degree of internationalization of enterprises by calculating the average for each year and province. Using this information, we created a binary variable to distinguish between organizations with a high degree of internationalization and those with a low degree. More specifically, if a firm's degree of internationalization exceeds the average value of its province in a given year, the dummy variable is set to 1. Conversely, if the firm's degree of internationalization is below the provincial average for that year, the dummy variable is set to 0. The regression results are displayed in the third and fourth columns of Table 8, respectively. The findings show that among firms with a low degree of internationalization, the coefficient of the interaction term for the opening of the CRE is 1.9111. The statistical significance level is below 0.01, indicating that the opening of the CRE has a substantial

Table 8. Results of the property rights heterogeneity test.

	SOE	Non-SOE	High degree of internationalization	Low degree of internationalization
Variables	Greeninn	Greeninn	Greeninn	Greeninn
Treat*Post	-0.3589	2.2191***	1.3461	1.9111***
	(-0.38)	(4.37)	(1.63)	(4.19)
Size	3.6268***	1.9938***	3.5674***	2.0288***
	(6.67)	(5.77)	(7.16)	(7.36)
Lev	3.4962	4.4855***	6.8703***	3.8156***
	(1.33)	(3.82)	(3.14)	(3.42)
ROA	1.6239	7.4043***	7.4068***	4.0897***
	(0.77)	(5.88)	(3.59)	(3.70)
Tobin'q	-0.1135	-0.0898	0.6053**	-0.4319***
	(-0.35)	(-0.65)	(2.55)	(-3.26)
GDP	0.8186***	0.8971***	1.1079***	0.9143***
	(4.16)	(3.12)	(3.17)	(3.82)
Ind	0.1179***	0.1218***	0.0971***	0.0946***
	(2.91)	(3.11)	(4.12)	(4.95)
Facility	0.1311	0.1142	0.0178	0.0684
	(0.49)	(0.71)	(3.74)	(1.01)
Constant	-147.4906	7.1377	2.4557	-63.1986
	(-1.37)	(0.07)	(0.01)	(-0.84)
Firm	Control	Control	Control	Control
Year	Control	Control	Control	Control
Province*Year	Control	Control	Control	Control
Observations	5,503	15,345	6,778	14,514
Pseudo R2	0.0543	0.0338	0.0482	0.0332

and positive impact on the green innovation activities of this particular group of firms. The ability of enterprises to access new markets and benefit from the convenient logistics of the CRE has led to reduced costs for green innovation and enhanced international competitiveness.

In particular, less internationalized firms tend to face higher initial barriers to cross-border expansion, including insufficient international logistics infrastructure, limited exposure to foreign innovation systems, and weak overseas networks. The launch of the CRE helps overcome these limitations by lowering transportation costs, expanding export channels, and improving information access, thereby enabling these firms to integrate more effectively into global value chains. This external connectivity acts as a catalyst, especially for firms that were previously constrained in their international operations, pushing them to adopt cleaner production practices and participate in environmentally oriented international collaboration.

Moreover, establishing the CRE may facilitate the transfer of technology and expertise across borders, providing these companies with new ideas and solutions for environmentally friendly advancements. However, among enterprises with a higher degree of internationalization, the Treat*Post coefficient did not meet the criteria for statistical significance. This suggests that CRE establishment has little impact on the green innovation activities of this particular group of firms. This could be because these enterprises already have strong talent in global market development and resource allocation. It is possible that they have already achieved green innovation through other means. As a result, establishing the CRE had a limited impact on them. Furthermore, highly internationalized firms often possess well-established overseas logistics frameworks and diversified innovation channels, making the marginal benefits of additional infrastructure, such as the CRE, relatively insignificant. In addition, these companies may have developed more advanced global supply chains and alliances, and the inauguration of the CRE has a lesser impact on their logistical and market strategies.

Firm Size Heterogeneity

According to prior studies, firm size plays a pivotal role in shaping corporate behavior, particularly in relation to innovation capabilities and resource allocation. Larger firms typically benefit from superior access to resources, extensive networks, and a greater capacity to absorb risks, enabling them to engage in innovation activities with greater consistency and scale. In contrast, smaller firms often encounter resource constraints and must rely on their adaptability and operational efficiency to remain competitive in dynamic markets. This heterogeneity test seeks to investigate whether establishing the CRE influences green innovation differently across firms of varying sizes. For this analysis, firms were grouped based on each province's annual median firm size. Firms with a size greater than or equal to the provincial annual median were classified as "large firms" (assigned a value of 1), whereas those below the median were categorized as "small firms" (assigned a value of 0). This grouping enables a more granular understanding of how firm size affects the capacity to leverage the CRE for green innovation.

