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ORIGINAL ARTICLE

Colonial origins of agglomeration: Evidence from Malayan rail stations

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Summary:
Using century-old data on rail stations, agglomeration hubs, tin mines, and rubber plantations, paired with current economic data, this study shows that early access to rail stations continues to drive higher economic activity today, emphasizing enduring agglomeration effects.

Abstract

This study examines how historical rail stations condition long-run development using Colonial Malaya as a laboratory. By constructing novel historical data on rail stations, agglomeration centres, tin mines, and rubber plantations dating back a century and matching contemporary data on economic activity at the 1-km cell level, we find that regions with earlier access to rail stations exhibit higher levels of economic activity today, owing to agglomeration economies. These results persist even in regions that have abandoned colonial stations. This study highlights the role of investment in transport infrastructure in accelerating local economic activity.

KEYWORDS
agglomeration, Colonial Malaya, nightlights, railroads

Do colonial rail stations shape local economic activity in the long run? Krugman argued that efficient transportation infrastructure, such as railroads, can reduce transaction costs, create increasing returns to scale, enhance the marginal productivity of private inputs, and ultimately stimulate economic activity.[1] By the mid-nineteenth century, several industrialized countries, including the United States (13,500 km), Great Britain (9800 km), Germany (5800 km), and France (2900 km), had built extensive railroad infrastructure.[2] These countries extended their spatial

[1] Krugman, ‘Increasing returns’.

[2] Büchel and Kyburz, ‘Fast track to growth’, p. 158.

control by building railroads in the late nineteenth century.[3] Although the long-term impact of railroad infrastructure has been widely studied, the focus has largely been on the Western and African contexts,[4] with only a few notable exceptions examining India and China.[5] To the best of our knowledge, no study has yet investigated the role of colonial railroad infrastructure in Southeast Asia.

This study is the first to leverage a natural experiment of the colonial railroad network in Malaya to examine how this infrastructure has shaped contemporary local economic activities in Malaysia.[6] This approach offers several advantages for spatial analyses. First, despite the extensive construction of 1900 km of railroads during the British colonial period (i.e. 1885–931), surprisingly Malaysia did not expand its railroad network until 1995, minimizing the potential omitted variable bias from post-colonial railroad expansions.[7] Second, although colonial Malaya has detailed records of its railroad stations, no study has systematically digitized such historical data. We address this gap by developing a novel dataset on the historical railroad network from 1885 to 1931, which includes 107,072 cells at the 1 × 1 km level and 307 stations across Peninsular Malaysia.[8] Unlike existing studies focusing primarily on rail lines, we estimate the enduring impact of railroad stations.[9] Third, we use night-time light intensity data from 1992 to 1994 at the 1 × 1 km cell level sourced from the United States Air Force Defense Meteorological Satellite Program (DMSP) as an outcome indicator of current local economic activity.[10] These fine-grained data combined with precise station locations allowed us to estimate both the colonial railroad infrastructure's spatial concentration and leapfrog spillover effects.

A potential concern with this historical natural experiment is the spatial endogeneity of the railroad network, as station locations may have been influenced by both observable and unobservable

[3] Atack et al., 'Did railroads induce'; Hornung, 'Railroads and growth'; Donaldson and Hornbeck, 'Railroads and American'; Büchel and Kyburz, 'Fast track to growth'; Braun and Franke, 'Railways, growth and industrialization'.

[4] Jedwab and Moradi, 'The permanent effects'; Berger and Enflo, 'Locomotives of local growth'; Jedwab et al., 'History, path dependence'; Hodgson, 'The effect of transport'; Okoye et al., 'New technology, better economy'.

[5] Donaldson, 'Railroads of the Raj'; Fenske et al., 'Railways and cities'; Banerjee et al., 'On the road'.

[6] In this paper, we interchangeably use 'Malaysia' as 'Peninsular Malaysia', which was the former colonial 'Malaya'.

[7] This approach also shields our estimations from biases related to reverse causality. A similar approach has been adopted by Jedwab and Moradi, 'The permanent effects'; Jedwab et al., 'History, path dependence', and Okoye et al., 'New technology, better economy'.

[8] We constructed a comprehensive network of historical railroad stations in Malaysia by compiling data extracted from various government repositories, historical reports, and railroad maps (see app. A1, which provides a full account of our data sources). We validated the accuracy of our dataset with Google Earth and cross-checked the geo-referencing of railroad stations to gain precision.

[9] Rail lines might capture dubious effects, as rail lines are ineffective unless locals can access rail services. The causal inference about the importance of railroad networks can be ascertained more precisely by examining the effect of railroad stations on local economic activity. Therefore, the findings of existing studies are somewhat downward biased, as data on railway stations are embedded into their data on rail lines (arguably, there should be at least one railroad station located in each city or locality).

[10] We used data from 1992 to 1994 to avoid our results being impacted by new railroads built after 1995. Our results are also robust to a harmonized night-time light intensity dataset generated by Li et al., 'A harmonized global', accounting for the newer night-time light intensity data from the Visible Infrared Imaging Radiometer (VIIRS). See Gibson, 'Better night lights' and Gibson et al., 'Which night lights', for a detailed explanation and comparison between data from both sources. Storeygard, 'Farther on down', used satellite data on lights at night as a proxy for economic activity and new road network data to calculate the shortest route between cities. Our work differs as we link the night-time light intensity data with the historical railroad network data to estimate its impact on current economic activity. Similarly, Jedwab and Moradi, 'The permanent effects', used the satellite-based night-time light intensity data in their auxiliary analyses.

preexisting economic characteristics. We addressed this concern in several ways. First, we compare the economic activity of 'treatment' cells (i.e. cells with stations) to its nearest 'comparison' cells (i.e. eight adjacent treatment cells without stations) within 1 km. Given the minimal variation in preexisting characteristics such as geographical, cultural, economic, and political differences between these closely situated treatment and comparison cells, our approach minimized potential pre-trend bias. Second, to mitigate confounding and omitted variable biases, we controlled for geographical factors such as colonial-era tin mining and rubber cultivation areas, terrain ruggedness, and proximity to the coast and rivers. Third, we included additional controls for the shortest distance between stations and the nearest straight-line path between major stations, accounting for potential location bias related to secondary stations. We further validated our findings through empirical tests examining junction railroads, as well as the impact of placebo, abandoned stations, and destroyed stations during the Second World War. These empirical checks indicate that our estimates reflect the causal effects of colonial railroad stations on long-term economic development.

Our results demonstrate that railroad stations increase long-term economic activity by 19 percentage points. We also investigated how this economic activity propagated to the stations (spatial concentration effect) and from the stations (leapfrog spillover effect) across varying distances. By expanding the cell size from 1×1 km to 3×3 km and 5×5 km around the stations, we observed that the economic impact of railway stations diminished as the treatment cell size increased, indicating a spatial concentration of economic activity near the stations. Next, we estimated the leapfrog spillover effect of railway stations on distant areas by horizontally shifting our treatment cells up to 25 km from the stations in both directions. We find that the economic activity spillovers from colonial rail stations diminish after 3 km and persist up to 10 km. Overall, our findings indicate that while the economic impacts are highly concentrated around the stations, they also extend spatially up to 10 km, consistent with Rosenthal and Strange.[11]

We find that historical railroad stations stimulate economic activity through agglomeration economies. At the cell level, we geo-referenced the locations of all agglomeration centres – villages, towns, district headquarters, and state capitals – that existed in 1922 (381 centres) and 1967 (1959 centres). Cells with railroad stations were more likely to evolve into new agglomeration centres by 1967 than by 1922. However, agglomeration data do not provide information on the size of these centres. To address this limitation, we conducted a mediation analysis at the *mukim* (subdistrict) level, including 1947 population census data as a mediator. This variable significantly reflects the effects attributed to railroad stations. Our findings indicate that railroad infrastructure fosters agglomeration economies, supporting Marshall's theory that firms and labour tend to cluster around railroad stations to reduce transport costs, thereby driving long-term economic development.[12]

This study contributes to the existing literature by exploring the agglomeration economies of railway stations.[13] In this strand of literature, Duranton and Puga identified three mechanisms through which agglomeration can evolve: sharing common infrastructure (e.g. railroads), matching between employers and employees (i.e. labour pooling) and learning between people (e.g. technology transfer).[14] We argue that large-scale agglomerations may emerge from rail stations

[11] Rosenthal and Strange, 'Geography, industrial organization'.

[12] Marshall, *Principle of economics*.

[13] See Rosenthal and Strange, 'Evidence on the nature', for a survey on the nature and sources of agglomeration economies.

[14] Duranton and Puga, 'Micro-foundations of urban'.

due to reduced transport costs facilitated factor mobility. Our finding on the spatial concentration effect – agglomeration economies are strongest at the local level but attenuate drastically with distance – is consistent with Myrdal and Sitohang's backwash effect: the lucky areas (cells with stations) attract economic resources away from the unlucky ones (cells without stations), particularly via labour pooling, capital movement, and trade.[15] Next, our finding on the leapfrog spillover effect – economic activity expands from stations but disappears beyond 10 km – aligns with Rosenthal and Strange's findings: some firms benefit from denser locations, while others avoid congestion by spreading out.[16] Overall, our study provides evidence on how and to what extent colonial railroad stations boost contemporary economic activity through the agglomeration of economies across space.

