RIETI Discussion Paper Series 25-E-006

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RIETI Discussion Paper Series 25-E-006
January 2025

Railway Expansion Reduces Carbon Emissions by Shifting Road Traffic to Railways*

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Abstract

Transportation is a major contributor to global carbon emissions due to its reliance on fossil fuels, with railways often cited as a promising solution for emission reduction. However, empirical evidence of railways' effectiveness in reducing carbon emissions has been limited. Our study reveals that the expansion of Japan's railway network over the past 30 years has led to a significant reduction in carbon emissions, ranging from 97.44 to 110.73 million metric tons. This translates to an annual reduction of up to 1.697% of Japan's transportation sector emissions in 2019, a finding that demonstrates the broader environmental implications of systemic railway development. In contrast, station openings have led to a slight overall increase in emissions, contributing an additional 2.5 million metric tons over the same period. These findings emphasize the greater impact of comprehensive network expansions in reducing carbon emissions compared to localized station openings and underscore the importance of strategic railway expansion as a key measure for mitigating carbon emissions and advancing sustainable urban development.

Keywords: Railway; Carbon Emission; Market Access; Environment; Sustainable Transportation
JEL classification: R1, R11, R12, L92

*This study is conducted as a part of the Project "Institutional design to achieve a society of well-being" undertaken at the Research Institute of Economy, Trade and Industry (RIETI). The draft of this paper was presented at the RIETI DP Seminar for the paper. We gratefully acknowledge Amy Ando, Jiro Yoshida, Akira Hibiki and Naoki Wakamori, and the participants from various conferences and seminars for providing constructive comments. All remaining errors are our own.

1 Introduction

1.1 Research Objectives

Transportation contributes significantly to global carbon dioxide (CO_2) emissions, accounting for about 22% of total emissions from 2000 to 2022, largely due to its reliance on fossil fuels (Davis et al. (2010), Xia et al. (2023), Schäfer and Yeh (2020)). In line with Sustainable Development Goals 11 and 13, global initiatives call for a 5% annual decrease in CO_2 emissions from private vehicles by 2050 (Rogelj et al. (2018), Meys et al. (2021)). Consequently, the IEA endorses substantial expansions of railway systems and a strategic pivot to rail transportation to decarbonize urban mobility, leveraging railways' greater energy efficiency over road transport (Lin et al. (2021)). This shift is crucial for urban planning as it offers a pathway to reduce CO_2 emissions, mitigate climate change, and promote sustainable urban growth by integrating efficient public transportation systems into city infrastructure.

However, direct empirical evidence on the effectiveness of railway network expansions in reducing CO_2 emissions is limited. Most existing studies, such as those by Li et al. (2019), Sun and Li (2021), and Lin et al. (2021), focus on the impact of new railway station openings, often employing Regression Discontinuity (RD) or Difference-in-Differences (DID) methods. While DID is useful, it has two key limitations: (1) it typically views the impact of railway expansions on CO_2 emissions as localized, whereas we hypothesize broader effects; and (2) it concentrates on the effects of individual station openings rather than the comprehensive impact of network expansions. This approach is particularly limiting in countries with mature railway networks, where the cumulative reduction of CO_2 emissions likely stems from a complex interplay of factors. These may include increased network density, improved interconnectivity, enhanced service frequency, and the network's ability to serve diverse travel needs across various spatial scales, from local commutes to long-distance trips. Our study addresses these limitations by incorporating Market Access (MA)—a continuous measure of a city's connectivity—alongside DID, for a more comprehensive analysis of both localized and broader impacts of enhanced accessibility. Employing MA allows us to assess the overall impact of railway network expansion across a city, rather than just the effects of adding individual railway stations.

This paper offers valuable contributions to the understanding of how large-scale railway network expansions influence urban transportation and emissions reduction, an area crucial for addressing the challenges of climate change and sustainable urban development. By examining the broad impacts of network expansions rather than focusing solely on individual station openings, this research provides a comprehensive view of how enhanced public transit infrastructure can reshape travel behavior and reduce reliance on private vehicles. The findings align with global efforts to decarbonize urban mobility, highlighting the potential of railways to promote more sustainable travel choices.

Japan, the fifth-largest CO_2 emitter in the world and a country facing escalating urban and environmental challenges due to rapid urbanization, is the focus of our study. Since the late 1890s, Japan has made massive investments in railway infrastructure as a measure to reduce emissions (Ministry of Land, Infrastructure, Transport and Tourism (2020)). However, there has been little empirical evidence to date on the long-term effectiveness of these investments in reducing emissions. Japan's mature railway infrastructure and significant emission levels offer an ideal context for our study, allowing us to assess the long-term impacts of railway expansions on CO_2 emissions.

Our contributions span three key areas. First, we provide empirical evidence that railway expansions significantly reduce CO_2 emissions, with a decrease of 97.44 to 110.73 million metric tons over a 30-year period. While railways are generally considered less environmentally harmful than road transport, previous studies have produced mixed findings on their effectiveness in reducing emissions. Some studies have reported reductions in CO_2 emissions following railway station openings (Sun and Li (2021); Lin et al. (2021)), while others have found only marginal improvements (Rivers et al. (2017); Yang et al. (2019); Jebli and Belloumi (2017)). These mixed results may stem from factors such as railways inducing additional travel demand (Givoni and Dobruszkes (2013)) or the uneven distribution of emission reductions, particularly in more developed areas (Avogadro et al. (2021)). Most of these studies focus on the impacts of individual stations rather than the broader effects of network-wide expansions. In contrast, our study provides quantitative evidence of the more extensive impact of railway network expansions on emissions, reinforcing the strategic expansion of railways as an effective approach to reducing CO_2 emissions.

The second contribution of this study is its relevance to mature railway infrastructures, contrasting with previous research that primarily examines newer networks in China (Zhao et al. (2021); Guo et al. (2020); Li et al. (2019)). In China, recent infrastructure developments offer clear pre-post scenarios that are well-suited for DID analysis. However, Japan's century-old, dense railway network presents a different challenge, where the high baseline of existing infrastructure makes DID less effective in capturing incremental changes, as the 'control' areas are often already influenced by the existing network. By utilizing MA, we capture the broad, cumulative effects of network enhancements over time. Our findings hold significant implications for urban planning, particularly in cities with established transportation systems in the United States and Europe. By contrasting the results obtained from both methods, our study complements existing research in highlighting how different analytical approaches can be appropriate for different stages of railway network development.

Third, we explore the mechanisms driving changes in emissions due to railway expansions. Following the framework established by Mohring (1972), we assess whether railway expansions induce a modal shift from road to rail. To this end, our study investigates whether railway expansions have effectively substituted traditional road travel. This substitution refers to changes in railway ridership and average vehicle kilometers traveled (VKT) to determine how railway expansions might reduce vehicle usage while simultaneously increasing ridership. We refer to Ministry of Land, Infrastructure, Transport and Tourism (2021) and identify private cars as the primary alternative to railways. Private cars account for the majority of transport modes, covering around 50% of travels, while other road transport options, such as buses, which account for around 10% of travels, typically operate on different routes that do not directly compete with railway lines, as supported by previous studies (Yang et al. (2023) and Shen et al. (2016)). Furthermore, buses are themselves sources of emissions, meaning that comparing CO_2 emissions from buses to railways would not provide a clear picture of the overall emissions. Instead, focusing on the substitution between private cars and railways offers a more meaningful assessment of how railway expansions contribute to reducing net carbon emissions. Urban planners can leverage these insights to design transportation policies that encourage this shift from road to rail, thereby lowering emissions and enhancing the overall sustainability of urban environments.

Railway expansion is a global trend and a promising strategy for reducing emissions.

However, assessments of its environmental impact often rely on projections rather than direct evidence (Lin et al. (2021)). Our study fills this gap by providing empirical evidence on the environmental benefits of railway expansions, helping to clarify the uncertainties associated with such projections. In doing so, our findings have the potential to influence policy decisions worldwide as nations seek to implement effective strategies for CO_2 reduction.

1.2 Contextual Background

The Japanese government has implemented a multi-faceted strategy for expanding transportation infrastructure, aimed at strengthening the national economy, fostering regional development, and promoting carbon-neutral transportation systems, as outlined in Ministry of Land, Infrastructure, Transport and Tourism (2020). A central focus of this strategy is the expansion of railway networks, particularly around Tokyo, to drive economic growth. The government is also working to connect various regions through HSR and railway extensions to support regional development. Additionally, efforts are being made to reduce highway traffic and promote long-distance rail travel, encouraging a shift from road to rail transportation to alleviate congestion.

These efforts require substantial investment. Between 1985 and 2019, HSR construction and operation in Japan demanded an estimated 448.78 billion USD, according to Ministry of Land, Infrastructure, Transport and Tourism (2020). Additionally, the railway sector required approximately 3 billion USD between 1995 and 2020, as reported by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT)[1]. Expansion continues, with further HSR and railway extensions currently under construction.