The heterogeneity test results are summarized in Table 9. The first column presents the regression results for large firms, while the second column shows the results for small firms. For large firms, the interaction term "Treat*Post" coefficient is 1.5232, which is positive but only statistically significant at the 10% level. This indicates that while establishing the CRE has a positive effect on green innovation for large firms, the impact remains relatively modest. By contrast, for small firms, the "Treat*Post" coefficient is 1.7377, which is positive and statistically significant at the 1% level, suggesting that the CRE exerts a more pronounced and significant influence on green innovation among smaller firms.

Several underlying mechanisms may account for this difference. First, small firms often exhibit higher marginal returns from external policy and infrastructure shocks, such as the CRE, since they start from a lower baseline in terms of market access, logistical capabilities, and innovation inputs. The CRE provides them unprecedented access to international logistics channels, enabling them to reach new markets, expand sales, and reinvest profits into environmentally friendly technologies. Second, small firms tend to be more organizationally flexible and adaptive, allowing them to respond swiftly to new opportunities created by improved trade routes. Third, reducing trade-related costs afforded by the CRE would be particularly impactful for small firms, which typically operate under tighter budget constraints and face higher relative transaction costs in international trade. Conversely, large firms, despite their abundant resources, may respond more sluggishly due to institutional inertia and the complexities of bureaucratic structures. Additionally, their already established logistics systems and diversified innovation portfolios may reduce the marginal benefit derived from the CRE. As such, the transformative impact of the CRE is more prominent among small firms, which are better positioned to internalize and act upon the CRE-driven externalities.

Regional Heterogeneity

Disparities in regional economic development, industrial structure, and resource allocation profoundly influence firms' capacity to adopt and implement green innovation. The heterogeneity test, based on regional divisions, seeks to explore whether establishing the CRE exerts differing impacts on green innovation across the eastern, central, and western regions, given their unique economic and industrial characteristics. For this analysis, the sample was categorized into three

Table 9. Test results of scale heterogeneity and regional heterogeneity.

	Large Firm Size	Small Firm Size	Eastern Region	Central Region	Western Region
Variables	Greeninn	Greeninn	Greeninn	Greeninn	Greeninn
Treat*Post	1.5232*	1.7377***	1.2745**	4.5971***	0.8666
	(1.91)	(4.84)	(2.28)	(3.88)	(0.72)
Size	4.3857***	1.3378***	2.7769***	3.0072***	2.6318***
	(7.89)	(4.33)	(7.20)	(4.92)	(4.05)
Lev	7.6482***	2.5966***	4.5215***	5.0984*	2.4293
	(3.64)	(2.79)	(3.06)	(1.95)	(1.03)
ROA	6.4855***	3.3894***	6.6180***	1.7281	5.0621**
	(3.73)	(3.35)	(4.45)	(0.76)	(2.50)
Tobin'q	0.1508	-0.3299***	0.0733	-0.3616	-0.9655***
	(0.61)	(-2.74)	(0.45)	(-1.36)	(-3.23)
GDP	1.2737**	1.1425***	0.9333**	2.0946***	1.4420
	(2.22)	(3.80)	(2.03)	(3.27)	(1.54)
Ind	-0.0505	-0.0470*	-0.1043**	-0.0018	-0.0026
	(-0.89)	(-1.74)	(-2.33)	(-0.02)	(-0.04)
Facility	0.1521	-0.5113	-0.8078	1.3578	-1.6919
	(0.15)	(-0.98)	(-0.89)	(1.30)	(-1.26)
Firm	Control	Control	Control	Control	Control
Year	Control	Control	Control	Control	Control
Province*Year	Control	Control	Control	Control	Control
Constant	-88.0791	18.7478	-99.0344	-232.6397	-352.5949
	(-0.78)	(0.23)	(-0.89)	(-0.70)	(-1.45)
Observations	9,569	11,723	15,024	3,094	3,174
Pseudo R2	0.0416	0.0216	0.0351	0.0539	0.0621

groups: eastern, central, and western regions, following the standard provincial classification in China. This approach allows for a nuanced understanding of how regional disparities shape the CRE's effectiveness in promoting green innovation.