This study adds to the rich body of literature on the impact of railroad infrastructure on economic activity. The effects of railroads in the nineteenth-century United States have been well documented, notably by Fogel and Fishlow.[17] More recently, the literature has increasingly focused on the causal relationship between transportation infrastructure and economic growth, although most studies have only estimated the effects of rail lines. This study departs from the existing literature by focusing on rail stations. Moreover, most studies examined medium-term effects (0–40 years).[18] Exceptions include Jedwab and Moradi, who estimated long-term effects (0–110 years).[19] Our study extends this strand by investigating the long-term impact (0–130 years) of colonial railroads, deepening our understanding of the economic effects of the colonial legacy.[20] Hence, this study builds on findings from Jedwab and Moradi, Jedwab et al., and Okoye et al.,[21] who investigated the long-term effects of colonial railroads in African countries.[22] These studies support the 'path dependence hypothesis', indicating that localized historical shocks (e.g. colonial railroad construction) have enduring effects on the distribution and level of economic activity.[23] Our findings add to the growing body of literature on the long-term impacts of railroads on economic development.

[15] Myrdal and Sitohang, *Economic theory*.

[16] Rosenthal and Strange, 'Geography, industrial organization'.

[17] Fogel, *Railroads and American*; Fishlow, *American railroads*.

[18] See Redding and Turner, 'Transportation costs', for a review of this literature. For example, studies looking into the medium-term effects in the context of nineteenth-century railroads include Atack et al., 'Did railroads induce', in American Midwest; Hornung, 'Railroads and growth', in Prussia; Berger, 'Railroads and rural', in Sweden; Braun and Franke, 'Railways, growth and industrialization', in Germany; and Esteban-Oliver, 'On the right track', in Spain.

[19] Jedwab and Moradi, 'The permanent effects'.

[20] Berger and Enflo, 'Locomotives of local growth', estimated the impact of railroads on urban growth in Sweden from 1855 to 2010, while Hodgson, 'The effect of transport', examined the impact of railroads built between 1868 and 1899 on the distribution of towns in 2010. On the investigation of the persistent impact of colonial railroad, Jedwab and Moradi, 'The permanent effects', and Okoye et al., 'New technology, better economy', focused on a period of 110 years in the context of African countries.

[21] Jedwab and Moradi, 'The permanent effects'; Jedwab et al., 'History, path dependence'; Okoye et al., 'New technology, better economy'.

[22] Other studies looking into the long-term impact of railroads include Berger and Enflo, 'Locomotives of local growth', focusing on urban growth in Sweden; Hodgson, 'The effect of transport', examined the persistent impact in the American West; while Banerjee et al., 'On the road', investigated the long-term economic outcome in China. Several studies also focused on the long-term impact of colonial roads, including Bertazzini, 'The long-term impact', and Marein, 'Colonial roads'. All five studies provided evidence of long-term economic impact in areas near historical transportation networks.

[23] Similarly, Bleakley and Lin, 'Portage and path', argued that cities persist in former portage sites even if no natural advantages exist to the present.

Finally, our study contributes to the literature on the long-term impact of colonial investment. Chaudhary and Garg found that the effects of colonial investments in education in India persisted for six decades but eventually dissipated due to effective policy interventions.[24] In contrast, Huillery found that colonial investments in health, education, and infrastructure have more persistent effects on development in West Africa.[25] Similarly, Dell and Olken demonstrated that areas near Dutch-established sugar factories in Java continue to exhibit higher levels of industrialization today.[26] Consistent with this strand of literature, our findings indicate that areas with colonial rail stations experience higher levels of economic activity today.

The remainder of the paper is organized as follows. Section I provides the historical background of Malaysia's railroad infrastructure. Section II describes the data sources and some summary statistics. Section III presents the empirical strategy explaining identification issues. Section IV, V, VI and VII discuss our results, robustness and other checks, and a potential mechanism. Section VIII concludes.

I | HISTORICAL BACKGROUND

Railroad development in Peninsular Malaysia can be divided into three phases during British colonization.[27] The first phase (1885–96) was concentrated on the west coast of Peninsular Malaysia to serve the tin mining industry. It consists of four major lines, as illustrated in appendix A2.[28] All four lines connected the inland tin mining area to the nearest coastal port.[29] Most of these initial lines were abandoned, except for the railroad lines that connected Klang to Kuala Lumpur and Ipoh to Batu Gajah.

The second phase (1897–1909) extended the existing railroads to connect major west coast cities to existing lines to facilitate the transport of tin ore to the nearest coastal port. The lines were primarily longitudinal and connected from south to north. Pahang was the only state under British control during that period yet to be connected by the end of the second phase. Several attempts were made to expand railroads into Pahang, primarily because of its rough topography.[30]

The third phase (1910–31) connected the northern states and the east coast to meet the needs of rubber plantations. Rubber was an important commercial commodity in the early twentieth century. The rubber cultivation area expanded from 2190 km^2 in 1910 to 13,860 km^2 in 1940.[31] Therefore, railroads likely inspired colonial Malaya to transform into an export-oriented economy specializing in tin and rubber. As Pahang is located between the west and east coasts, railroad lines must extend through Pahang before extending to Kelantan from the west coast. The railroad network on the east coast was constructed in 1931.

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[24] Chaudhary and Garg, 'Does history matter'.

[25] Huillery, 'History matters'.

[26] Dell and Olken, 'The development effects'.

[27] Kaur, 'Road or rail', p. 47.

[28] Fisher, 'The railway geography', p. 125.

[29] Kaur, 'The impact of railroads', p. 695.

[30] Fisher, 'The railway geography', p. 128; Kaur, 'Road or rail', p. 47.

[31] Lees, *Planting empire*, p. 211.

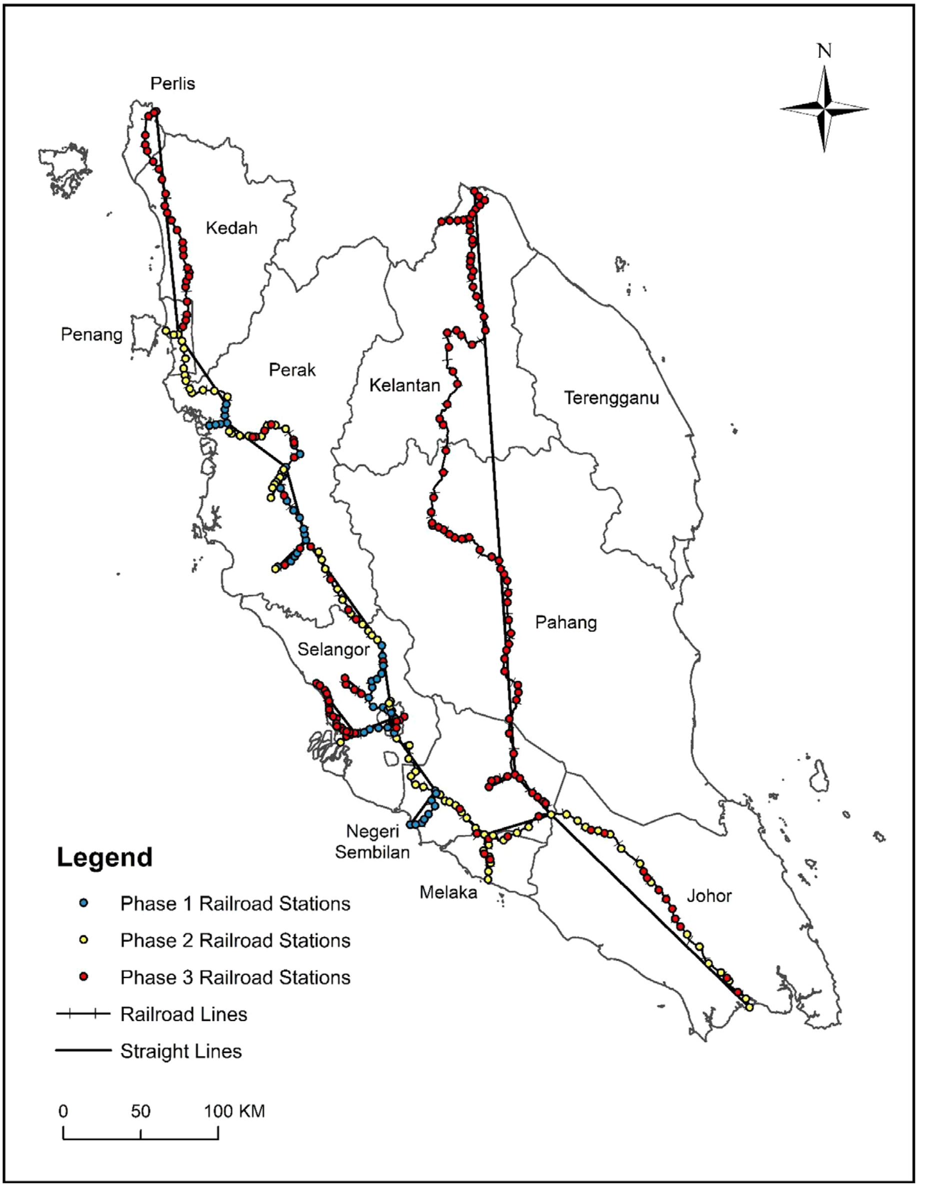

FIGURE 1 Historical railroad network in Peninsular Malaysia. *Sources*: See sect. II.