Despite these large-scale investments, comprehensive evaluations of their success in achieving carbon neutrality remain limited. Much of the existing research has predominantly focused on economic outcomes, leaving a significant gap in understanding the impact on carbon emissions. Assessing both economic and carbon-neutrality outcomes is crucial for developing sustainable urban systems that balance growth with environmental preservation. Our study seeks to address this gap by providing empirical evidence on the role of transportation infrastructure in achieving carbon neutrality.

[1] See MLIT report, http://fine-foods.net/wordpress/wp-content/uploads/2017/12/zatugaku5_2014.6.11.pdf (Accessed January 31, 2024, in Japanese).

2 Method

2.1 Data

Our analysis examines city-level and annual variations in CO_2 emissions and railway infrastructure. Thus, our data is all city and annual level data, spanning from 1990-2019.

CO_2 emission. The Ministry of the Environment of Japan provides city-level CO_2 emission data from 1990 to 2021, which are available at https://www.env.go.jp/policy/local_keikaku/tools/suikei2.html. These emissions are derived from social statistics published by the Japanese Government and segmented by sectors such as industry, business, households, transport, and general waste. The total CO_2 emissions from the transport sector incorporate emissions from private cars, railways, and shipping. Further details on the CO_2 emission calculation process are provided in the Ministry of Environment's manual, available at https://www.env.go.jp/policy/local_keikaku/tools/siryou/suikei-2.pdf.

Railway and highway networks. To compute the MA of railway (conventional railways and HSRs) and highway networks, we measure travel times between cities for each transportation mode. We calculate these network distances using Geographic Information System (GIS) data on Japan's railways and highways, obtained from the Digital National Land Information (DNLI) provided by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) of Japan. The transport network datasets are available at: https://nlftp.mlit.go.jp/ksj/. From these data, we construct annual datasets spanning 1990 to 2019 for railway and highway networks. These datasets facilitate the identification of potential routes that individuals might use within the railway or highway systems, allowing for the calculation of travel distance between all possible combinations of origin and destination cities.

Railway ridership and VKT. To thoroughly examine the impact of railway expansion on CO_2 emissions, we leverage data on rail ridership and VKT. Railway ridership data, sourced from the DNLI, provide annual passenger counts per station across Japan from 2011 to 2021. We aggregate these passenger counts to the city level to represent railway ridership for each city. For VKT, we utilize data from the MLIT, which conducts the Road Traffic Census approximately every five years. This dataset includes average travel distances per vehicle (measured in kilometers per trip) at the regional level from 1990 to

2021. These distances are multiplied by the number of vehicles in each city to derive aggregate annual VKT. The vehicle count data are sourced from the Statistics Bureau of Japan and are available at https://www.e-stat.go.jp/statistics/00600580. We interpolate these data to produce annual estimates, using them as an index of travel volume for each region, referencing studies such as Gendron-Carrier et al. (2022).

Table 1 shows the summary statistics of the variables included in our analytical model.

Table 1: *Summary statistics of key variables*

Variable	Obs	Mean	Std. Dev.	Min	Max
CO_2 Emissions (1,000 kg)					
CO_2 emissions from Transportation	52,170	122.81	238.33	0.39	3431.10
Market Access					
Railway MA	52,170	87,450.91	284,837.40	0	4,394,492
Highway MA	52,170	44,998.51	131,863.40	0	1,892,274
Other Variables					
Ridership	15,651	68,467.49	448,530.60	0	10,500,000
Population	52,170	72,802.05	180,820.50	0	3,753,701
VKT (10,000 km)	52,170	102.38	59.90	7.34	265.46

2.2 Market Access (MA) Calculation

A key strength of our research is the use of Market Access (MA) to assess a city's connectivity to larger and more populous markets. MA can increase through the addition of new stations or highways, infrastructure enhancements in neighboring cities, or the growth of nearby cities into larger markets. To prevent artificial inflation from population growth, we exclude the city's own population from MA calculations, which helps address concerns about MA growth being driven solely by population increases.

We utilize MA to quantify the growth of railway and highway network expansion. Conceptually, MA is the market potential of a city, such as its ease of trade, based on its geographical location (Redding and Venables (2004)). In previous studies, MA has been calculated as an index that increases with the size of nearby markets and decreases with the travel cost to those markets (Donaldson and Hornbeck (2016), Lin (2017), Zheng et al. (2022)). In transportation contexts, the cost of travel is calculated based on the transportation networks and the unit cost of each travel mode.[2]

Following previous works such as Donaldson and Hornbeck (2016), we define the MA of origin city o as follows[3]:

$$MA_{otm} = \sum_{d}^{o \neq d} (\tau_{odtm}^{-\theta} \times pop_{dt}), \qquad m = \{Railway, Highway\}. \tag{1}$$

where τ_{odtm} is the travel time from origin city o to destination city d in year t when adopting travel mode assumption m and pop_{dt} is the population size of city d in year t. The number of population for each city is obtained from the System of Social and Demographic Statistics (SSDS) provided by the Ministry of Internal Affairs and Communications. This data is provided every five years. We interpolate the population data to obtain annual values. We set $\theta = 3$ according to previous studies that have targeted passenger travel (Lin (2017) and Zheng et al. (2022)). By excluding the city o's own population from MA_{otm}, we can estimate the effects of the MA on CO_2 emission separately from the impacts of population growth in the city o.

To calculate each city's MA based on equation (1), we first need to determine the travel time matrix τ_{odtm}. This requires setting (1) assumptions about travel speed, (2) the possible travel routes from origin to destination, and (3) how individuals choose their mode of travel. In terms of (1) travel speed assumptions: We set travel speeds based on previous studies, as shown in Table A1 in Appendix A.

For (2) and (3), we calculate the MA under the assumption that individuals select

[2]We employ travel time as the cost indicator for calculating MA primarily for two reasons. First, travel time directly reflects improvements in accessibility and has been demonstrated to have significant economic impacts, as evidenced in studies such as those by Ahlfeldt and Feddersen (2017), Zheng et al. (2022), and Yoo et al. (2023a). These studies support the use of travel time as a robust indicator for travel cost. Second, unlike certain previous research that differentiates between passenger and freight transportation—such as Yoo et al. (2023b) and Lin (2017), which focus on passenger trains, and Donaldson and Hornbeck (2016), which concentrates on freight trips—our study encompasses both aspects. In our context, passenger and freight transportation often share the same networks, complicating the segregation of travel purposes based solely on network usage. Thus, we adopt travel time as a comprehensive cost indicator, ensuring our approach remains applicable and relevant across different modes of transportation.

[3]We do not use actual OD trip data when calculating MA. Instead, we use the minimum travel cost between origin and destination cities, which is calculated by our assumptions about travel routes and speeds, and actual railway lines existing in each year. Therefore, railway MA is not calculated based on actual travel, but can be considered the potential of accessibility and market activities.

the option that minimizes travel time among available alternatives. The possible travel modes, we consider five modes of travel: (a) Using only the railway (excluding HSR); (b) using only HSR; (c) transferring from railway to HSR; (d) using only the highway; (e) using other modes.[4] To calculate MA for railways, we determine the fastest travel option from the following: (a), (b), (c), and (e). It is assumed that for most options involving railways or HSRs, individuals will access the nearest station by (e) other modes. For MA related to highways, we choose the faster mode between (d) and (e). This methodology ensures that our MA calculations accurately reflect the most efficient transportation options available, thereby aligning with realistic user behaviors and network efficiencies. [5]

We calculate two types of MA: one reflecting population changes from 1990 to 2019 and another with population levels fixed at 2019 values. The former accounts for both population changes and travel time variations, while the latter isolates the effects of reduced travel time from population growth. Figure 1 illustrates MA growth from 1990 to 2019. The left map depicts MA with population changes included, while the right map shows MA with population fixed at 2019 levels. Both types of MA increased by approximately 20% during this period.

Additionally, to assess the specific impact of long-distance travel, we compute an MA that includes only destinations located beyond certain distances from the center of city o—specifically 50 miles, 100 miles, and 200 miles—referred to as, for example, the 50-mile buffer MA. These supplementary indicators allow for a more exploration of the impacts of railway expansion as well as the standard MA.

[4] Mode (e) includes various other unspecified means of transportation, assumed to be the modes such as cars, motorcycles, and buses.

[5] The specific assumptions for each move are as follows: For modes (a), (b), and (d), we assume individuals depart from the origin city, travel to the closest station or interchange, take the train, HSR, or drive on the highway to the station or interchange nearest to the destination city, and finally travel to the destination city. For mode (c), individuals travel by train from the origin city to the nearest HSR station and, if possible, travel by train from the HSR station closest to the destination city.