The regression results, presented in Table 9, offer separate estimates for each region. In the eastern region, the interaction term "Treat*Post" coefficient is 1.2745 and statistically significant at the 5% level. This modest positive effect reflects the region's advanced economic development, robust industrial base, and superior innovation infrastructure. Firms in the eastern region already benefit from mature logistics networks and extensive access to international markets, which may reduce the marginal benefits of the CRE. However, the CRE still provides incremental advantages by further enhancing trade efficiency and facilitating access to green technologies, thereby fostering green innovation. The relatively smaller effect size suggests that infrastructure improvements yield diminishing returns in highly developed regions. In the central region, the "Treat*Post" coefficient is 4.5971 and statistically significant at the 1% level, indicating a markedly stronger positive effect of the CRE on green innovation. This result can be attributed to the central region's transitional role as a bridge between the economically advanced eastern region and the resource-rich western region. The CRE offers a critical opportunity for firms in the central region to enhance connectivity with international markets, lower logistical costs, and access advanced technologies. Moreover, the region's balanced industrial structure and growing emphasis on industrial upgrading will enable firms to leverage the CRE effectively to accelerate green innovation. This substantial positive impact highlights the central region as a key beneficiary of the CRE. In contrast, in the western region, the "Treat*Post" coefficient is 0.8666 and not statistically significant. This limited impact underscores the structural challenges firms face in this region, including a less developed industrial base, weaker technological capabilities, and constrained access to financial resources. Geographical remoteness and infrastructural deficits further hinder the CRE's ability to drive significant innovation gains. Specifically, many western provinces lack high-density industrial clusters and innovation hubs, resulting in weaker agglomeration effects and lower knowledge spillovers. Moreover, the region's relatively limited exposure to global markets restricts the diffusion of advanced technologies and green practices. In addition, the financing environment in the West is less favorable, with firms encountering higher credit constraints and fewer institutional support channels for innovation. The mismatch between the advanced logistics capacity brought by the CRE and the local firms' absorptive capacity limits the translation of transportation advantages into innovation performance. While the CRE holds the potential to reduce transportation costs, firms in the Western region often lack the capacity to capitalize on these benefits for innovation.

Intra-Industry Heterogeneity

A regression analysis incorporating data from all industries was conducted to address the limitations of focusing exclusively on listed manufacturing firms and enhance the generalizability of the findings. This broader analysis aims to determine whether the CRE's influence on green innovation extends beyond the manufacturing sector and to explore its potential effects on other sectors, such as services and agriculture. The results for all industries, presented in Table 10, reveal that the interaction term "Treat*Post" coefficient is 0.0882, significant at the 10% level. This indicates that while the CRE positively impacts green innovation across all industries, the effect is relatively modest. Compared to the manufacturing subcategories, the smaller effect size reflects varying degrees of reliance on cross-border trade and logistics infrastructure across different sectors. For instance, industries such as services and agriculture may indirectly benefit from

Table 10. Results of intra-industry heterogeneity test.

	All Industries	High-Tech Manufacturing	Medium-Tech Manufacturing	Traditional Manufacturing
Variables	Greeninn	Greeninn	Greeninn	Greeninn
Treat*Post	0.0882*	3.1125***	2.1753***	1.1841**
	(1.91)	(6.45)	(5.32)	(2.48)
Size	1.6601***	5.8427***	4.2271***	3.1543***
	(6.45)	(7.89)	(6.14)	(5.03)
Lev	0.3073	7.2216***	5.0134**	4.0931**
	(0.28)	(4.21)	(2.45)	(2.10)
ROA	4.9130***	6.3124***	4.3875***	2.5486**
	(4.97)	(3.67)	(3.22)	(2.01)
Tobin'q	0.0109	0.2521	-0.3156**	-0.8242***
	(0.10)	(0.92)	(-2.31)	(-3.84)
GDP	0.9748***	1.7423**	1.2714*	0.8746
	(2.95)	(2.34)	(1.91)	(1.15)
Ind	0.0140	-0.0541	-0.0925	-0.1343
	(0.45)	(-1.21)	(-1.65)	(-1.88)
Facility	0.0443	0.3274	0.1753	-0.0724
	(0.08)	(1.54)	(1.12)	(-0.41)
Firm	Control	Control	Control	Control
Year	Control	Control	Control	Control
Province*Year	Control	Control	Control	Control
Constant	-27.2744	-45.1243	-67.3251	-92.1587
	(-0.45)	(-0.76)	(-0.89)	(-1.02)
Observations	32,584	9,421	7,182	4,689
Pseudo R2	0.0225	0.0715	0.0538	0.0376

enhanced supply chain efficiency and improved market access, yet the CRE less directly influences them than manufacturing. This finding underscores the critical importance of logistics and international connectivity for trade-dependent industries like manufacturing while highlighting the CRE's broader, albeit less pronounced, potential to foster green innovation across a wider array of sectors.