After the third phase, no railroad lines were extended until 1995. Nonetheless, several colonial railroad stations were abandoned, and some were destroyed during Japanese strategic bombing operations in the 1940s. Figure 1 illustrates the railroad network in Peninsular Malaysia.

II | DATA AND MEASUREMENT

We constructed a dataset consisting of 107,072 cells of 0.01×0.01 decimal degrees (roughly 1 km^2), covering the entire Peninsular Malaysia. The rail line and station data were collected and compiled from various sources.[32] A validation exercise was carried out to crosscheck the locations of all railroad stations using a recent Google Earth map. Several historical rail lines and stations in East Malaysia were excluded from the analysis owing to data unavailability.

We use a binary indicator (1 if a cell contains one or more railroad stations, 0 otherwise).[33] Our treatment group consisted of cells with at least one historical railroad station, whereas our comparison group consisted of cells without railroad stations. Our data are limited to railroad stations built before 1931, the end of major railroad construction, and there were no additional railroad network developments until 1995. We identified 307 colonial railroad stations built between 1885 and 1931.

Following most of the literature, we adopted geo-coded night-time light intensity data to indicate economic and human activity.[34] These were derived from satellite images from Operational Linescan System sensors installed on the DMSP satellites. The raw dataset was then processed to remove light from sunlight, moonlight, aurorae, forest fires, and clouds to capture only human-made light. The night-time light intensity in each cell is depicted by a digital number (DN) ranging from 0 to 63, where 0 indicates no light and 63 is the maximum brightness level. We relied on the average visible DN of cloud-free light detection multiplied by the percentage frequency of light detection to capture the time required for each light detection. If light was only detected half the time, the value was discounted by 50 per cent.

We used night-time light intensity between 1992 and 1994 as our dependent variable to measure levels of economic activity. These years were chosen because night-time light data became available in 1992, whereas modern railroad connections were built in 1995. Modern railroads were constructed to enhance connectivity between major cities surrounding the capital city of Kuala Lumpur. We can reasonably expect that modern railroads may have affected the economic growth pattern from 1995 onwards, and excluding these modern railroads may surmount the endogeneity concern.

We incorporated various controls into our analysis to account for potential confounding factors. These control variables include (i) the distance to the nearest tin mining sites to account for local geographical endowment, (ii) rubber cultivation areas to take into account pre-existing endowment, (iii) distance to the nearest major rivers to control for an alternative mode of transport, (iv) topographic ruggedness that may affect the construction of railroads, (v) distance to the nearest coastal area accounting for potential transport and resource advantage gained from the ocean, and (vi) a state dummy to account for the different historical institutions and economic development between all 11 states.[35] The tin mining areas were geo-referenced from a historical map from 1891, the earliest possible date we could obtain. Rubber cultivation areas were geo-referenced from the 1940 historical map produced by Lees and measured in square kilometres.[36] Similarly, these were the earliest possible data available. All the control variables were measured at the cell level.

[32] See app. A1 for the list of data sources.

[33] The cell is considered to have railroad access if the railroad station has ever been constructed in that cell, even if it was later abandoned.

[34] Henderson et al., 'Measuring economic growth', and Chen and Nordhaus, 'Using luminosity data', justified that night-time light intensity is a reliable proxy for economic growth. They found that the annual variations in gross domestic product (GDP) are highly correlated with the night-time light intensity changes. Hu and Yao, *Illuminating economic growth*, argued that using GDP per capita to proxy for economic development is less accurate for low- and middle-income countries, and night-time light intensity can be used to improve the previously mentioned measure.

[35] See app. A1 for a full account of data sources.

[36] Lees, *Planting empire*, p. 172.

TABLE 1 Summary statistics (mean) for treated and comparison cells.

Variables	Station (1)	Non-station (2)
Average nightlights digital number 1992–4	17.736	2.499
	(21.463)	(8.415)
Distance to nearest river (km)	1.518	2.426
	(1.470)	(2.480)
Distance to nearest coast (km)	37.489	44.857
	(33.094)	(34.714)
Terrain Ruggedness Index (m)	25.145	101.447
	(26.992)	(134.081)
Distance to nearest tin mining site (km)	60.105	100.575
	(55.655)	(61.065)
Rubber cultivation area (km^2)	0.522	0.181
	(0.553)	(0.408)
Observations	307	106765

Note: This table presents the mean of each variable for cells with railroad stations (col. 2) and cells without railroad stations (col. 3). The standard deviations are in parentheses.
Sources: See sect. II.

Table 1 presents the mean values of our variables of interest. Column 1 of table 1 illustrates that, on average, cells with railroad station access had a nighttime light intensity of 17.736 DN between 1992 and 1994. However, it was only 2.499 DN in cells without station access, as illustrated in column 2, suggesting a positive relationship between both variables.[37] Exploring the difference between states, we found that cells without railroad stations in Penang have a DN value of 22.376, which is much larger than that of all other states (except Selangor), regardless of the presence or absence of railroad stations. The large difference in nighttime light intensity across states suggests that the effect of railroad stations is heterogeneous across different regions, hence providing the rationale for including the state dummy in the analysis. A table comparing nighttime light intensity between the states is provided in appendix A4.

III | EMPIRICAL STRATEGY

We exploit time lags within a cross-sectional setting to examine the persistent effects of colonial railroad stations on economic development. Specifically, we investigate the impact of historical railroad access on nighttime light intensity-based measures of current economic activity. The ordinary least squares (OLS) model has the following form:

$$\text{DN}_c = \beta_0 + \beta_1 \text{STATIONS}_c + \pi' X_c + \gamma_s + \epsilon_c \quad (1)$$

[37] App. A3 presents the visual comparison between areas with and without railroad stations, showing that economic activity mostly concentrates around rail stations.

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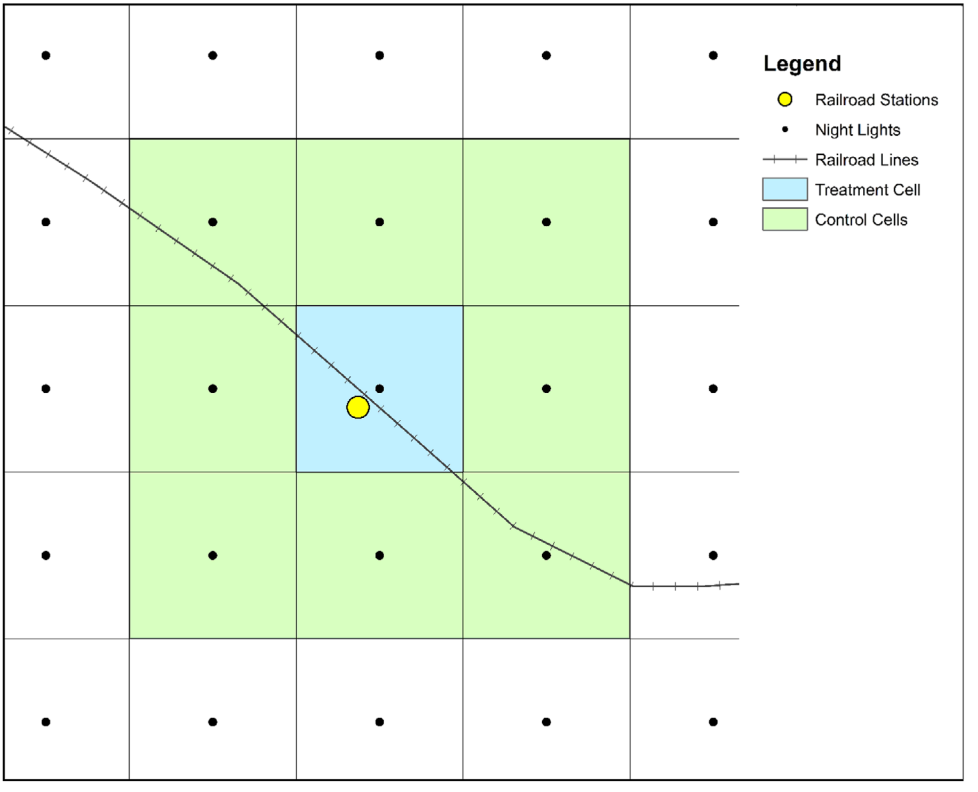

FIGURE 2 Treatment and comparison cells for truncated sample. *Sources*: See sect. II.

where DN_c is the average nighttime light intensity, ranging from 0 to 63, between 1992 and 1994 for cell *c*; $STATIONS_c$ is a dummy variable showing the historical railroad station access in cell *c*; X_c refers to a set of covariates; γ_s is the state dummy; and ϵ_c is the disturbance term.