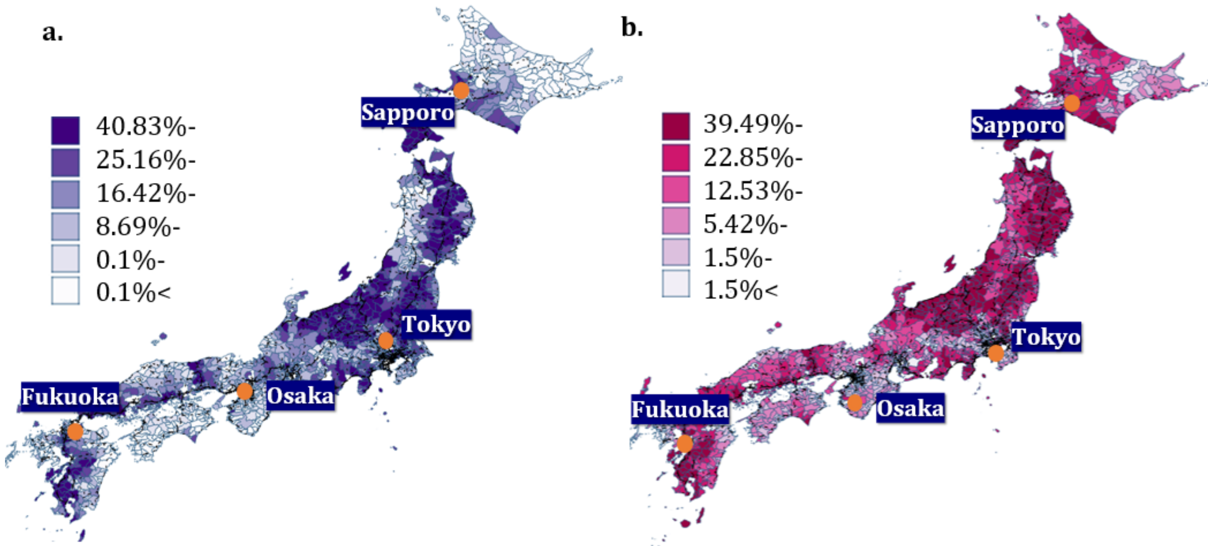

Figure 1: *30-year growth of MA: a.) 30-year population growth in unfixed MAs, b.) 30-year population growth in fixed MAs. Darker colors indicate higher MA growth.*

2.3 Estimation

2.3.1 Difference-in-difference (DID) specification

We begin our analysis by evaluating the impact of new railway station openings on CO_2 emissions using a staggered Difference-in-Differences (DID) approach, which accommodates multiple station openings over varied timelines. Cities with newly opened stations within a 1km radius from the geographical city center were selected as the treatment group, while cities without stations within this radius served as the control group. The 1km radius was chosen based on the typical 10-15 minute travel time to railway stations in Japan, which generally corresponds to a 1-2 km distance (a 15-minute walk at 4-5 km/h).

Our DID framework is specified as:

$$\ln V_{ot} = \beta^{DD} Treatment_{ot} + \sum_{j \in Dist} \delta_j Station_{ojt} + \delta_o + \delta_{rt} + f(x_o, y_o) + \varepsilon_{ot}, \tag{2}$$

In our model, $Treatment_{ot}$ serves as an indicator variable assigned a value of 1 if city o is located within a 1 kilometer radius from any railway station in year t. The parameter of interest, β^{DD}, quantifies the treatment effect of station openings on CO_2 emissions.

Since the treatments in our model are introduced at varying times across different cities, we utilize the staggered DID approach. Referring to the two-way fixed effects estimator (e.g., Goodman-Bacon (2021)), we include the following: the city fixed effects δ_o, which capture the time-invariant characteristics of cities; and the prefecture-by-year fixed effects (δ_{rt}), which capture the prefecture-level trends in CO_2 emissions. We account for the spillover effects of railway expansion. To do so, we introduce a "Station Opening" group based on Butts (2021), which includes cities that lack immediate proximity to a railway station but are close enough to access newly built stations in neighboring areas. In the equation (2), the spillover effects are expressed as the term $\sum_{j \in Dist} \delta_j Station_{ojt}$, where $Dist$ = {[1000, 2000), [2000, 5000), [5000,10000} measured in meters. $Station_{ojt}$ is a dummy variable that equals 1 if any stations exist in the distance buffer j from city o in the year t. This setup is critical for understanding how residents might use alternative transportation means, such as cars, to reach these stations, potentially increasing travel volume and associated CO_2 emissions.

The key assumption of the DID is that, in the absence of a new subway opening, emission in the treatment and control groups follow parallel trends. We adopt event study design and confirm the parallel trend, in Appendix B.

2.3.2 Market Access (MA) Estimation

The main goal of this paper is to examine the impact of MA on CO_2 emissions from the transport sector. The estimation model is as follows:

$$\ln V_{ot} = \beta_1 \ln(MA_{ot,Railway}) + \beta_2 \ln(MA_{ot,Highway}) + \delta_{it} + \delta_o + f(x_o, y_o) + \varepsilon_{ot}, \tag{3}$$

where V_{ot} refers to the CO_2 emissions from the transport sector of city o in year t, $MA_{ot,Railway}$ and $MA_{ot,Highway}$ are the MA of city o by using railway and highway, respectively. We also include a prefecture-by-year fixed effect (δ_{it}) and a city-level fixed effect (δ_o). Additionally, a cubic polynomial for city latitude and longitude ($f(x_o, y_o)$) is included to control for geographical characteristics. For models focusing on VKT as the dependent variable, we omit city fixed effects because the data is based on regional categories larger than cities.

These fixed effects are included based on previous studies such as Donaldson and Hornbeck (2016) and Lin (2017). While we use the same set of fixed effects in both (2) and (3), their implications differ slightly here. The prefecture-year fixed-effect term and city fixed-effect term control for relative changes driven by prefecture-specific shocks (e.g., decreases in traffic volume due to natural disasters) and time-invariant city characteristics (e.g., car travel behaviors and railway usage patterns), which impact CO_2 emissions from the transport sector. By controlling for these fixed effects, the model identifies the variation in city-level CO_2 emissions relative to the average prefectural emissions trends, explained by the variance in MA.

While our baseline specification addresses some endogeneity concerns by including a set of fixed effects, residual issues persist due to the tendency to prioritize transport infrastructure expansion in economically developed cities. The location of stations and route connections between major stations often correlate with population distribution, which can in turn correlate with environmental outcomes such as CO_2 emissions.

To counter these concerns, we employ a two-stage least squares (2SLS) estimation with instrumental variables (IV) that correlate with actual MA but do not affect CO_2 emissions through other pathways. Such IVs can be realized based on hypothetical networks for HSR and highways, considering only geographical construction costs (Faber (2014)). We formulate these hypothetical HSR and highway networks with the lowest construction costs that connect major stations or interchanges on the actual network using the least-cost path spanning tree (LCPST) algorithm. The results from the LCPST algorithm correspond to the scenario where HSR expansion is driven solely by geographical construction cost minimization.

We select HSR networks over conventional railway stations for constructing our LCPST networks for two principal reasons. First, by 1990, Japan's railway network had already achieved a high density, with very short distances between stations—often mirroring the distances modeled in LCPST networks. Using regular railway stations could thus undermine the validity of our IV due to this overlap. Second, HSR stations serve as pivotal railway hubs and are recognized as "main stations" that accommodate rapid transit services, justifying our use of HSR LCPST as an IV in the regression model, with railway MA as the independent variable. The constructed LCPST networks for HSR and highways are detailed in Appendix C, while the first-stage regression estimation results are presented in Appendix D.

2.4 Calculation for Net CO_2 Emission Reduction

This section describes the methodological procedure for calculating the net reduction in CO_2 emissions, as shown in section 4.

We calculate the net change in CO_2 emissions caused by actual railway expansion, taking population dynamics into account. The percentage changes in CO_2 emissions due to station openings are calculated as follows:

$$\%\overline{\Delta V}^{DD} = \hat{\beta}^{DD} \times \overline{\Delta Treatment}, \tag{4}$$

where $\%\overline{\Delta V}^{DD}$ represents the average percentage change in CO_2 emissions V_{ot} due station openings, $\hat{\beta}^{DD}$ is the estimated coefficient for station openings from the DID regression equation (2), and $\overline{\Delta Treatment}$ is the mean change in $Treatment_{ot}$.

Similarly, the changes in CO_2 emissions due to the change in MA are calculated as follows:

$$\%\overline{\Delta V}^{MA} = \hat{\beta}_1 \times \%\overline{\Delta MA}, \tag{5}$$

where $\%\overline{\Delta V}^{MA}$ is the average percentage change in CO_2 emission V_{ot} due to the changes in MA Railway, $\hat{\beta}_1$ is the estimated coefficient of MA Railway from equation (3), and $\%\overline{\Delta MA_s}$ is the mean percentage change in MA railway.

The total change in CO_2 emissions is then calculated by multiplying the total national CO_2 emissions over 30 years by the percentage increase in CO_2 emissions. Mathematically, the change in CO_2 emissions is expressed as follows:

$$\Delta V = \sum_t \sum_o V_{ot} \times \%\overline{\Delta V}, \tag{6}$$

where ΔV represents the estimated change in CO_2 emissions, $\%\overline{\Delta V}$ is the percentage change in CO_2 emissions due to station openings (calculated using equation (2)) or changes in MA (equation (3)), and $\sum_t \sum_o V_{ot}$ denotes the total national CO_2 emissions from 1990 to 2019.