In addition to this all-industry analysis, the study further dissects the manufacturing sector into three subcategories: high-tech, medium-tech, and traditional manufacturing. This classification is based on technological intensity, innovation capacity, and reliance on global supply chains, following established frameworks in industrial economics and innovation studies. High-tech manufacturing industries, such as electronics, pharmaceuticals, and aerospace, are characterized by their significant R&D investments, dependence on cutting-edge technologies, and sensitivity to international logistics. Medium-tech manufacturing, including automotive and machinery, balances technological innovation with traditional production methods, demonstrating moderate reliance on trade and supply chains. Traditional manufacturing, such as textiles and furniture, is labor-intensive and oriented towards local or regional markets, with limited innovation activity and low reliance on advanced logistics. High-tech industries are expected to exhibit the strongest response to the CRE due to their dependence on global markets and advanced infrastructure, while medium-tech and traditional industries show progressively smaller effects due to their lower trade reliance and innovation intensity. The results, detailed in Table 10, confirm this heterogeneity. For high-tech manufacturing, the "Treat*Post" coefficient is 3.1125, which is significant at the 1% level. This result highlights the substantial benefits of the CRE for high-tech industries, which leverage international markets and advanced logistics to foster green innovation. The CRE reduces logistical barriers, enhances access to global resources, and enables these industries to enhance their green innovation capacity, reflecting their high sensitivity to supply chain improvements. In particular, high-tech sectors often require timely access to international technological components, specialized materials, and cross-border R&D collaboration, all of which are facilitated by the CRE. The enhanced predictability, frequency, and connectivity offered by the CRE not only reduce transportation costs but also improve supply chain resilience, which is crucial for innovation cycles in high-tech production. Furthermore, these sectors face intense competitive pressure to continuously upgrade technologies and comply with environmental regulations in export markets, making them more likely to exploit the CRE's logistical advantages to implement green innovation strategies.

In medium-tech manufacturing, the "Treat*Post" coefficient is 2.1753, which is also significant at the 1% level. While the impact is slightly smaller than in high-tech manufacturing, it remains substantial. Medium-tech industries benefit from logistical enhancements and trade facilitation, but their moderate reliance on global integration results in a smaller effect size than high-tech industries. For traditional manufacturing, the "Treat*Post" coefficient is 1.1841, which is significant at the 5% level. The positive but smaller impact reflects the limited reliance of traditional industries on international logistics and their focus on local markets. These industries exhibit lower innovation intensity and rely more on incremental improvements, constraining their ability to fully leverage the CRE's benefits.

Conclusion

The empirical results of this study demonstrate that the China-Europe Railway Express (CRE) has a significant and positive impact on corporate green innovation, with particularly pronounced effects on substantive green innovation. In the baseline regression, the Treat*Post coefficient for overall green innovation is 1.8563 ($p<0.01$), while for substantive green innovation (Greeninn_inv), it is 1.4873 ($p<0.01$), and for strategic green innovation (Greeninn_uti), 1.0815 ($p<0.01$). These findings underscore the transformative role of CRE in enhancing firms' green innovation capacity and advancing sustainable industrial development. Unlike strategic green innovation, which is often shaped by external policy frameworks or market demands, substantive green innovation represents deeper technological advancements driven by substantial R&D investments.

This study identifies two key mechanisms through which CRE fosters green innovation. First, by alleviating financial constraints, CRE enables firms to allocate more resources to green projects. In the mechanism tests, the Treat*Post coefficient on financial constraints (SA) is 0.0256 ($p<0.01$), and the impact of SA on green innovation is 7.8302 ($p<0.01$), while the indirect effect remains significant with Treat*Post at 1.6358 ($p<0.01$). Improved access to funding supports long-term R&D investments, thereby facilitating the development of advanced green technologies. These results empirically validate the role of CRE in improving firms' financial environments to support innovation. Second, CRE promotes the cross-border flow of innovation resources, accelerating technological diffusion and knowledge sharing. In this mechanism, Treat*Post significantly increases innovation factor mobility (Flow), with a coefficient of 0.0071 ($p<0.01$). Flow, in turn, positively influences green innovation with a coefficient of 8.4407 ($p<0.01$), and the corresponding indirect pathway remains significant with Treat*Post at 1.7882 ($p<0.01$). By integrating firms into global innovation networks, CRE enhances the exchange of expertise and green technologies, fostering competitive advantages in international markets.

The heterogeneity analysis reveals the nuanced nature of CRE's impact across different firm characteristics. The results indicate that non-state-owned enterprises (NSOEs) benefit more from CRE than state-owned enterprises (SOEs). The regression results show a significant effect for NSOEs (coefficient = 2.2191, $p<0.01$) but no significant effect for SOEs (coefficient = -0.3589). This is consistent with prior studies suggesting that NSOEs are more responsive to market dynamics and exhibit greater efficiency in resource allocation. Their flexible governance structures and greater operational autonomy allow them to rapidly adapt to policy opportunities such as CRE. Conversely, SOEs may suffer from bureaucratic rigidity and delayed internal decision-making, hindering their ability to leverage CRE for green innovation.

Similarly, firms with lower degrees of globalization experience stronger benefits from CRE, likely due to their heavier reliance on improved logistics and expanded international market access facilitated by the railway. The interaction term for low-internationalization firms is 1.9111 ($p<0.01$), while it is 1.3461 (not significant) for highly internationalized firms. Enterprises with limited global integration tend to depend more on the logistic facilitation and market linkages brought by CRE, whereas highly internationalized firms may already possess sophisticated supply chains and face diminishing marginal benefits from additional infrastructure improvements.