Our high-resolution spatial unit of a 1×1 km cell level (the Cell Approach) allows us to compare the current economic activity in cells with rail stations and their associated neighbouring cells within 1 km peripheries but without any railroad station. As these cells are located in proximity, pre-existing factors (including geographical, cultural, and political differences) are almost identical. The only difference between these cells is the existence of railroad stations (see figure 2, which illustrates a schematic of the treatment cell and its associated comparison cells). Hence, any difference in nighttime light intensity between these adjacent cells is likely attributable to differences in accessibility to railroad stations. Thus, our findings drawn from 1 km cell-level analyses likely represent the causal impact of historical stations on current economic activity.

Colonial British rulers constructed a railroad network in places that enabled the expropriation of ‘tin’ in the first and second phases and ‘rubber’ in the third. It tends to impose ‘location bias’ into our estimations. We controlled for tin mining areas in 1891 to account for the initial local endowments that determined the location for constructing railroad networks. Similarly, we georeferenced 1940 rubber cultivation areas and included them in the estimation models. Thus, by controlling for the tin mining sites and the rubber cultivation areas, we minimize the location bias of pre-existing endowments that may contaminate our estimation setting.

Moreover, there could be other unobserved spatial factors such as topographic barriers, political pressures (e.g. pork barrelling), and more importantly, the extractive spatial choice of the colonial rulers that may seriously plague our estimation with endogenous location choices. Following Atack et al., Hornung, Jedwab and Moradi, and Berger and Enflo,[38] we further tackle 'location bias' by augmenting our model with a control variable that measures the shortest distance from the endogenous location of actual to the exogenous location of counterfactual rail stations (see appendix A5 that illustrates the locations and the creation of the straight lines).[39] Incorporating this additional control in the model accounts for the factors that deviate stations away from the respective straight lines, which further minimizes location bias.

Furthermore, as pointed out by Kelly, spatial data tend to be highly autocorrelated, which could cause major issues, leading to spurious estimates and the underestimation of standard errors.[40] We addressed these concerns in three ways, following Kelly.[41] First, our estimation model includes longitude and latitude variables to control for potential spatial serial correlations. Second, our regression analysis incorporated controls that accounted for major rail stations. This ensures that our results are not disproportionately influenced by the higher economic activity generated by these key stations but reflect the impact of all rail stations. Third, we estimate the degree of spatial autocorrelation using Moran's I statistic. Our results are robust to spatial autocorrelation if the Moran's I statistics are statistically insignificant. In addition, we estimated Conley standard errors, adjusted for spatial autocorrelation. These approaches will likely minimize location biases that might impact our estimation setting.[42] The results are discussed in section VI.

Despite incorporating a set of observed covariates with a state dummy, our estimates may still suffer from omitted unobservables correlating with railroad stations and economic development. Following Oster, we employed an auxiliary analysis to address the concern of bias from unobservables.[43] Oster argues that coefficient stability is insufficient to address omitted variable bias. Instead, both coefficients and R-squared movements are essential to estimate a bias-adjusted treatment effect.[44] Hence, we employ this approach as a robustness check (see section VI) to mitigate omitted variable bias.

IV | MAIN RESULTS

Using the 'cell approach', table 2 presents the estimates of the effect of historical rail stations on economic activity using equation (1). We report the least squares estimates and robust standard errors clustered at the district level. Column 1 indicates that, on average, cells with historical rail

[38] Atack et al., 'Did railroads induce'; Hornung, 'Railroads and growth'; Jedwab and Moradi, 'The permanent effects'; Berger and Enflo, 'Locomotives of local growth'.

[39] Rail lines tend to be built straight (i.e. the shortest track) between two major rail stations to minimize their construction cost, which can only deviate due to location-specific endogenous factors. Using this analogy, we define counterfactual rail stations on straight lines but within the closest proximity of their associated actual stations. The straight lines and their associated rail stations are shown in fig. 1.

[40] Kelly, 'The standard errors of persistence', unpublished working paper (2019); Kelly, 'Understanding persistence', unpublished working paper (2020).

[41] Ibid.

[42] Conley, 'GMM estimation'.

[43] Oster, 'Unobservable selection'.

[44] Ibid.

TABLE 2 Persistent impact of colonial railroad stations.

	Dependent variable: average digital number (DN), 1992–4						
	Peninsular Malaysia	Phase 1	Phase 2	Phase 3	West coast	East coast	Truncated sample
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Station access by 1931	11.7***	23.7***	15.2***	5.90***	14.4***	2.26***	1.53***
	(2.691)	(5.834)	(3.010)	(1.801)	(2.972)	(0.741)	(0.364)
Distance to nearest river	−0.061	−0.060	−0.059	−0.060	−0.13	−0.038	−1.84***
	(0.043)	(0.042)	(0.042)	(0.043)	(0.091)	(0.036)	(0.647)
Distance to nearest coast	−0.024**	−0.023**	−0.023**	−0.023**	−0.035	−0.021*	−0.22*
	(0.011)	(0.011)	(0.011)	(0.011)	(0.025)	(0.011)	(0.117)
Terrain Ruggedness Index	−0.0011	−0.0011	−0.0012	−0.0011	−0.0018	−0.00039	−0.014
	(0.001)	(0.001)	(0.001)	(0.001)	(0.002)	(0.001)	(0.016)
Distance to nearest tin mining site	−0.0015	−0.0013	−0.0012	−0.0014	0.0015	−0.0048	−0.0030
	(0.012)	(0.012)	(0.012)	(0.012)	(0.020)	(0.011)	(0.064)
Rubber cultivation area	4.03***	4.08***	4.07***	4.09***	4.00***	3.83***	−3.73
	(1.072)	(1.073)	(1.072)	(1.075)	(1.294)	(1.287)	(2.502)
Observations	107 072	106 821	106 851	106 930	55 089	51 983	2546
R^2	0.18	0.18	0.18	0.18	0.18	0.048	0.30

Note: Using the 'cell approach' at 1 km^2 level, this table presents OLS estimates regressing average night light intensity (in DN) for 1992–4 on the access to historical rail stations. The robust standard error clustered at the district level is in parentheses. *Significant at 10% level, **significant at 5% level, ***significant at 1% level.
Sources: See sect. II.

stations have a night-time light intensity of 11.7 DN more than cells without rail stations, and the effect is statistically significant at the 99 per cent confidence level. Given the (0, 63) range of DN scores, an 11.7 point nighttime light intensity corresponds to an increase of 19 percentage points (analogous to an increase in economic activity). This estimate serves as the benchmark for subsequent analyses.[45]

Columns 2–4 of table 2 test whether historical rail stations have an accumulation effect on economic activity over time. We do so by estimating how rail stations built in three different historical periods (1885–96, 1897–1909, and 1910–31) affect today's economic activity.[46] We hypothesize that cells that gained railroad station access earlier would experience greater economic development. Our estimates support this notion: the coefficient for the first phase is 23.7, which is significantly higher than the coefficients of 15.2 and 5.9 in the second and third phases, respectively. This finding concurs with that of Berger and Enflo,[47] that is, the transient shock

[45] As Melaka was also colonized by the Portuguese and Dutch, the impact might differ from the rest of Peninsular Malaysia due to differences in political culture. Nevertheless, dropping Melaka from the sample provides similar estimations. The result is recorded in app. A6.

[46] Our treatment group takes a binary dummy indicator that assigns the value of 1 if a cell obtains railroad station access during the first phase, while the comparison group takes a value of 0. Using the same approach, we create second- and third-phase dummies. We remove cells that gained railroad access for the other two phases from each sample to ensure our estimation reveals the effect of railroad stations in only one of the phases.

[47] Berger and Enflo, 'Locomotives of local growth'.

of initial railroads induces path dependence, through which historical railroad networks have enduring influence on current economic activity. Following the (0, 63) range of the DN score, the coefficient of 23.7 DN for the first phase (i.e. rail stations built in 1885–96) is equivalent to 38 percentage points. That is, the colonial rail station boosted contemporary economic activity by 38 per cent. In comparison, Jedwab and Moradi find that the earlier phase of colonial rail in Ghana accounted for 42 per cent of the change in the urbanization rate from 1901 to 2000.[48] Our long-term findings are not far off in magnitude from their estimates, given that our outcome of interest comes from a more granular proxy for economic activity (i.e. night-time light intensity).