3 Results

3.1 Station Opening Effects

In Table 2, we observe that emissions do not decrease, as the coefficient is statistically insignificant within a 1 km radius (Model (1)). In fact, emissions increase when we consider intermediate zones (Models (3) and (4)) and beyond the immediate vicinity of the stations. To explain these findings, we analyze railway ridership and Vehicle Kilometers Traveled (VKT) using the same staggered DID specifications, also presented in Table 2.

Our results show a significant rise in railway ridership, but simultaneously, an increase in VKT beyond the 1km radius. This pattern suggests that while station openings boost railway usage, stations located more than 1 km from city centers lead to increased car usage in those areas, potentially contributing to higher emissions. Thus, the CO_2 reductions from increased ridership may be offset by the rise in VKT. This mechanism aligns with the findings of Givoni and Dobruszkes (2013), which suggest that station openings can induce additional travel demand.

However, these DID estimates capture only the localized effects of station openings. To determine whether railway expansions ultimately reduce or increase emissions overall, we must consider network-wide expansions and their broader impacts, which we explore in the following sections.

3.2 MA Approach

Our results demonstrate that railways, on average, reduce CO_2 emissions from transportation. This is detailed in Models (1) to (4) (population-unfixed MA) and Models (5) to (8) (population-fixed MA) of Panel (A) in Table 3. Models (5) to (8) isolate the effect of travel time improvements by keeping the population constant at 2019 levels. Models (1) and (5) assess the impact of MA increases on overall transportation-related CO_2 emissions. Models (2), (3), and (4), along with Models (6), (7), and (8) for the population-fixed version, focus on MA beyond 50, 100, and 200-mile radii, thus emphasizing long-range travels. All models account for existing highway networks.

The analysis reveals that a 1% increase in MA for railways leads to reductions in CO_2 emissions from transportation, with greater reductions for longer travels. For example,

Table 2: *Station opening impact in CO_2 emissions*

	Model (1)	Model (2)	Model (3)	Model (4)
DV: Logarized Emissions from Transport (1,000 kg) (N=51,570)				
Treatment (1km)	-0.008	0.008	0.048***	0.046***
	(0.006)	(0.007)	(0.007)	(0.008)
Station Opening between 1km-2km		0.044***	0.089***	0.086***
		(0.006)	(0.007)	(0.007)
Station Opening between 2km-5km			0.059***	0.056***
			(0.004)	(0.005)
Station Opening between 5km-10km				-0.007
				(0.005)
Constant	3.975***	3.965***	3.935***	3.938***
	(0.001)	(0.002)	(0.003)	(0.004)
R-sq	0.995	0.995	0.995	0.995
	Model (1)	Model (2)	Model (3)	Model (4)
DV: Logarized Railway Ridership (N=52,170)				
Treatment (1km)	0.984***	1.289***	1.567***	1.498***
	(0.090)	(0.094)	(0.105)	(0.108)
Station Opening between 1km-2km		0.903***	1.208***	1.131***
		(0.086)	(0.100)	(0.104)
Station Opening between 2km-5km			0.394***	0.314***
			(0.065)	(0.072)
Station Opening between 5km-10km				-0.205***
				(0.078)
Constant	4.857***	4.662***	4.457***	4.541***
	(0.014)	(0.023)	(0.041)	(0.052)
R-sq	0.935	0.935	0.935	0.935
	Model (1)	Model (2)	Model (3)	Model (4)
DV: Logarized VKT (10,000 km) (N=49,410)				
Treatment (1km)	-0.016	0.001	0.061***	0.083***
	(0.011)	(0.011)	(0.012)	(0.013)
Station Opening between 1km-2km		0.068***	0.136***	0.164***
		(0.010)	(0.011)	(0.012)
Station Opening between 2km-5km			0.090***	0.118***
			(0.007)	(0.008)
Station Opening between 5km-10km				0.089***
				(0.009)
Constant	2.593***	2.579***	2.533***	2.500***
	(0.001)	(0.002)	(0.004)	(0.005)
R-sq	0.304	0.305	0.306	0.308

Note: Standard errors are shown in parentheses. * $p<0.1$, ** $p<0.05$, and *** $p<0.01$. All models include prefecture-by-year fixed effects, city fixed effects, and cubic-polynomial fixed effects. Two-sided t-tests are employed to test the significance of the coefficients.

emissions decrease by 0.027% in Model (1), 0.025% in Model (2), and 0.030% in Model (5). Conversely, a 1% increase in MA for highways corresponds to an increase in CO_2 emissions over the 30-year period. The estimates from the population-fixed MA are similar to those from the population-unfixed MA.

We test a mechanism by which railway expansions can effectively reduce CO_2 emissions. Supported by the findings of Mohring (1972) and Guo et al. (2020), our hypothesis posits that railway expansions facilitate a modal shift from cars to trains, thereby decreasing road traffic emissions. To test this, we analyze city-level railway ridership and VKT, using MA to regress these variables. Results from Panels (B) and (C) in Table 3 demonstrates that railway expansions increase ridership and reduce VKT, suggesting a substitution effect from cars to railways. Ridership increases were more pronounced for shorter trips, while travel distance reductions were more significant for longer trips. This contrast supports the hypothesis that railway expansions can effectively substitute car usage with railway transport, corroborating Mohring (1972)'s theories and offering a counterpoint to the complementary usage concepts proposed by Vickrey (1969) and Duranton and Turner (2011). Conversely, while highway expansions also enhance ridership—likely due to improved access to stations—they lead to increased VKT.

4 Net impact on CO_2 emissions

We calculate both the total and annual net changes in CO_2 emissions resulting from railway expansion via the substitution of road traffic for railway, measured in MMton of CO_2. First, we aggregate the total CO_2 emissions from transportation from 1990 to 2019. For the annual CO_2 reduction calculations, we calculate the annual total CO_2 emissions by year. Using the coefficients from Table 3 and the actual MA changes throughout 1990-2019–annually, for each year–, we compute both the aggregate and annual CO_2 emissions reductions attributable to MA railway growth. For the station openings, we sum up the number of new stations opened during 1990-2019, and calculate both the total and annual CO_2 emissions using the estimated coefficients in Table 2.

Figure 2 presents the results. For annual emissions, station openings increase emissions by 0.236 MMtons, while using MA, we observe annual emissions decreases of 3.045 (population unfixed MA) and 3.461 (population fixed MA) MMtons, respectively. Notably, the results from the MA analysis suggest that railway expansions alone can reduce emissions by as much as 1.697%. For aggregate emissions from 1990 to 2019, CO_2 emissions decreased by 97.44 to 110.73 MMtons, whereas station openings indicate an emission increase of 7.548 MMtons.

Two key observations arise from the analysis. First, the population-unfixed MA shows a slightly smaller reduction in CO_2 emissions compared to the population-fixed MA. This

Table 3: *Impact of transportation infrastructure on CO_2 emissions, railway ridership, and VKT*

	Population Unfixed MA				Population Fixed MA			
	Model (1)	Model (2)	Model (3)	Model (4)	Model (5)	Model (6)	Model (7)	Model (8)
	Panel (A): DV: ln (CO_2 from transportation) (N=51,570)							
ln (MA Railway)	-0.027***				-0.030***			
	(0.004)				(0.005)			
ln (MA Railway: 50 Miles Buffer)		-0.025***				-0.025***		
		(0.004)				(0.004)		
ln (MA Railway: 100 Miles Buffer)			-0.028***				-0.028***	
			(0.003)				(0.003)	
ln (MA Railway: 200 Miles Buffer)				-0.036***				-0.037***
				(0.003)				(0.003)
ln (MA Highway)	0.490***	0.490***	0.475***	0.477***	0.486***	0.475***	0.477***	0.486***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Constant	-0.051	0.008	-0.004	-0.075	-0.023	0.011	-0.002	-0.067
	(0.104)	(0.105)	(0.104)	(0.103)	(0.105)	(0.106)	(0.104)	(0.103)
R-sq	0.997	0.997	0.997	0.997	0.997	0.997	0.997	0.997
	Panel (B): DV: ln (Railway Ridership) (N=52,170)							
ln (MA Railway)	1.232***				1.374***			
	(0.078)				(0.087)			
ln (MA Railway: 50 Miles Buffer)		0.543***				0.552***		
		(0.066)				(0.067)		
ln (MA Railway: 100 Miles Buffer)			0.344***				0.347***	
			(0.056)				(0.056)	
ln (MA Railway: 200 Miles Buffer)				0.094***				0.097***
				(0.054)				(0.056)
ln (MA Highway)	2.130***	2.907***	2.932***	2.970***	2.130***	2.907***	2.932***	2.970***
	(0.217)	(0.210)	(0.210)	(0.211)	(0.217)	(0.210)	(0.210)	(0.211)
Constant	-25.19***	-24.45***	-22.92***	-21.51***	-26.49***	-24.51***	-22.96***	-21.53***
	(1.851)	(1.876)	(1.856)	(1.842)	(1.851)	(1.876)	(1.856)	(1.842)
R-sq	0.939	0.939	0.939	0.939	0.939	0.939	0.939	0.939
	Panel (C): DV: ln (VKT) (N=49,410)							
ln (MA Railway)	-0.014***				-0.016***			
	(0.006)				(0.007)			
ln (MA Railway: 50 Miles Buffer)		-0.004				-0.004		
		(0.004)				(0.004)		
ln (MA Railway: 100 Miles Buffer)			-0.019***				-0.019***	
			(0.003)				(0.003)	
ln (MA Railway: 200 Miles Buffer)				-0.030***				-0.030***
				(0.003)				(0.003)
ln (MA Highway)	0.296***	0.286***	0.278***	0.275***	0.296***	0.286***	0.278***	0.275***
	(0.014)	(0.014)	(0.014)	(0.014)	(0.014)	(0.014)	(0.014)	(0.014)
Constant	0.138	0.127	0.292**	0.351***	0.152	0.127	0.293**	0.357***
	(0.121)	(0.126)	(0.124)	(0.122)	(0.123)	(0.126)	(0.124)	(0.122)
R-sq	0.396	0.396	0.396	0.396	0.396	0.396	0.396	0.396