In terms of firm size, the analysis shows that smaller firms gain more from CRE compared to larger firms. The Treat*Post coefficient is 1.7377 ($p<0.01$) for small firms and 1.5232 ($p<0.1$) for large firms. Smaller firms, known for their flexibility and agility, are better equipped to capitalize on enhanced logistics and market connectivity. Conversely, larger firms, despite their resource advantages, may exhibit relatively weaker responses due to institutional inertia and more complex internal decision-making structures. This suggests that CRE plays a critical role in reducing logistical barriers for smaller firms, promoting a more equitable innovation ecosystem.

The regional heterogeneity analysis further demonstrates that the CRE's positive impact on green innovation is most pronounced in central regions, followed by eastern regions, while the effect in western regions is not statistically significant. The regression results show coefficients of 4.5971 ($p<0.01$) for the central region, 1.2745 ($p<0.05$) for the eastern region, and 0.8666 (not significant) for the western region. As transitional hubs between the developed eastern areas and resource-abundant western areas, central regions appear better positioned to capitalize on the CRE's benefits. In contrast, the limited industrial capacity, underdeveloped R&D infrastructure, and logistical bottlenecks in the western region constrain the CRE's effectiveness in driving innovation. This highlights the need for tailored support policies to overcome structural obstacles and unlock green growth potential in lagging regions.

Extending the analysis to all industries reveals that the positive effect of CRE on green innovation is smaller than its impact within the manufacturing sector. In the all-industry regression, the coefficient is 0.0882 ($p<0.1$), suggesting a more moderate effect outside of manufacturing. This reflects differences in logistics dependence across sectors, with manufacturing being particularly reliant on global supply chains.

A subcategory analysis uncovers notable differences within the manufacturing sector: high-tech manufacturing, which relies heavily on advanced supply chains and international markets, benefits most significantly from CRE. The coefficient for high-tech firms is 3.1125 ($p<0.01$), followed by 2.1753 ($p<0.01$) for medium-tech and 1.1841 ($p<0.05$) for traditional industries. These differences are consistent with theoretical expectations – high-tech firms are more sensitive to infrastructure quality and international linkages, while traditional sectors with localized markets and low R&D intensity respond less strongly to transnational infrastructure improvements.

Discussion

This study significantly advances the existing body of literature on transportation infrastructure by extending the analysis to a transnational framework, particularly focusing on its micro-level impacts on firm-level innovation. Previous research has predominantly investigated the role of high-speed rail (HSR) in fostering green governance, emphasizing its contributions to urban low-carbon transitions, technological innovation, transport substitution, and structural adjustments [12-17, 26, 47]. However, the discourse has largely centered on domestic corridors. This study illuminates its firm-level environmental implications by shifting the focus to transnational transportation infrastructure, epitomized by the China-Europe Railway Express (CRE). The findings reveal that CRE not only fosters significant enhancements in green innovation but also advances substantive green innovation, broadening the understanding of infrastructure's role in promoting sustainability.

The positive outcomes associated with CRE are particularly impactful when examined within the broader global trade framework and the United Nations Sustainable Development Goals (SDGs). By enhancing connectivity between China and Europe, CRE strengthens global supply chains, reduces transportation costs, and facilitates the seamless exchange of goods and services across borders. These efficiencies not only bolster firms' competitiveness but also incentivize the adoption of green technologies and practices that align with international environmental standards. For instance, the streamlined trade logistics enabled by CRE directly contribute to fostering sustainable industrialization and technological advancement. Simultaneously, the transition to greener practices facilitated by enhanced international connectivity supports SDG 13 (Climate Action) by encouraging resource efficiency and lowering carbon emissions in production systems.

The mechanisms through which CRE operates - namely, alleviating financing constraints and facilitating the cross-border flow of innovation resources - also resonate with global trade dynamics. By improving firms' access to international markets, CRE integrates them into global value chains, accelerating the diffusion of environmentally friendly production techniques and green technologies. This integration acts as a catalyst for a greener global economy by compelling firms to conform to international sustainability benchmarks. Furthermore, by lowering barriers to technology transfer, CRE enables under-resourced firms, particularly those in developing regions, to capitalize on cutting-edge innovations, fostering more inclusive and equitable trade practices.

The heterogeneity analysis deepens this understanding by illustrating how CRE's impact on green innovation differs across firms and regions, providing key insights into its potential to drive regional development. Central regions, which benefit the most from CRE, exemplify its role as a logistical and industrial hub aligned with broader regional development objectives. CRE's facilitation of industrial upgrading in these regions contributes to reducing regional disparities. Conversely, the comparatively limited effects observed in Western regions underscore the importance of tailored policy interventions to ensure that the advantages of CRE are equitably shared. This dual role of CRE as a trade facilitator and a driver of spatially balanced development underscores its multifaceted utility.