We employ regional disparities to substantiate the accumulation effects of historical railroads. In colonial Malaya, the west coast gained railroad access three decades earlier than the east coast. The estimates in columns 5 and 6 of table 2 illustrate that the magnitude of the coefficient on the west coast is larger than that on the east coast. Such a variation can be partly, but not completely, attributed to their duration of gaining railroad access. Another compelling argument is that railroad networks produce greater economic gains when they connect areas with export ports. For instance, Okoye et al. reported that railroads had a sizable economic impact in northern Nigeria,[49] where pre-railway access to export ports was restricted.[50] This line of argument seems plausible in our context: the west coast railroad network of Malaysia was characterized by its interconnections with five ports, including Penang, Weld, Klang (previously named Swettenham), Port Dickson, and Malacca, whereas the east coast was connected to a port of Tumpat only. That is, extensive railroad connections with ports of export on the west coast of Malaysia might explain its relatively higher economic gains than those on the east coast.

As a robust identification strategy, we truncate our comparison groups and compare the treatment cells with only its eight immediate neighbouring cells (peripheral cells). In this setting, endogeneity concerns related to pretreatment conditions are further minimized because two neighbouring cells within the same vicinity are almost identical, except for their status of accessing rail stations. A spatial diagram of the peripheral cells is depicted in figure 2. Our estimates in column 7 indicate that the economic effect of historical rail stations is substantial.[51]

As most studies examine the economic impact of rail lines instead of rail stations, we run a horserace between them. We repeated the same analyses as in table 2, using rail lines as our treatment, and summarized the results in table 3. Overall, our estimates suggest that railroad stations have a higher economic impact than rail lines; the coefficients in table 3 are smaller in magnitude than those in table 2. Such coefficient differences are expected because we can only access the rail network from rail stations, not rail lines. These results indicate that the treatment of railroad stations captures the true effects of the rail network more accurately.[52] One potential explanation for the significant effect of rail lines, even when there are no stations, could be the spatial concentration and spillovers around railroad stations, which we discuss in detail in the next section.

48 Jedwab and Moradi, 'The permanent effects', p. 279.

49 Okoye et al., 'New technology, better economy'.

50 Other evidence includes Hornung, 'Railroads and growth', indicating that railroads had a larger impact in West Prussia.

51 Note that the coefficient is relatively smaller in magnitude. This is because the peripheral cells (i.e. comparison cells) at 1 km^2 are likely to receive economic spillovers, making our estimates downward biased.

52 App. A7 provides a more detailed comparison of rail stations and rail lines.

TABLE 3 Persistent impact of colonial railroad lines.

	Dependent variable: average digital number (DN), 1992–4					
	Peninsular Malaysia	Phase 1	Phase 2	Phase 3	West coast	East coast
	(1)	(2)	(3)	(4)	(5)	(6)
Rail line access by 1931	8.59***	20.7***	9.93***	2.98*	11.5***	0.77
	(2.044)	(5.620)	(1.948)	(1.622)	(2.245)	(0.855)
Observations	107 072	105 400	105 845	105 977	55 089	51 983
R^2	0.19	0.19	0.18	0.17	0.20	0.048

Note: Using the 'cell approach' at 1 km^2 level, this table presents OLS estimates regressing average night lights intensity (in DN) for 1992–4 on the access to historical rail lines. Controls include distance to river, distance to coast, topography ruggedness, distance tin mining site, rubber cultivation area, and state dummy. The robust standard error clustered at the district level is in parentheses. *Significant at 10% level, and ***significant at 1% level.
Sources: See sect. II.

V | SPATIAL CONCENTRATION AND LEAPFROG SPILLOVER EFFECTS

Our estimates in section IV demonstrate that railroad stations improve economic activity in 1×1 km cells with rail stations. However, as Cantos et al. indicate, transport infrastructure induces economic activity beyond its localities.[53] This section provides insights into the extent of the long-term spatial concentration and leapfrog spillover effects of railroad stations.

We begin by distinguishing between the 'spatial concentration effect' and the 'leapfrog spillover effect'. In our setting, concentration refers to the tendency of economic activity to cluster in an area, whereas spillover refers to the tendency of economic activity to disperse from an area. As depicted in figure 3, the higher nighttime light intensity surrounding railroad stations represents the concentration effect, where economic activity is attracted inwards and concentrated towards rail stations to take advantage of the improved connectivity. Conversely, the higher nighttime light intensity away from railway stations exhibits a leapfrog spillover effect, where economic activity is transmitted outwards. One plausible reason behind such spillovers is that some industries are better off located in slightly dispersed and less overcrowded areas.[54]

Using our benchmark 'cell approach' framework, we now turn to estimate the concentration effect by expanding our initial cell size to a 0.03 × 0.03 decimal degree (approximately 9 km^2) and 0.05 × 0.05 decimal degrees (approximately 25 km^2).[55] Analogous to our benchmark setting, an expanded cell is considered the treatment group if at least one station is located within the cell. In other words, we measured the impact of railroad stations on extended areas. The estimated coefficients are shown in columns 1 and 2 of table 4. At the 1 km^2 cell level, our benchmark analysis demonstrates that our treatment cells, on average, have 11.7 DN higher than the comparison cells, but the effect reduces to 10.3 DN at the 9 km^2 cell level and further to 7.61 at the 25 km^2 cell level. Such a declining effect indicates that night-time light intensity is highly concentrated near the rail stations.

[53] Cantos et al., 'Transport infrastructure, spillover effects'.

[54] Rosenthal and Strange, 'Geography, industrial organization'.

[55] App. A8 illustrates the diagrams for comparing the three different cell sizes.

TABLE 4 Spatial concentration effect.

Dependent variables	Average digital number (DN), 1992–4						Average night lights concentration index (DN), 1992–4					
	Cell approach				Ring approach		Cell approach				Ring approach	
	Full sample		Truncated sample		Full sample		Full sample		Truncated sample		Full sample	
	9 km^2	25 km^2	9 km^2	25 km^2	9 km^2	25 km^2	9 km^2	25 km^2	9 km^2	25 km^2	9 km^2	25 km^2
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Station access by 1931	10.3***	7.61***	4.91***	4.75***	9.80***	8.75***	0.47***	0.16***	0.47***	0.17***	0.48***	0.28***
	(2.408)	(1.955)	(1.076)	(1.284)	(2.254)	(2.102)	(0.067)	(0.034)	(0.066)	(0.037)	(0.063)	(0.047)
Observations	107 072	107 072	13 015	22 919	107 072	107 072	107 072	107 072	13 015	22 919	107 072	107 072
R^2	0.21	0.21	0.29	0.25	0.21	0.23	0.0098	0.0039	0.025	0.010	0.010	0.0080

Note: This table presents OLS estimates regressing average DN for 1992–4 on historical railroad station access at 9 km^2 and 25 km^2 level using both cell size approach and ring approach. Controls include distance to river, distance to coast, topography ruggedness, distance tin mining site, rubber cultivation area, and state dummy. The radius for ring approach is 1.88 km for 9 km^2 level and 3.13 km for 25 km^2 level, respectively. The radius for extended ring analysis is double of the radius for ring approach. The robust standard error clustered at the district level is in parentheses.
***Significant at 1% level.
Sources: See sect. II.

THE ECONOMIC HISTORY REVIEW

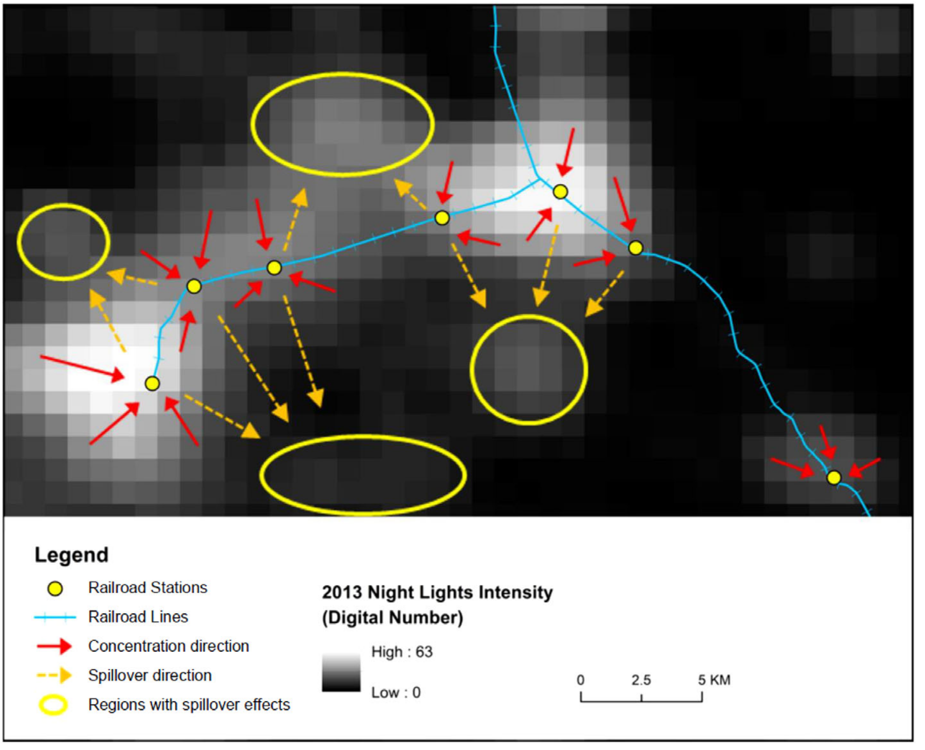

FIGURE 3 Spatial concentration and leapfrog spillover effects. *Sources*: See sect. II.