Note: Standard errors are shown in parentheses. * $p<0.1$, ** $p<0.05$, and *** $p<0.01$. All models include prefecture-by-year fixed effects, city fixed effects, and cubic-polynomial fixed effects. Two-sided t-tests are employed to test the significance of the coefficients.

indicates that when excluding the effects of population distribution changes from 1990 to 2019, the reduction in emissions attributable solely to railway network expansion was more pronounced. The population-fixed MA does not account for the population decline in rural regions like Hokkaido, where railway expansions occurred. Without considering population decrease, these areas show significant CO_2 reductions purely due to the impact of railway development. However, when considering population dynamics, the migration from rural areas to urban centers seems to diminish the potential CO_2 reduction from rail network expansion. As urban populations grow, the opportunity for reducing CO_2 emissions through improved rural-urban connectivity weakens, as fewer people are engaged in long-distance travel.

Second, station openings, when considered without the broader context of network expansions, tend to increase emissions. This finding is consistent with Lin et al. (2021), who reported emission increases from passenger railway expansions ranging from 0.716 to 3.974 MMton. This discrepancy likely occurs because station openings induce additional vehicle travel around stations, offsetting potential emission reductions that might result from increased ridership, as our results indicate. However, by employing MA, we observe a decrease in aggregate vehicle travel, leading to an overall reduction in emissions. These results suggest that in countries like Japan, which have mature railway networks, the potential for significant emission reductions through DID analysis alone is limited. Therefore, employing MA is more advantageous in such contexts, as it captures the comprehensive impacts of network-wide enhancements on CO_2 emissions.

5 Heterogeneous Effect of Railway Expansion

As a sensitivity analysis, we explore the heterogeneity of our results to identify which areas experience the most significant reductions in emissions, alongside increases in ridership and decreases in VKT. This analysis provides insights into the demographic and geographic characteristics that enhance the effectiveness of railway expansions in reducing CO_2 emissions, offering valuable guidance for targeted policy.

We categorize our analysis into three groups: Initial CO_2 Levels, Rising Income, and Station Distance. Each group is detailed below.

Initial CO_2 Levels: Cities with initially high CO_2 levels from transportation may experience more pronounced emission reductions through the substitution of high-emission vehicles, as suggested by Xie et al. (2024) and Gendron-Carrier et al. (2022). We define "High CO_2" areas as cities where CO_2 levels exceeded the mean value in 1990, typically

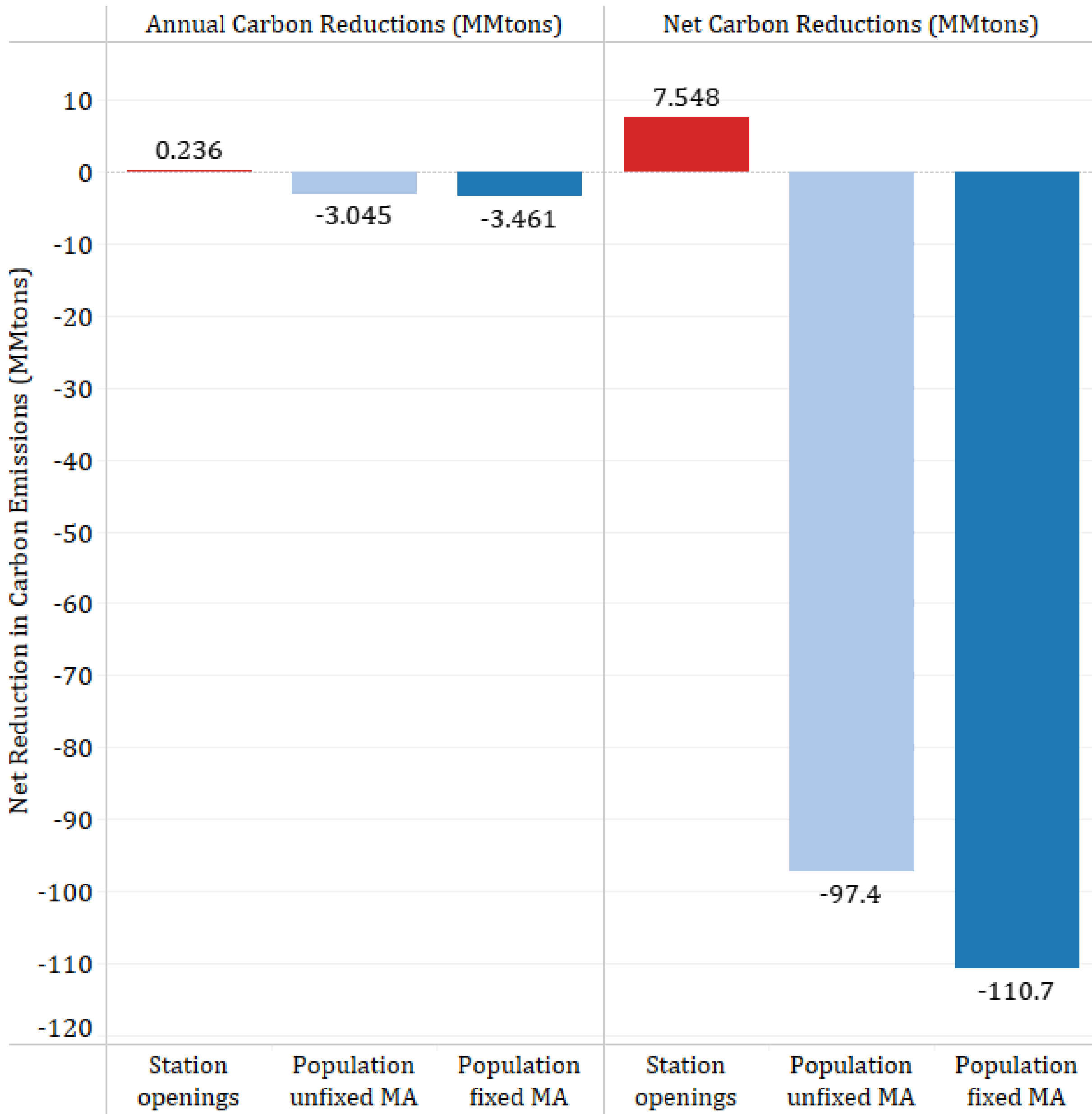

Figure 2: *Annual and net reduction of CO_2 emissions from railway expansions*

urban centers like Tokyo. In contrast, "Low CO_2" areas, with CO_2 levels below the average, usually represent rural locales like Sapporo.

Rising Income: Previous research shows that railway lines significantly reduce emissions, especially in lower-income areas experiencing rapid growth Xiao et al. (2020). This reduction is primarily driven by a shift from car usage to railways, motivated by cost savings crucial for residents in these areas (Xie et al. (2024)). We classify regions based on their 1990 income levels: "Low income" for cities below the average and "High income" for those above. Growth rates are categorized as "Low growth" for regions with less than the average per capita income increase from 1990 to 2019, and "High growth" for those exceeding the average. The "Rising Income" group includes cities that are both "Low income" and "High growth," indicating initially low-income cities that have seen significant growth over the past 30 years.

Station Distance: We assess whether CO_2 emission reductions associated with railway expansions are more pronounced in city centers closer to railway stations. Proximity typically enhances accessibility, increasing railway usage and reducing environmental impacts as people opt to walk or cycle to nearby stations (Li et al. (2019)). To explore this, we calculate the median distance to the nearest railway station across all cities, defining the "Station Far" group as cities beyond this median distance of 3.78 km. This allows us to compare CO_2 emission changes between cities farther from stations and those closer. The median is chosen over the mean to better represent station distance distribution, as the mean can be skewed by extremely long distances in rural areas, sometimes nearing hundreds of kilometers, making the median a more practical measure for our analysis.