By embedding green innovation within the context of global trade and sustainability, CRE facilitates systemic transformations that extend beyond individual firms or regions. Its pronounced positive effects on high-tech and medium-tech industries exemplify its capacity to act as a driver for cleaner and more sustainable production models. This shift aligns with the principles of a circular economy, which emphasizes resource efficiency and regenerative practices over linear consumption patterns. Promoting green innovation within these industries not only enhances their global competitiveness but also strengthens broader efforts toward climate neutrality and sustainable economic growth.

Implications for Practice

Building upon the empirical findings of this study, three strategic policy recommendations are proposed to unlock the full potential of the China-Europe Railway Express (CRE) in advancing corporate green innovation and fostering sustainable development. First, enhancing targeted financial mechanisms is imperative to address the critical issue of financing constraints that limit firms' ability to invest in green innovation. Non-state-owned enterprises (NSOEs) and smaller firms, which have demonstrated heightened responsiveness to CRE, require customized financial support to capitalize on the railway's enhanced logistics and market access. Policymakers should consider implementing preferential loans, green innovation subsidies, and tax incentives for R&D activities. Specifically, financial institutions could be guided to develop CRE-linked green credit instruments and risk-sharing mechanisms for small and medium-sized enterprises (SMEs). Government-backed innovation funds could be earmarked for high-risk, long-cycle green R&D projects aligned with CRE logistics corridors. These measures would alleviate financial barriers, enabling firms to channel greater resources into substantive green innovation. Such interventions are particularly critical in the central and western regions, where capital markets are underdeveloped and access to commercial financing is limited, thus requiring stronger public-sector involvement to offset regional disparities.

Second, region-specific policies are critical to addressing the disparities in CRE's impact across different geographical regions. Central regions, which have shown the most significant response to CRE, should be prioritized for additional investments in green innovation ecosystems. Establishing regional innovation hubs could foster collaboration among firms, research institutions, and international stakeholders, accelerating technology transfer and the adoption of advanced green practices. These hubs could be supported through targeted fiscal transfers, industrial cluster development plans, and cross-border research platforms integrated with CRE logistics nodes. Conversely, in Western regions, where CRE's impact remains limited, targeted measures such as industrial upgrading initiatives, infrastructure development, and workforce training programs are necessary to strengthen their capacity to leverage CRE's advantages. For instance, policies could support the deployment of digital infrastructure (e.g., smart logistics, supply chain digitization) in western CRE terminals, along with subsidies for vocational training in green manufacturing and export-oriented skills.

Finally, sector-specific policies should be formulated to amplify CRE's role in driving green innovation across industries. For high-tech manufacturing industries, which derive the greatest benefits from CRE, policies aimed at integrating them into global supply chains and enhancing advanced logistics infrastructure are essential. This includes expanding bonded logistics zones, optimizing customs clearance procedures for R&D-intensive goods, and incentivizing international R&D collaboration through CRE-supported export channels. Medium-tech industries, such as the automotive and machinery sectors, require support for adopting cleaner production technologies and fostering incremental innovation. Traditional industries, including textiles and furniture, could benefit from localized training programs and access to cost-effective green technologies to facilitate their transition toward sustainable practices. A national CRE-Linked Green Technology Exchange Platform could be established to facilitate the flow of green solutions to traditional industries through targeted dissemination and adoption support. Beyond the manufacturing sector, the broader potential of CRE to promote green logistics and sustainability in services and agriculture should be realized through targeted incentives and the creation of collaborative platforms. Examples include pilot programs for green supply chain certification in agricultural exports or subsidies for digital logistics platforms in service-based CRE nodes.

Limitations and Future Research Directions

While this study provides valuable insights into the impact of the China-Europe Railway Express (CRE) on corporate green innovation, certain limitations remain. Despite incorporating a comprehensive analysis across all industries, the reliance on publicly available data may restrict the generalizability of the findings to privately owned enterprises or smaller firms with limited data representation. Moreover, the ten-year study period offers substantial evidence of medium-term effects but may not adequately reflect the long-term dynamics of CRE, as infrastructure projects often exhibit evolving impacts over extended timeframes in response to changing economic conditions, technological advancements, and policy frameworks.

The study also relies heavily on secondary data sources, which, while extensive and reliable, may introduce inherent biases or fail to capture unobserved factors influencing green innovation and financial constraints. These could include informal institutional influences, nuanced regional policy dynamics, or industry-specific challenges that remain beyond the scope of the current analysis.

Future research could build upon these findings by exploring the persistence and evolution of CRE's impacts over longer time horizons, providing a deeper understanding of its sustained role in shaping green innovation. Additionally, examining how CRE interacts with global trade systems and international sustainability frameworks would offer richer insights into its broader implications. Comparative analyses across diverse countries and regions could further illuminate how varying economic contexts and institutional frameworks shape the effectiveness of transnational infrastructure projects like CRE. Lastly, investigating the interplay between CRE and emerging digital technologies could uncover new pathways for promoting environmentally sustainable industrial transformation, offering a more comprehensive perspective on the synergies between physical and digital infrastructure advancements.