We present our estimates in columns 3 and 4 for the samples that include the treatment along with only the peripheral cells at 9 km^2 and 25 km^2 levels, respectively. This sampling technique can potentially improve the precision of our identification strategy. Overall, this set of results provides qualitatively similar findings in that the coefficients of interest decrease as the cell area increases. This finding supports our spatial concentration hypothesis that areas closer to rail stations enjoy greater economic benefits.

Expanding the size of cells within our ‘cell approach’ framework may not be ideal for examining the concentration effect. For instance, a rail station located at the border of a cell will only be considered to affect this cell, even if it is located next to the border of a neighbouring cell (see appendix A8). This is likely to contaminate our estimates. Therefore, as illustrated in appendix A9, we propose an alternative ‘ring approach’ in that we draw circles with varying radii lengths using rail stations as centre points, and the circles are considered as treatment and the outer areas as comparison.[56] The results are presented in columns 5 and 6 of table 4. As expected, our estimates from this ‘ring approach’ imply that the coefficients become smaller when the size of rings gets bigger. This finding is consistent with the ‘cell approach’, that is, evidence for the concentration effect increases in areas closer to rail stations.[57]

[56] Consistent with the total areas of cells in our benchmark approach, the radii for treatment rings are 1.88 km for 9 km^2 level and 3.13 km for 25 km^2 level, respectively.

[57] This finding aligns with Bogart et al., ‘Railways, divergence’, in which the impact from rail stations is mostly concentrated in areas within 3 km of the station. Similarly, Rosenthal and Strange, ‘Geography, industrial organization’, demonstrate that agglomeration economies are the strongest within the first mile and diminish quickly between 2 and 5 miles.

TABLE 5 Leapfrog spillover effect.

	Dependent variable: average digital number (DN), 1992–4					
	3 km	**5 km**	**10 km**	**15 km**	**20 km**	**25 km**
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
Station access by 1931	8.15***	6.48***	4.25**	1.95	1.34	0.18
	(2.501)	(2.423)	(1.735)	(1.226)	(1.113)	(0.687)
Observations	107 072	107 072	107 072	107 072	107 072	107 072
R^2	0.18	0.18	0.18	0.18	0.18	0.18

Note: This table presents OLS estimates regressing average DN for 1992–4 on historical railroad station access at neighbouring cells of 3 km up to 25 km. Controls include distance to river, distance to coast, topography ruggedness, distance tin mining site, rubber cultivation area, and state dummy. The robust standard error clustered at the district level is in parentheses. **Significant at 5% level, ***significant at 1% level.
Sources: See sect. II.

Our measure of average night-time light intensity is rather naive, particularly when capturing the relative concentration of economic activity. We addressed this issue by constructing a night-time light concentration index that gauges how night-time light intensity concentrates in a particular cell relative to its neighbouring areas.[58] The results are presented in columns 7–12 of table 4. Our estimates provide qualitatively similar results – the relative concentration of night-time light intensity decreases as distances from rail stations increase.

Next, we attempt to understand the extent of leapfrog spillover effect by horizontally shifting the locations of rail stations in both east and west directions at varying distances such as 3, 5, 10, 15, 20, and 25 km, respectively.[59] The estimates are summarized in table 5. Unequivocally, the coefficient decreases as distance from the stations increases and becomes statistically insignificant beyond 15 km. Taken together with earlier analyses, our findings affirm that the spatial concentration effect dilutes immediately after 3 km (i.e., 9 km^2), whereas the leapfrog spillover effect disappears 10 km away from the stations.[60] These results also indicate that our benchmark estimates capture only night-time light intensity from rail stations because the results are still significant beyond the immediate vicinity of rail stations.

[58] In the spirit of Riley et al., 'Index that quantifies', we constructed our concentration index by calculating the square root of the sum of the squared differences in night-time light intensity between a given cell and its eight immediate neighbouring cells. A visual schematic of the night-time light intensity concentration index is provided in app. A10.

[59] The construction of neighbouring cells is presented in app. A11. The rationale for including east and west neighbouring cells is that rail lines in Malaysia are mainly longitudinal, connecting south to north. Therefore, including north and south neighbouring cells might be misleading because the results not only capture the spillover effect, but also the direct impact of other railroad stations.

[60] Berger and Enflo, 'Locomotives of local growth', and Hodgson, 'The effect of transport', found evidence of agglomeration shadow and reorganization of economic activity from railroad networks. That is, areas slightly farther away from railroads suffer as economic activity agglomerates around the railroads. However, this analysis is not feasible in our context, as the average distance between railroad stations (e.g. North and South directions) in colonial Malaya is only roughly 6 km. Studying an area beyond 6 km would then result in estimating the impact of another station. Nevertheless, the positive coefficients of our horizontal leapfrog spillover analyses (e.g. East and West directions) suggest that no area within 10 km suffers from agglomeration shadow.

VI | ROBUSTNESS, PLACEBO, AND FALSIFICATION CHECKS

In this section, we address potential endogeneity concerns related to location bias. Rail stations may be built in areas with a relatively higher potential for economic growth or in areas that had already been thriving prior to the construction of the railroad network. Such pre-existing conditions could affect our identification and contaminate our estimates. We have already addressed this location bias in all our estimation models by controlling for historical tin mining and rubber cultivation areas, as colonial rulers strategically selected the locations of rail stations to expropriate natural resources. We further augmented our specification with an additional control that captured the spatial variation in rail stations from the straight line between the nearest major stations, as explained in section III.[61] Column 1 of table 6 presents the coefficient as still being positively significant and slightly larger than our benchmark. This slightly higher coefficient is possibly because of the downwards bias in the benchmark estimates, as the location choice of railway stations intentionally deviated to connect regions with lower economic growth.[62]

Second, we included longitude and latitude in our estimation to account for the directional gradient, as suggested by Kelly.[63] The results in column 2 illustrate that the benchmark coefficient remains unchanged. Our third robustness check included additional controls for terminal and junction stations in the estimation model. We define terminals as the first and last stations of each rail line route, whereas junctions are stations intersecting two or more routes. The reasoning is that these stations are likely to be economically more significant stations, which are supposed to facilitate higher economic activity. Columns 3 and 4 in table 6 present the results. Unsurprisingly, both the terminal and junction stations had a higher level of night-time light intensity than the others. Nevertheless, the magnitude of the benchmark coefficient remains stable, suggesting that the economic effect from railroad stations is not limited to just the significant stations. We also perform a placebo test to check whether our estimates capture the true effects of historical railroad stations. Our placebo treatment did not produce statistically significant results, as illustrated in appendix A12, indicating that our benchmark results likely represent a true causal relationship.

Next, we conduct several falsification tests to verify whether our estimates capture the true effects of railroad stations. First, we attempt to understand whether historical stations that are not in service affect economic activity.[64] We do so by including additional controls for abandoned railway stations in the benchmark model. The results are presented in column 5 of table 6, where we find that the coefficient of our outcome variable increases significantly to 17.9 (relative to 11.7 in our benchmark analysis). The dummy coefficient for abandoned stations has a negative value of 9.31 DN. This implies that areas with abandoned colonial rail stations experience approximately half the economic benefits of stations still in service. This result validates our path-dependence hypothesis, showing that abandoned colonial rail stations continue to stimulate economic development today. Jedwab and Moradi and Okoye et al. reported similar results in the African context.[65]

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[61] Railroads should be built straight for cost minimization. Any deviations in railroads from the straight line are likely due to localized factors that might trigger endogeneity in our estimation setting.

[62] Hornung, 'Railroads and growth', also found that straight-line estimates are higher than respective OLS results, suggesting that railroads might be assigned to disadvantaged regions.

[63] Kelly, 'Understanding persistence'.

[64] App. A13 provides a map showing the stations that are operating and abandoned at present.

[65] Jedwab and Moradi, 'The permanent effects'; Okoye et al., 'New technology, better economy'.

TABLE 6 Robustness and falsification tests.

	Dependent variable: average digital number (DN), 1992–4						
	Robustness checks				Falsification tests		
	Location bias		Terminal stations	Junction stations	Abandoned stations	Destroyed stations	Abandoned and destroyed
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Station access by 1931	14.9***	11.7***	11.0***	10.8***	17.9***	12.7***	18.4***
	(3.501)	(2.670)	(2.635)	(2.472)	(4.028)	(2.946)	(3.942)
Nearest spatial distance to straight line	−0.57**						
	(0.217)						
Longitude		−181.1					
		(121.735)					
Latitude		−7.11					
		(5.533)					
Longitude^2		0.88					
		(0.596)					
Latitude^2		0.80					
		(0.599)					
Terminal stations			15.2***				
			(5.275)				
Junction stations				21.8***			
				(5.001)			
Abandoned stations					−9.31***		−9.01***
					(3.018)		(2.950)
Stations destroyed during Japanese occupation						−5.53	−4.60
						(4.460)	(4.820)
Observations	107 072	107 072	107 072	107 072	107 072	107 072	107 072
R^2	0.18	0.19	0.18	0.18	0.18	0.18	0.18

Note: This table presents OLS estimates regressing average DN for 1992–4 on historical railroad station access. Controls include distance to river, distance to coast, topography ruggedness, distance tin mining site, rubber cultivation area, and state dummy. The robust standard error clustered at the district level is in parentheses. **Significant at 5% level, ***significant at 1% level.
Sources: See sect. II.