The findings from these analyses are illustrated in Figure 3, which provides a detailed breakdown of the beta coefficients for each category. For example, the 'High CO_2=1' category includes cities with initially high CO_2 levels, while 'High CO_2=0' includes those with lower levels. Figure 3 reveals two critical insights: first, railway expansions are linked to reductions in CO_2 emissions. Second, regions with initially high CO_2 levels, lower incomes with higher growth rates, and proximity to railway stations show significant decreases in emissions.

Next, we examine the heterogeneity of impacts on ridership and VKT across different regional categories, as shown in Figure 3. This figure confirms that railway expansions lead to an increase in ridership and a decrease in VKT, supporting the hypothesis of a shift from cars to railways. Specifically, cities with high CO_2 levels see greater increases in ridership and more significant reductions in VKT compared to cities with lower levels, suggesting a more active substitution from car to rail in these areas. In the Rising Income and Station Far categories, cities exhibit smaller increases in ridership but greater reductions in VKT than their counterparts. This pattern may indicate that while road-to-rail substitution is occurring, larger VKT reductions—likely due to reduced congestion—are driving more significant emissions reductions.

These findings affirm that while railway expansions generally facilitate a shift from road to rail, regional differences shape the outcomes. This underscores the importance of considering local conditions in transportation planning to maximize the benefits of infrastructure investments. The complete regression tables detailing the impacts of railway (and highway) expansions on CO_2 emissions, railway ridership, and average VKT are available in the Appendix E.

6 Discussion and Conclusion

This study examines the effects of railway expansions on CO_2 emissions during 1990-2019. Our results show that railway expansions have led to a substantial decrease in CO_2 emissions, ranging from 97.44 to 110.73 MMtons. We also show that this reduction is primarily attributable to a modal shift from road to rail travel, resulting in increased rail ridership. These findings have practical implications for railway projects currently proposed and implemented worldwide. The magnitude of emission reductions estimated in our study supports projections for major initiatives. For instance, the California High-Speed Rail project anticipates a 102 MMtons CO_2 equivalent reduction over its initial 50 years of operation, mainly due to shifts from car and airplane travel to more energy-efficient rail systems[6].

Beyond this direct environmental benefit, our analysis reveals broader implications for urban development and planning. Based on our findings, we derive several urban implications.

Network-wide effects of railway expansions: A novel insight

This study offers a renewed perspective on the role of railway infrastructure in urban

[6]This study focuses on the structural changes resulting from the expansion of land transportation systems, such as railways and highways. However, it does not address the impacts of long-distance travel, including air transportation. Additionally, the analysis does not account for detailed considerations of transportation infrastructure, such as the proportions of various transportation modes (e.g., electric versus conventional vehicles) or technological advancements. These areas are left for future research.

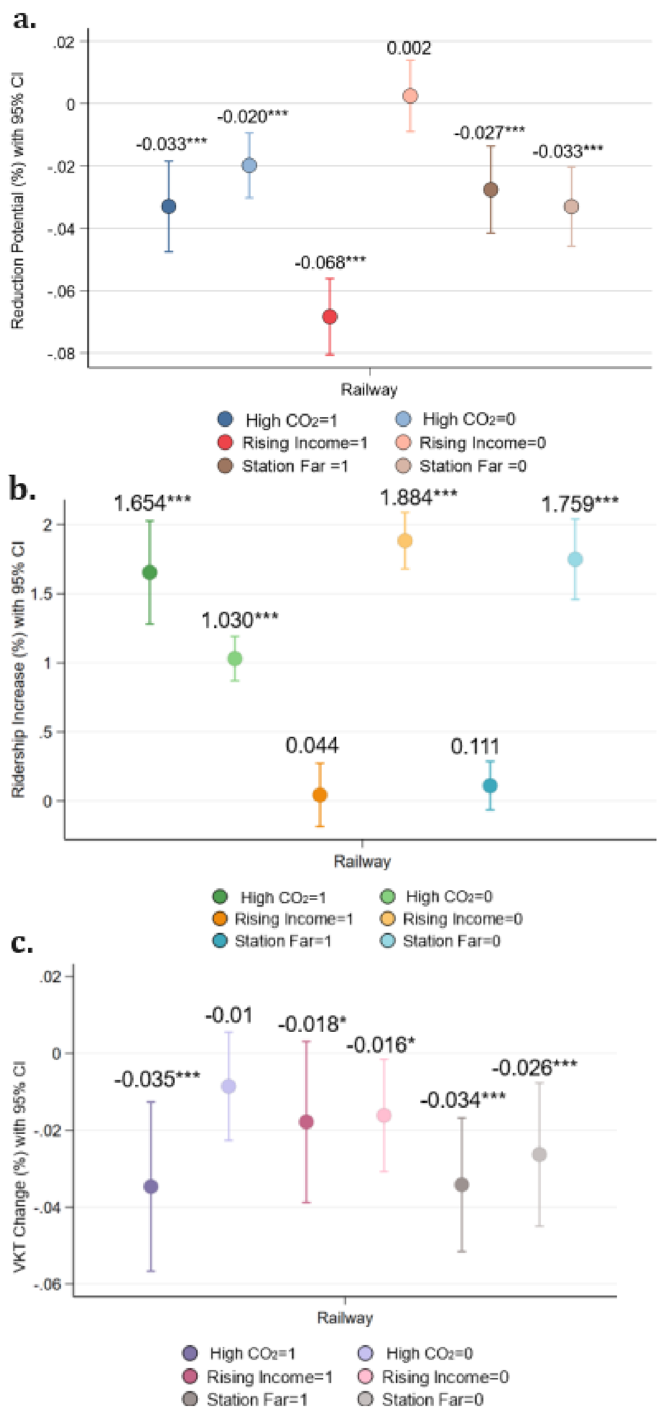

Figure 3: *Heterogeneity test results: a) Impact of railway expansion on CO_2 emissions, b) Impact of railway expansion on ridership, c) Impact of railway expansion on VKT.*

sustainability. We find that the effects of expansions extend far beyond new station locations, propagating throughout the entire railroad network. This insight, while intuitive, has been largely overlooked in existing literature.

The contrasting results from our DID and MA approaches illustrate this network-wide phenomenon. The DID approach, focused on localized station openings, showed minimal changes in CO_2 emissions. In contrast, the MA method, capturing system-wide changes, revealed substantial reductions. This discrepancy exposes the limitations of evaluating railway expansions solely through the lens of discrete station additions.

The observed modal shift from road to rail suggests the potential benefits of connected railway networks among cities, particularly with longer distances. This finding suggests that the full benefits of railway investments are best realized when considered in the context of the entire urban system, including broader urban form and regional connections. This network-wide perspective not only offers a more effective approach to sustainable urban development through railway expansion but also emphasizes integrated planning that considers both local impacts and system-wide effects.

Heterogeneity in urban contexts and equity considerations

Our heterogeneity analysis reveals varied effects of railway expansions across different urban contexts in Japan, which in turn offers insights for targeted development strategies. Cities with historically high CO_2 levels and those with lower relative incomes but high growth rates both show significant benefits, albeit in different ways.

In high-emission cities, railway expansions appear to function as a corrective mechanism for car-dependent urban forms, leading to more pronounced emission reductions. In cities with relatively lower incomes and high growth rates, by providing not only cost-efficient transportation options to travel but also mitigate emissions through decreasing potential car dependency increase

In high-emission cities, railway expansions serve as a corrective mechanism for car-dependent urban forms, resulting in more significant emission reductions. In cities with relatively lower incomes and high growth rates, railway expansions offer cost-efficient transportation options that not only facilitate travel but also mitigate emissions by curbing the potential rise in car dependency.

The potential of railway investments to address multiple urban challenges simultaneously, from environmental sustainability to economic growth and urban form, merits further investigation. Future research could explore how transit infrastructure integrates with broader urban policies, such as urban redesign and land use changes in high-emission areas, or coordination with regional development strategies in areas experiencing rapid growth. This research could provide valuable insights for other developed economies facing similar urban development challenges.

Long-term implications and future directions

Our long-term analysis shows that railway investments are generational commitments that profoundly shape urban form and function. The gradual materialization of emission reductions over decades extends beyond current evaluation frameworks, calling for the incorporation of longer-term societal and environmental benefits into cost-benefit analyses of urban transit investments.

Railway system planning requires adaptability, raising critical questions about future urban mobility. As developed economies likely confront challenges such as aging populations, flexible and multi-modal transit systems become crucial for optimal urban design. Future research should examine how these unprecedented demographic shifts might influence the effectiveness and planning of railway infrastructure in urban areas.