Conflict of Interest

The authors declare no conflict of interest.

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References

1. ZHANG X., WANG Z. Implicit Government Guarantee and Corporate Investment: Evidence from China' s Belt and Road Initiative. Emerging Markets Finance and Trade, **59** (2), 528, **2022**.
2. NG A.K.Y., JIANG C., LI X., O'CONNOR K., LEE P.T.-W. A conceptual overview on government initiatives and the transformation of transport and regional systems. Journal of Transport Geography, **71**, 199**, 2017**.
3. LEE P.T.W., HU Z.-H., LEE S.-J., CHOI K.-S., SHIN S.-H. Research trends and agenda on the Belt and Road (B&R) initiative with a focus on maritime transport. Maritime Policy & Management, **45** (3), 282, **2018**.
4. JIANG Y., SHEU J.-B., PENG Z., YU B. Hinterland patterns of China Railway (CR) Express in China under the Belt and Road Initiative: A preliminary analysis. Transportation Research Part E: Logistics and Transportation Review, **119,** 189, **2018**.
5. HE P., TIAN X., ZHANG J., YU S., LI S., LIN C., CHEN L., QIAN L. Can the China-Europe Railway Express reduce carbon dioxide emissions? New mechanism of the manufacturing industry substitution effect. Economic Analysis and Policy, **82,** 1384, **2024.**
6. HE P., ZHANG J., XU X., LIN C., CHEN L. Unintended environmental gains: The impact of China-Europe Railway Express on carbon dioxide emissions in China. Transport Policy, **153**, 127, **2024**.
7. State Council of China. China-Europe Railway Express exceeds 87,000 cumulative trips. Available online: https://www.gov.cn/yaowen/liebiao/202404/content_6945198.htm (accessed on 14 April 2024).
8. LI J., HU J., YANG L. Can trade facilitation prevent the formation of zombie firms? Evidence from the China-Europe Railway Express. China & World Economy, **29** (1), 130, **2021**.
9. LI C., ZHANG J., LYU Y. Does the opening of China Railway Express promote urban total factor productivity? New evidence based on the SDID and SDDD model. Socio-Economic Planning Sciences, **80**, 101269, **2022**.
10. MAO Y., XIE Y., ZHUO C. How does international transport corridor affect regional green development: Evidence from the China-Europe Railway Express. Journal of Environmental Planning and Management, **67** (7), 1602, **2023**.