We find similar evidence for the temporary closure of some rail stations during the Japanese occupation of colonial Malaya. In the early 1940s, Japanese troops bombed parts of the railroad network, destroying 40 stations. Most of these were eventually rebuilt.[66] We extend our benchmark model by incorporating a dummy for destroyed rail stations in column 6 of table 6. Our results suggest that the coefficient for historical rail stations increased to 12.7 after controlling for the temporary closure of some stations during the Japanese occupation. We find a similar pattern when we control for both abandoned and destroyed stations together, as shown in column 7.

[66] Railroad networks and stations that were destroyed during the Japanese invasion are shown in app. A14.

Our falsification tests on abandoned and destroyed stations show strong evidence for the path dependence hypothesis. Even if these stations were permanently removed or destroyed during the wars, they would still influence the economic growth trajectory in the long run. One reason for this could be that the colonial rulers ran tin mining and rubber cultivation operations by hiring migrant workers, primarily from China and India. They then migrated to Malaysia in groups and lived collectively. Such a communal structure increased the adjustment costs to move away, even when natural resources were exhausted by the colonizers. This is consistent with Krugman's 'adjustment cost hypothesis', where historically important locations will thrive today if the adjustment cost of inhabitants is high.[67] Moreover, rubber cultivation was replaced by palm production in Malaysia, which discouraged the local labour force from moving away and even attracted new immigrants to such agglomeration centres.

We also addressed the concern of omitted variable bias. Despite our attempt to control for several observables and the state dummy, our estimates may still suffer from the exclusion of unobservable factors that railway stations and economic activity could confound. We adopted Oster's approach to estimate the effects of bias-adjusted treatment. A detailed explanation and the results are provided in appendix A15.[68] The signs of the coefficients remain positive, suggesting that our benchmark analysis is robust to omitted variable bias and is unlikely to be driven by unobservable factors.

In the subsequent analyses, we addressed the concerns of spatial correlation. This refers to the tendency of nearby locations to have similar values, which can bias our estimates if not accounted for. First, we estimate the degree of spatial autocorrelation using Moran's I statistic, which Kelly states will be insignificant for estimations that are robust to potential misspecification.[69] The results are presented in appendix A16, where Moran's I statistics are insignificant across various thresholds. Second, we adopt Conley standard error adjustment,[70] allowing for spatial correlation at different bandwidths. The results are presented in appendix A16 and are statistically significant.

Next, we verified our benchmark table using an alternative data source as the outcome variable. Gibson found that night-time light data from the VIIRS are more precise than the DMSP data because they have greater spatial resolution, no blurring, and no geo-location errors.[71] Gibson et al. empirically compared the accuracy of both VIIRS and DMSP data in predicting the GDP of developing countries, including Indonesia, China, and South Africa.[72] They found that VIIRS data were a better proxy for local economic activity in developing countries than DMSP data. However, the disadvantage of VIIRS data is that they are only available after 2012. Hence, we utilized night-time lights harmonized between the VIIRS and DMSP data sources that Li et al. generated as our alternative outcome variable.[73] We have re-run table 2 and obtained qualitatively similar results. The complete table is summarized in appendix A17.

Finally, we estimated the annual economic effects of rail stations on night-time light intensity from 1992 to 2013. The results are presented in figure 4. Interestingly, the general trend showed

[67] Krugman, 'History versus expectations'.

[68] Oster, 'Unobservable selection'.

[69] Kelly, 'The standard errors'.

[70] Conley, 'GMM estimation'.

[71] Gibson, 'Better night lights'.

[72] Gibson et al., 'Which night lights'.

[73] Li et al., 'A harmonized global'. Studies including Martinez, 'How much should', and Widmer and Zurlinden, 'Ministers engage', have also used this newly harmonized nighttime light intensity data to measure economic development.

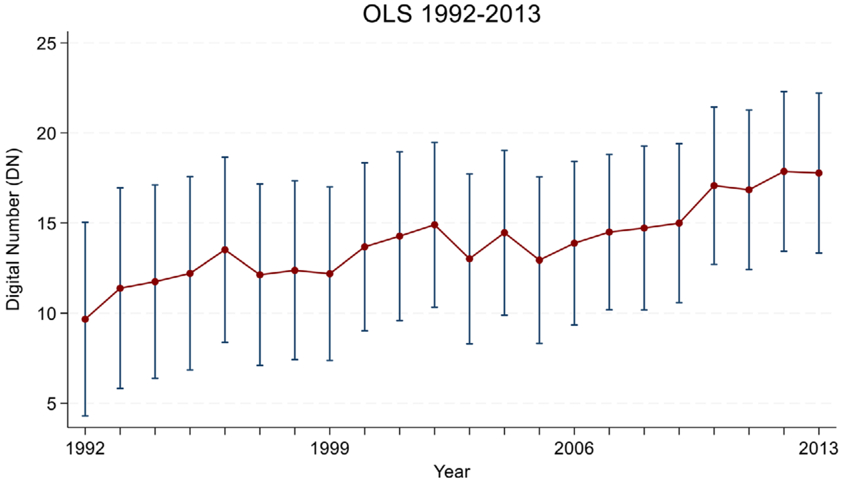

FIGURE 4 Economic impact of colonial railroad stations from 1992 to 2013. *Sources*: See sect. II.

that the night-time light intensity in our treated cells increased gradually over time, from 9.67 DN in 1992 to 17.8 DN in 2013. This suggests that the economic impact of colonial rail stations accumulates over time – the longer a region has access to rail stations, the larger the economic gains it enjoys.

VII | AGGLOMERATION ECONOMIES: A POTENTIAL MECHANISM

Our main results demonstrate the general equilibrium effect, that is, the total effect of historical railroad stations on contemporary economic activity. Such effects are likely driven by sharing common rail station infrastructure, labour pooling, and knowledge sharing. In our case, agglomeration economies can capture all three channels, as depicted by the Marshallian externalities.[74] In this section, we pin agglomeration economies as a potential mechanism to explain the effect of railroad stations on contemporary economic activity.

We report that historical railroad stations stimulate economic activity in their surrounding regions, which has persisted for a century. However, there is still a missing piece to the puzzle: How have historical railroad stations affected economic development to date? We aim to unriddle one such mechanism by following the agglomeration effect. Rail stations reduce transaction costs, which may lead to the emergence of agglomeration centres (e.g. cities, towns, and other economic growth hubs). Such centres may be ideal candidates for explaining economic activity to the present. To verify this reasoning, we geo-referenced the location of the 1967 agglomeration centres (see figure 5 illustrating the 1967 map showing the locations of the agglomeration centres).[75] We then constructed two measures of agglomeration centres, including a 'dummy' for and 'number' of agglomeration centres in a given cell at 25 km^2 (i.e. 0.05 × 0.05 decimal degree). We expanded

[74] Marshall, *Principles of economics*.

[75] We used 1967 because it is the only data item available to us that lies almost in the middle of 1931 (the completion of the third phase of railroad construction) and 1992 (the year of our night-time light intensity data) period.