To conclude, this study provides empirical evidence of the substantial CO_2 emission reductions achieved through railway expansions, primarily through modal shifts from road to rail travel. Our findings suggest broader implications for urban development beyond mere emission reduction. The observed network-wide effects and heterogeneous impacts across different urban contexts indicate that railway investments may play a significant role in shaping sustainable, equitable, and adaptive urban environments.

These insights invite a reconsideration of urban planning processes, suggesting the potential for integrating railway developments into more comprehensive strategies for urban transformation. By considering railway expansions within this broader urban development context, planners and policymakers may develop more comprehensive approaches to sustainable urban growth. Such perspectives could address environmental concerns while potentially fostering more livable, equitable, and economically vibrant urban spaces for future generations.

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Data Availability The Transportation Network Data and Ridership data used in our research are available on the Digital National Land Information (DNLI) website at "https://nlftp.mlit.go.jp/ksj/". For CO_2, we turned to Ministry of Environment("https://www.env.go.jp/policy/local_keikaku/tools/suikei2.html"). It is crucial to highlight that access to the air pollution and weather-related data is restricted, as these datasets were utilized under license for the current study, making them not publicly accessible. However, we are prepared to provide these data to researchers upon reasonable request. Our approach to data sharing aligns with practices documented in sources like the example from Nature ("https://www.nature.com/articles/s41562-021-01255-w").

Code Availability Data sets and codes generated during the current study are available from the corresponding author on request.

Competing Interests The authors declare no competing interests.

Appendix A: Assumptions of Travel Speed

Table A1 displays the assumption of travel speed and restrictions based on the previous works.

Table A1: *Assumptions of travel speed by each travel mode*

Mode	Speed	Restrictions	Source
Railway	80 km/h	$t < 12h$	MLIT (2005)
HSR	1990-1991: 154.4 km/h 1992-2012: 189.5 km/h 2013-2020: 200 km/h	$t < 12h$	Shirakuni (2017)
Highway	70 km/h	$t < 6h$	MLIT (2010)
On foot	5 km/h	$d < 1.6km$	Daganzo (2010)
Local road/other mode	30 km/h	$t < 6h$	MLIT (2010)

Note: t: travel time; d: travel distance.

Appendix B: Parallel Trend Check

We first check the parallel trends assumption referring to seminal works such as Li et al. (2019), Lin et al. (2021), Callaway and Sant'Anna (2021), and De Chaisemartin and d'Haultfoeuille (2020). We adopt an event study design, dividing the time window around station openings into pre-opening (1-5 years before) and post-opening (up to 5 years after) periods. This interval choice is based on previous works by Donaldson (2018), Wang et al. (2020), and Chen and Haynes (2017), which use similar time lags. For most of the variables, the pre-treatment periods show no significant differences between treatment and control groups. Figure A1 graphically illustrates the coefficients of the regression results, reconfirming our parallel trends assumption. Overall, these findings confirm the parallel trends assumption for all of our data.

Appendix C: LCPST Network

Figure A2 shows the actual networks and the LCPST networks of HSR and highway, respecively. The extracted LCPST network is structured to connect each station with a

Table A2: *Event study analysis of subway openings (parallel test)*

	Logarized CO_2 emissions from Transport	Logarized Railway Ridership	Logarized VKT
	Model (1)	Model (2)	Model (3)
Treatment (1km) at Year 0	0.0390**	0.467*	0.134***
	(0.0183)	(0.267)	(0.0272)
Treatment (1km) at Year -1	0.0000430	-0.00697	-0.0190
	(0.0163)	(0.238)	(0.0243)
Treatment (1km) at Year -2	0.00109	0.00685	-0.00153
	(0.0152)	(0.224)	(0.0229)
Treatment (1km) at Year -3	0.00142	0.00510	-0.00596
	(0.0149)	(0.219)	(0.0223)
Treatment (1km) at Year -4	-0.00219	-0.115	0.00596
	(0.0146)	(0.216)	(0.0219)
Treatment (1km) at Year -5	0.0186*	0.403***	-0.0248
	(0.0106)	(0.156)	(0.0159)
Treatment (1km) at Year +1	-0.0264	0.110	0.000438
	(0.0206)	(0.298)	(0.0313)
Treatment (1km) at Year +2	-0.00574	0.0241	-0.00239
	(0.0223)	(0.320)	(0.0341)
Treatment (1km) at Year +3	-0.00470	0.0350	-0.00196
	(0.0223)	(0.320)	(0.0341)
Treatment (1km) at Year +4	-0.00368	0.132	0.00197
	(0.0226)	(0.324)	(0.0346)
Treatment (1km) at Year +5	-0.00176	1.301***	0.00185
	(0.0177)	(0.253)	(0.0272)
Station Opening: 1km-2km	0.0723***	1.030***	0.115***
	(0.00754)	(0.112)	(0.0110)
Station Opening: 2km-5km	0.0409***	0.262***	0.0837***
	(0.00512)	(0.0765)	(0.00713)
Station Opening: 5km-10km	-0.0188***	-0.303***	0.0680***
	(0.00576)	(0.0860)	(0.00816)
Constant	3.967***	4.432***	2.528***
	(0.00378)	(0.0568)	(0.00515)
N	49,851	50,431	47,763
R-sq	0.997	0.951	0.439
F	13.40	27.28	14.43

Note: Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1. Models (1) and (2) include prefecture-by-year, city fixed effects, cubic-polynomial fixed effects, and weather control variables (omitted for brevity). Model (3) includes prefecture, year, city, cubic-polynomial fixed effects, and weather control variables (omitted for brevity). Two-sided t-tests are employed to test the significance of the coefficients.

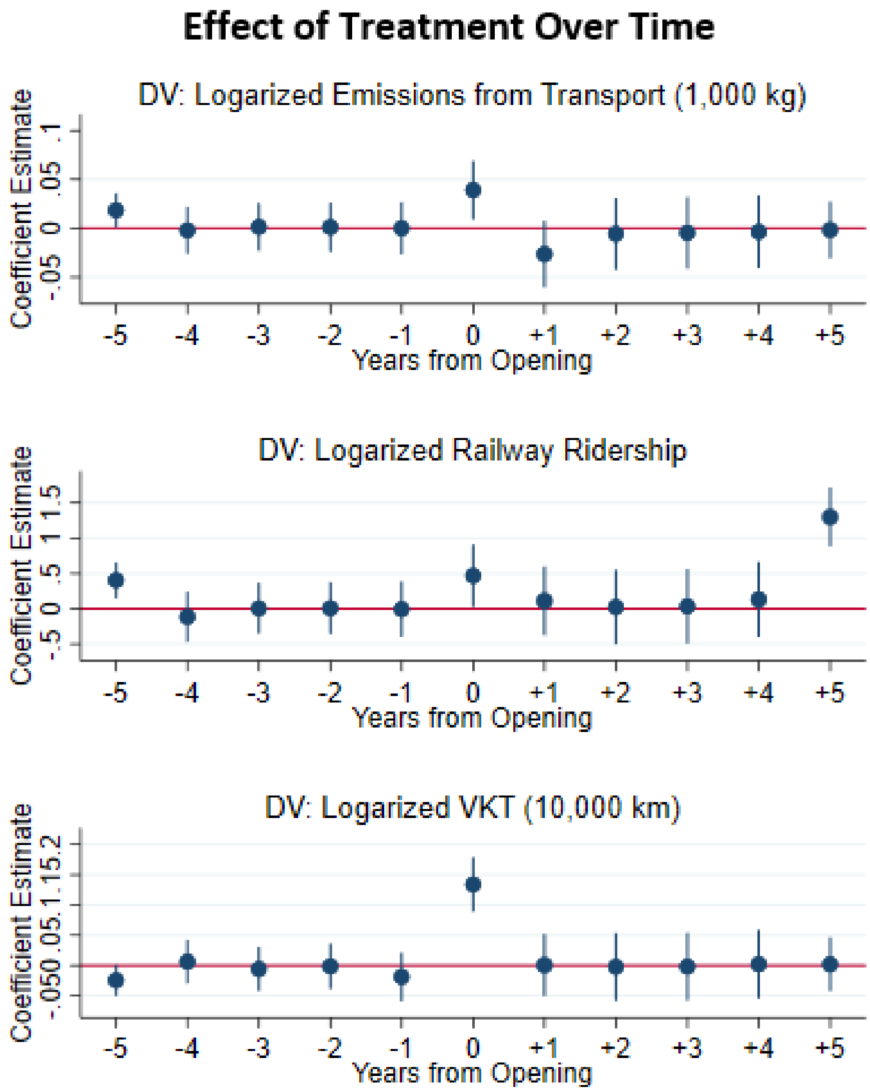

Figure A1: *Parallel trends results*

shorter total length of the whole network than the actual network. In the LCPST network, paths are determined based on geographical considerations such as water areas, elevations, and land fluctuations, aiming to identify the minimum-cost routes connecting major HSR stations or major highway interchanges. We calculate the geographical construction cost at the cell level using land-cover and geographical traits data. The land cover data are retrieved from JAXA ALOS High-Resolution Land Use and Land Cover Map Products: https://www.eorc.jaxa.jp/ALOS/en/dataset/lulc_e.htm; the digital elevation data are retrieved from JAXA ALOS Global Digital Surface Model "ALOS World 3D - 30m (AW3D30)": `https://www.eorc.jaxa.jp/ALOS/en/dataset/aw3d30/aw3d30_e.htm`. The construction cost function is based on Zheng et al. (2022).