11. WANG X., LI J., SHI J., LI J., LIU J., SRIBOONCHITTA S. Does China-Europe Railway Express improve green total factor productivity in China? Sustainability, **15** (10), 8031, **2023**.
12. DALKIC G., BALABAN O., TUYDES-YAMAN H., CELIKKOL-KOCAK T. An assessment of the CO2 emissions reduction in high-speed rail lines: Two case studies from Turkey. Journal of Cleaner Production, **165**, 746, **2017**.
13. LIN Y., QIN Y., WU J., XU M. Impact of high-speed rail on road traffic and greenhouse gas emissions. Nature Climate Change, **11**, 952, **2021**.
14. NIE L., ZHANG Z. Is high-speed rail heading towards a low-carbon industry? Evidence from a quasi-natural experiment in China. Resource and Energy Economics, **72,** 101355, **2023**.
15. ZHAO L., ZHANG X., ZHAO F. Evaluating the impact of high-speed rail on county-level air quality in China. Transportation Research Part D: Transport and Environment, **86**, 102485, **2020**.
16. GUO X., SUN W., YAO S., ZHENG S. Does high-speed railway reduce air pollution along highways? Evidence from China. Transportation Research Part D: Transport and Environment, **89**, 102607, **2020**.
17. CHEN J. High-speed rail and energy consumption in China: The intermediary roles of industry and technology. Energy, **230**, 120816, **2021**.
18. DELMAS M.A., MONTES-SANCHO M.J. Voluntary agreements to improve environmental quality: Symbolic and substantive cooperation. Strategic Management Journal, **31** (6), 575, **2010**.
19. LIAN G., XU A., ZHU Y. Substantive green innovation or symbolic green innovation? The impact of ER on enterprise green innovation based on the dual moderating effects. Journal of Innovation & Knowledge, **7** (3), 100203, **2022**.
20. LIAN F., HE Y., YANG Z. Competitiveness of the China-Europe Railway Express and liner shipping under the enforced sulfur emission control convention. Transportation Research Part E: Logistics and Transportation Review, **135**, 101861, **2020**.
21. ZHOU X., ZHANG Z. International transport corridor and China's trade growth: Evidence from China-Europe Freight Train. Management World, **4**, 49, **2021** [In Chinese].
22. ZOU W., FENG J. International Transportation Infrastructure and China Enterprises Green Innovation: Evidence from the China Railway Express Sustainability, **16** (18), 8160, **2024**.
23. FORSLID R., OKUBO T., ULLTVEIT-MOE K.H. Why are firms that export cleaner? International trade, abatement and environmental emissions. Journal of Environmental Economics and Management, **91**, 166, **2018**.
24. WANG X., BU L. International export trade and enterprise innovation: Research based on a quasi-natural experiment of "CR Express". China Industrial Economics, **10**, 80, **2019**. (In Chinese)
25. JIANG Y., ZHANG J. The Effects of a Cross-Border Freight Railway Project on Chinese Cities' Green Innovation Intensity: A Quasi-Natural Experiment Based on the Expansion of the China Railway Express. Sustainability, **15** (15), 11707, **2023**
26. JIA R., SHAO S., YANG L. High-speed rail and CO_2 emissions in urban China: A spatial difference-in-differences approach. Energy Economics, **99**, 105271, **2021**.
27. ZHUO C., XIE Y., MAO Y., CHEN P., LI Y. Can cross-regional environmental protection promote urban green development: Zero-sum game or win-win choice? Energy Economics, **106**, 105803, **2022**.
28. LI Y., ZHANG X., JIN C., HUANG Q. The Influence of Reverse Technology Spillover of Outward Foreign Direct Investment on Green Total Factor Productivity in China' s Manufacturing Industry. Sustainability, **14** (24), 16496, **2022**.
29. 29.SUN L., ABRAHAM S.Estimating Dynamic Treatment Effects in Event Studies with Heterogeneous Treatment Effects. Journal of Econometrics, **225** (2), 175, **2021**.
30. ZHANG P. The fiscal and economic impacts of municipal dissolution: Evidence from New York. International Tax Public Finance, **30**, 948, **2023**.
31. WANG W., LIANG S., YU R., SU Y. Theoretical evidence for green innovation driven by multiple major shareholders: Empirical evidence from Chinese listed companies. Sustainability, **14** (8), 4736, **2022**.
32. GOMPERS P.A., LERNER J. The money of invention: How venture capital creates new wealth. Ubiquity, **4**, 1, **2002**.
33. LIN J. What affects new venture firm's innovation more in corporate venture capital? European Management Journal, **38** (4), 646, **2020**.
34. CHENG Z., ZHAO L., WANG G., LI H., HU Q. Selection of consolidation center locations for China Railway Express to reduce greenhouse gas emission. Journal of Cleaner Production, **305**, 126872, **2021**.
35. ZHANG Z., LUO X., DU J., XU B. Substantive or strategic: Government R&D subsidies and green innovation. Finance Research Letters, **67** (Part A), 105796, **2024**.
36. JIANG L., BAI Y. Strategic or substantive innovation? The impact of institutional investors' site visits on green innovation evidence from China. Technology in Society, **68**, 101904, **2022**.
37. SU Y., LIU Z., LIANG S. Does CEO information technology background promote substantive green innovation or strategic green innovation? Technology Analysis & Strategic Management, **37** (3), 253, **2023**.
38. LIU M., LIU L., FENG A. The impact of green innovation on corporate performance: An analysis based on substantive and strategic green innovations. Sustainability, **16** (6), 2588, **2024**.
39. HORBACH J. Determinants of environmental innovation-new evidence from German panel data sources. Research Policy, **37** (1), 163, **2008**.
40. HALL B.H., JAFFE A.B., TRAJTENBERG M. Market value and patent citations. Rand Journal of Economics, **36** (1), 16, **2005**.
41. CALLAWAY B., SANT'ANNA P.H.C. Difference-in-differences with multiple time periods. Journal of Econometrics, **225** (2), 200, **2021**.
42. HADLOCK C.J., PIERCE J.R. New evidence on measuring financial constraints: Moving beyond t he KZ Index. Review of Financial Studies, **23** (5), 1909, **2010**.
43. WEI J., GENG C. The impact of inter-provincial capital flow on regional innovation disparities. Economic Survey, **40** (3), 34, **2023** [In Chinese].
44. YANG C.H., TSOU M.W. Globalization and firm growth: Does ownership matter? Small Business Economics, **55**, 1019, **2020**.
45. AIVAZIAN V.A., GE Y., QIU J. Can corporatization improve the performance of state-owned enterprises even

without privatization? Journal of Corporate Finance, **11** (5), 791, **2005**.
46. CULL R., XU L.C. Who gets credit? The behavior of bureaucrats and state banks in allocating credit to Chinese state-owned enterprises. Journal of Development Economics, **71** (2), 533, **2003**.
47. YU Y., HAN L., WU J., ZHAO W., ZHANG Y. Green growth effects of high-speed rail in China: The role of industrial transformation. Emerging Markets Finance and Trade, **58** (3), 668, **2020**.