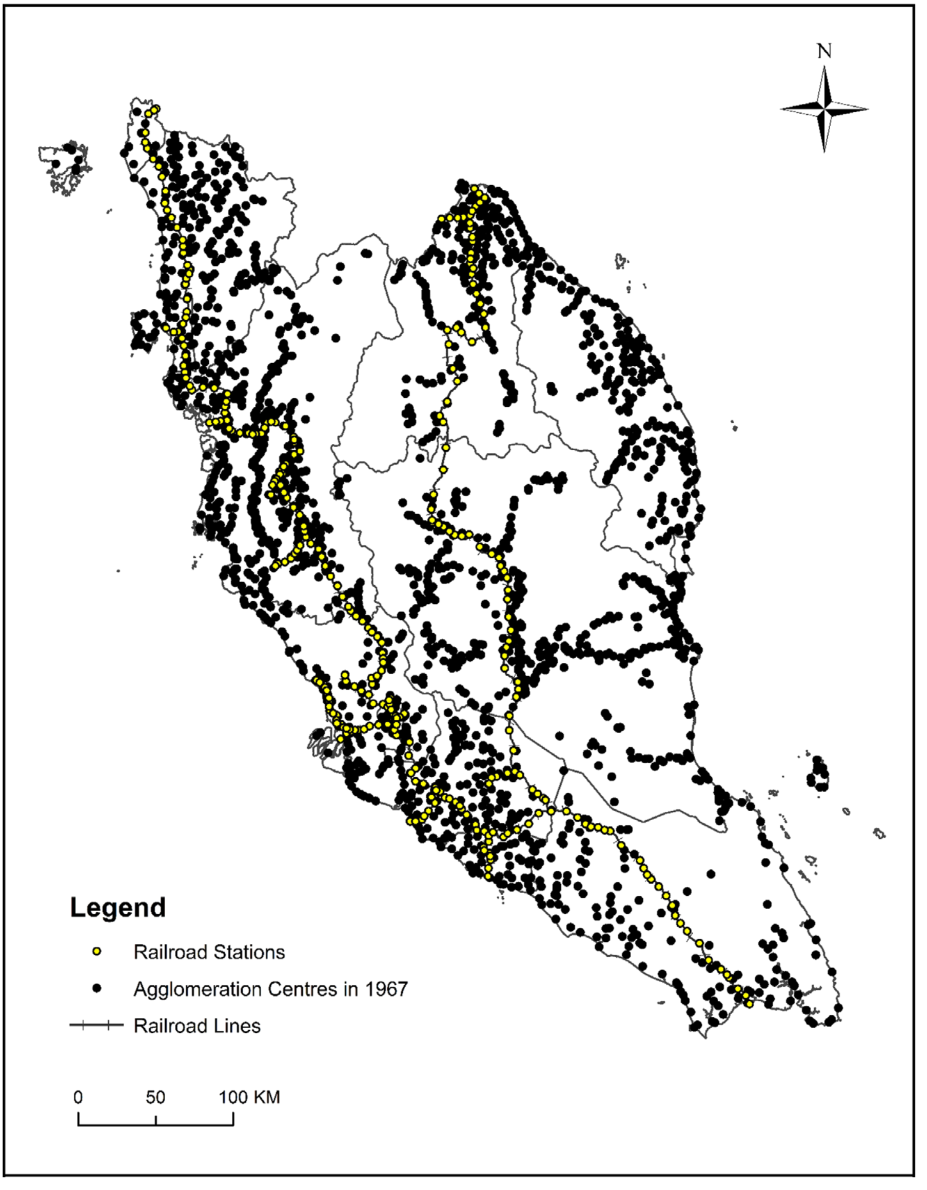

FIGURE 5 Agglomeration centres in 1967. *Sources*: See sect. II.

the cell as the location of towns is likely to be more spread out, and the 1 km cell level might be too small to measure it accurately.

As we expanded our cell for this section, we changed our treatment to the total number of rail stations instead of a naive rail station dummy to estimate the impact more accurately. Columns 1–2 in table 7 summarize the results. Both coefficients are positively significant, indicating that (i) cells with railroad stations are 11 per cent more likely to have at least one agglomeration centre and (ii) every 100 cells with rail stations contain approximately 16 agglomeration centres on average. Nonetheless, these results do not provide any causal link, because these agglomeration centres might have already existed prior to the construction of railroad stations. We resolved this issue

TABLE 7 Agglomeration economies as a potential mechanism.

Dependent variable	Agglomeration centre dummy, 1967	Total agglomeration centre, 1967	Change in agglomeration centre, 1922–67	Average DN, 1992–4	Total population, 1947	Average DN, 1992–4	
	5 km cell analysis			Mukim level analysis			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Total station by 1931	0.11***	0.16***	0.11*	2.08***	5385.1**	0.51	0.51
	(0.027)	(0.054)	(0.058)	(0.638)	(2152.262)	(0.540)	(0.540)
Total population in 1947						0.00029***	0.00029***
						(0.000)	(0.000)
Mukim area (km^2)							−0.00022
							(0.002)
N	4296	4296	4296	800	800	800	800
R^2	0.17	0.14	0.10	0.21	0.30	0.28	0.28

Note: This table presents OLS estimates regressing growth centres on total historical stations, and OLS estimates regressing agglomeration centres on historical railroad station access at the 5 km cell level and average DN for 1992–4 on historical railroad station access at the *mukim* level. Controls include distance to river, distance to coast, topography ruggedness, distance tin mining site, rubber cultivation area, and state dummy. The robust standard error clustered at the district level is in parentheses. *Significant at 10% level, **significant at 5% level, ***significant at 1% level.
Sources: See sect. II.

by computing the changes in agglomeration centres before and after the railroad networks were completed. In particular, we geo-referenced the locations of the 1922 agglomeration centres.[76] We then calculated the difference in the number of agglomeration centres between 1922 and 1967 and estimated the effect of railroad stations on such changes. Column 3 of table 7 reports a positive coefficient of 0.11, which is statistically significant at the 10 per cent level, suggesting that railroad stations trigger the formation of agglomeration centres in surrounding areas.

One limitation of geo-locating agglomeration centres is that we only identified the location and have no information on the size of each agglomeration centre. For instance, our current approach provides the same measurement for a small rural town and a major urban city, although the population size and economic activity in both areas could be significantly different. In addition, we estimate only the increase in agglomeration centres and do not account for any growth within each agglomeration centre. Thus, in the subsequent analysis, we gather historical population data to further understand the mechanisms of agglomeration economies. As the railroad network was completed in 1931 and Malaya gained independence from the British in 1957, we collected population data from the 1947 census to examine the impact of rail stations on population growth during the colonial period. Next, we examined whether population growth serves as a mechanism to explain long-term economic development. Census population data are only available at the *mukim* (sub-district) level, hence, we aggregate all treatment and control variables at this level of analysis.

First, we estimated the benchmark analysis at the mukim level. Consistent with our benchmark results in table 2, column 4 of table 7 illustrates that mukims with more rail stations had higher night-time light intensity than those without stations. Next, we examine the impact of railway stations on the total population in 1947. The results in column 5 illustrate that, on average, *mukims* with an extra rail station have 5385 more people than *mukims* without stations. As a back-of-the-envelope calculation, this coefficient was equivalent to an increase of approximately 34 per cent in the Malaysian population. This finding supports our earlier analysis of agglomeration centres, suggesting that there is an agglomeration force from rail stations as people cluster near them.

Next, we incorporated the 1947 population as a control to serve as a mediator and examined the strength of this mechanism. Column 6 illustrates that the coefficient of the 1947 population is positively significant, indicating that population clustering is one of the mechanisms by which railway stations impact economic development. More importantly, the magnitude of the coefficient for the total rail stations fell from 2.08 to 0.51, and it is now statistically insignificant. This finding suggests that population growth absorbs the effect of rail stations, proving that it is a strong and important channel through which rail stations impact long-run economic development. We further control for the area of each mukim to account for mukims of various sizes in column 7, and the results stand.

Our analysis in this section demonstrates that the agglomeration force is an important mechanism by which railway stations impact long-term economic development. In short, our findings concur with Krugman's theory,[77] indicating that economic development is gained from improved railroad access, mainly through agglomeration economies with clusters of people and businesses.

[76] These are the earliest data available to us on the location of agglomeration centres before railroad networks were completed. The 1922 map showing the location of agglomeration centres is given in app. A18.

[77] Krugman, 'Increasing returns'.

VIII CONCLUSIONS

This study proposes a novel framework to identify the long-term economic impact of railroad networks in colonial Malaysia. To understand the spatial differences in economic activity, we provide evidence that agglomeration gains geared towards colonial rail stations persist today. Drawing upon this strand of literature, we uncover new evidence of the extent to which railway stations affect economic activity. We differ from the extant studies in that we examine the economic impact of rail stations instead of naive rail lines. Our disaggregated approach to constructing a novel dataset of historical rail stations contributes to the literature in two major ways. First, we address potential endogeneity concerns by comparing cells with and without railway stations located in proximity that were otherwise similar. Second, and more importantly, the station-level data allow us to examine how railroad networks propagate their spatial concentration and leapfrog spillover effects.

Our results demonstrate that regions with colonial rail stations have enjoyed larger economic benefits to the present, even if they are not in operation (e.g. abandoned or destroyed) today. We identify agglomeration economies as the underlying mechanism by which economic activity is generated around rail stations. By exploring the spatial concentration effect, our estimates indicate that the effects of colonial stations are highly concentrated around railway stations, whereas the spillover effect spreads as far as 10 km away.

We provide a comprehensive historical account of the economic impact of colonial railroads over time. To the best of our knowledge, this study is the first attempt to analyse the persistent economic impact of historical rail stations in Malaysia. Therefore, we venture into less-explored developing countries and Southeast Asian regions in terms of transportation infrastructure. The policy implications of our study are far-reaching and not limited to Malaysia. This study emphasizes the importance of railroad infrastructure in stimulating long-term economic growth, as the economic benefits of railroad networks can accumulate over time. Our findings support the path dependence of historical railroad stations on current economic activity, suggesting that infrastructure development can have a long-term impact on the spatial dispersion of economic activity.

This study may provoke further research, particularly when new datasets become available. For instance, some stations can be used for moving passengers or freighting goods, and delineating such effects will likely provide new insights. In addition, some stations may be used for local resource extraction, and distinguishing the effects of such stations from others may improve our understanding of the persistence of historical institutions. That is, historical accounts of railroad networks at the station level can open new avenues for research.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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