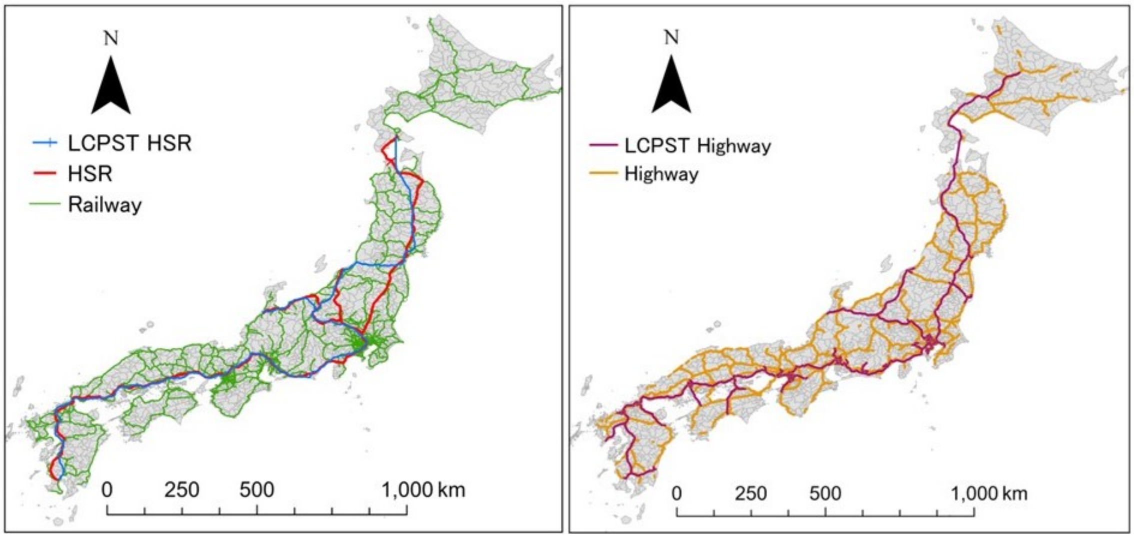

Figure A2: *LCPST networks for HSR and highway*

Appendix D: First Stage Result

Table A3 details the first-stage regression results of our empirical analysis. We employ three distinct models for each dependent variable: Railway MA in Model (1) and Highway MA in Model (2), with independent variables being the Least Cost Path Spanning Tree (LCPST)-based Railway MA and Highway MA.

Echoing the insights from Herzog (2021), the significant positive coefficient on the LCP-based distance instrumental variable (IV) emphasizes the importance of construction costs and geographic characteristics in determining railway and highway placements. In line with the approach used by Dong et al. (2021), we implement the Lagrange multiplier (LM) statistic and the Anderson canonical correlation LM statistic to validate our IV analysis. The results from these diagnostic tests confirm that our IV strategy successfully addresses both underidentification and weak identification issues across all models. This robust validation not only ensures that our models are correctly specified but also demonstrates a strong link between the IVs and the endogenous regressors, significantly enhancing the credibility of our findings.

Table A3: *First stage regression result*

DV	Model (1) Railway Market Access	Model (2) Highway Market Access
LCPST based Railway Market Access	0.956***	
	(0.003)	
LCPST based Highway Market Access		0.733***
		(0.009)
Constant	0.193***	0.009***
	(0.132)	(0.179)
N	51,570	51,570
R-sq	0.999	0.999
Underidentification test		
Anderson canon. corr. LM statistic	31,582.77	5,954.31
Weak Identification test		
Cragg-Donald Wald F statistic	76,616.58	6,329.11

Note: Standard errors are shown in parentheses. * $p<0.1$, ** $p<0.05$, and *** $p<0.01$. All models include prefecture-by-year fixed effects, city fixed effects, and cubic-polynomial fixed effects. Two-sided t-tests are employed to test the significance of the coefficients.

Appendix E: Heterogeneity Results

Tables A4, A5, and A6 present the estimation results exploring the heterogeneity of impacts on CO_2 emissions, railway ridership, and travel distances across various regional categories. The findings consistently indicate that railway expansions have generally reduced CO_2 emissions, increased ridership, and decreased travel distances, affirming the hypothesized substitution effect from car usage to railway transport. Our analysis employs multiple models to capture distinct regional impacts: Models (1) and (2) compare cities with high versus low CO_2 emission levels; Models (3) and (4) contrast cities characterized by low income and high growth with other cities; and Models (5) and (6) examine cities within versus beyond the median distance from railway stations, assessing the influence of station proximity on the observed outcomes.

Table A4: *Heterogeneity result: CO_2 emissions*

	Model (1) High CO_2=1	Model (2) High CO_2=0	Model (3) Rising Income=1	Model (4) Rising Income=0	Model (5) Station Far=1	Model (6) Station Far=0
DV: Logarized Emissions from Transport (1,000 kg)						
ln (Railway MA)	-0.033***	-0.020***	-0.068***	0.002	-0.028***	-0.033***
	(0.007)	(0.005)	(0.006)	(0.006)	(0.007)	(0.007)
ln (Highway MA)	-0.024	0.713***	0.641***	0.357***	0.461***	0.558***
	(0.023)	(0.014)	(0.021)	(0.015)	(0.018)	(0.016)
Constant	6.070***	-2.412***	-0.975***	0.907***	0.198	-0.647***
	(0.219)	(0.121)	(0.167)	(0.136)	(0.143)	(0.154)
N	12,360	39,180	16,863	34,396	25,838	25,731
R-sq	0.991	0.995	0.998	0.997	0.997	0.997
F	11.73	1254.7	480.7	293.3	319.6	590.0

Note: Standard errors are shown in parentheses. * p<0.1, ** p<0.05, and *** p<0.01. All models include prefecture-by-year fixed effects, city fixed effects, and cubic-polynomial fixed effects. Two-sided t-tests are employed to test the significance of the coefficients.

Table A5: *Heterogeneity result: railway ridership*

	Model (1) High CO_2=1	Model (2) High CO_2=0	Model (3) Rising Income=1	Model (4) Rising Income=0	Model (5) Station Far=1	Model (6) Station Far=0
DV: Logarized Railway Ridership						
ln (Railway MA)	0.629***	0.242***	0.0814**	0.696***	0.394***	0.674***
	(0.0880)	(0.0213)	(0.0344)	(0.0767)	(0.0379)	(0.111)
ln (Highway MA)	0.601*	0.530***	0.241**	0.732**	0.633***	0.534
	(0.333)	(0.0696)	(0.116)	(0.303)	(0.109)	(0.345)
Constant	-10.16***	-6.701***	-2.255***	-12.49***	-7.717***	-10.58***
	(3.300)	(0.637)	(0.803)	(2.997)	(0.811)	(3.537)
N	12960	39180	16867	34992	25979	26190
R-sq	0.918	0.970	0.968	0.920	0.980	0.910
F	28.24	107.4	11.35	46.91	119.9	21.08

Note: Standard errors are shown in parentheses. * p<0.1, ** p<0.05, and *** p<0.01. All models include prefecture-by-year fixed effects, city fixed effects, and cubic-polynomial fixed effects. Two-sided t-tests are employed to test the significance of the coefficients.

Table A6: *Heterogeneity result: logarized VKT*

	Model (1) High CO_2=1	Model (2) High CO_2=0	Model (3) Rising Income=1	Model (4) Rising Income=0	Model (5) Station Far=1	Model (6) Station Far=0
DV: Logarized VKT						
ln (Railway MA)	-0.035***	-0.009	-0.018*	-0.016**	-0.034***	-0.026***
	(0.011)	(0.007)	(0.011)	(0.007)	(0.009)	(0.010)
ln (Highway MA)	0.296***	0.288***	0.074**	0.267***	0.249***	0.349***
	(0.030)	(0.017)	(0.035)	(0.017)	(0.020)	(0.022)
Constant	0.211	0.198	2.144***	0.327**	0.868***	-0.421**
	(0.284)	(0.139)	(0.281)	(0.147)	(0.160)	(0.204)
N	11,520	37,890	16,329	32,890	25,148	24,261
R-sq	0.362	0.409	0.368	0.473	0.459	0.329
F	49.450	157.300	3.032	131.800	75.680	126.600

Note: Standard errors are shown in parentheses. * $p<0.1$, ** $p<0.05$, and *** $p<0.01$. All models include prefecture-by-year fixed effects, city fixed effects, and cubic-polynomial fixed effects. Two-sided t-tests are employed to test the significance of the coefficients.