The Railway Gauge Muddle in Australia

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Nicholas Sheard
Centre of Policy Studies,
Victoria University

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Nicholas Sheard†

Centre of Policy Studies, Victoria University

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Abstract

The mainline railways in Australia were initially built in three different gauges, with 'breaks-of-gauge' where passengers and goods transferred between them. This paper studies how the gauge situation affected regional development and the railway network in the 20th century. Regional breaks-of-gauge caused substantial local growth, with population and employment levels increasing by around 50% within a decade relative to otherwise similar places. However, these effects were unwound within two decades of the break-of-gauge being closed. There is little evidence for the gauge-segmented railway network causing different paces of regional development. The gauge muddle also appears to have led to a more limited railway network than if a uniform gauge had been used from the beginning.

Keywords: Agglomeration, Rail transport, Railway gauge, Trade frictions, Transport infrastructure

JEL classification: H54, L92, N77, N97, R42

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†Centre of Policy Studies, Victoria University, 300 Flinders Street, Melbourne, VIC 3000, Australia. E-mail: nicholas.sheard@vu.edu.au. Website: https://sites.google.com/site/nicholassheard/.

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1 Introduction

Due to a series of historical accidents, the mainline railways in Australia were initially built in three different gauges. This necessitated gauge transfer operations or 'breaks-of-gauge', where passengers and goods could be transferred between the gauges. These operations added to the costs of transport and appear to have limited goods flows, partially isolating places on either side of a gauge divide.[1] The breaks-of-gauge required the presence of labour and capital and most were in rural or remote locations. Thus a trade-off may have existed, whereby the lack of a uniform gauge was costly for trade and hampered growth in places it isolated, but the breaks-of-gauge brought economic stimulus to their local areas.

The purpose of this paper is to study the regional economic implications of the historical railway gauge situation in Australia. The primary focus is the effects of break-of-gauge operations on economic growth in the communities that hosted them. I estimate these using techniques that compare the regions with and without breaks-of-gauge. I then address the economic effects of regions being segmented into railway systems of different gauges. Finally, I discuss the implications of the eventual gauge unification for the configuration of the railway network.[2]

Railway gauge is the distance between the inner edges of the rails. As railway equipment can only operate on track of a specific gauge, a single gauge must be chosen for a network that will use a given set of equipment. Typically, a particular gauge is chosen for a railway network, often with compatibility across an entire country or region. Australia is peculiar as historical events led to a railway network with multiple gauges and thus numerous locations where gauge transfers were required. When railway construction began in Australia in the early 1850s, a dispute between the two largest colonies – New South Wales and Victoria – and an arguably lax intervention by the colonial secretary in London led to large networks being built in two different gauges: the 'standard' gauge of 4'8½" and a 'broad' gauge of 5'3". In the late 1850s, a 'narrow' gauge of 3'6" was used for the first railways in Queensland because of claimed lower construction

[1] According to the Bureau of Transport Economics (1977; 1979), it took an average of 27 hours for a wagon to pass through the bogie exchange at Port Pirie and roughly the same cost was incurred as travelling an additional 100 kilometres by rail. Smith (1963) found that the patterns of goods trade by rail between New South Wales and Victoria had a large discontinuity at the gauge divide at Albury.

[2] It would be ideal to also study the effects of the gauge situation on trade, but this is not feasible given the lack of historical data on transport costs and trade within Australia.

costs and suitability to rugged terrain, then its success led to it being used for railways in other remote or mountainous parts of the country. Efforts were eventually made to unify the gauge, at least for connections between the state capitals, resulting in the first single-gauge connections between Sydney and Melbourne in 1962 and between Sydney and Perth in 1970. However, the costs of conversion have prevented complete gauge unification. More detail on technical aspects of railway gauge and the history of the gauge situation in Australia are given in Appendix A.

The estimation in this paper is conducted on data by region and census year, using difference-in-differences (DiD), propensity-score matching (PSM), and synthetic controls (SC) techniques. The DiD analysis shows the correlations between railway infrastructure and growth, but is unlikely to reflect the causal effects of infrastructure as it may simply be built where growth is planned or anticipated. The PSM and SC methods are applied to get a better impression of the causal effects. Local economic activity is measured using population and employment. The data are limited to South Australia, as it had all three gauges of mainline railways for most of the 20th century and several locations where the gauges intersected, and the period from 1911 to 1996, which begins with the first year the region-level data are available and ends after the last regional break-of-gauge was closed.

The results present no clear evidence of the railways leading to local population or employment growth. There is a negative correlation between the presence of a railway line and local growth during the sample period, though this is likely due to railways having caused growth before 1911 and then the population dispersing between 1911 and 1996. The PSM and SC results show no significant effects of railways on local growth. The SC analysis also shows that regions where railway lines were closed were in decline before but not after the closing.

The results for railways by gauge are at best ambiguous, though there is some evidence that narrow-gauge and standard-gauge lines have positive effects on local growth. These results do not support the hypothesis that being isolated in gauge from the core of the network reduces the benefit from having a railway line, as the narrow-gauge lines were the most isolated and appear from the estimates to have had relatively large effects on local growth.

Break-of-gauge activities are found to have led to significantly higher rates of population and employment growth in the communities that hosted them, relative to otherwise similar places.

The PSM results indicate that having a break-of-gauge led to on average 1% higher annual growth in the local population and employment. The SC results show that the effect of the breaks-of-gauge is large – with population and employment levels being around 50% higher because of the break-of-gauge – and mainly accrues within one decade of the break-of-gauge being opened. However, when the breaks-of-gauge were closed, the local population and employment levels drop to near the original growth path within two decades.

As gauge standardisation occurred in South Australia, many regional lines were abandoned. This was especially true of branch lines that were isolated in gauge by the conversion of the trunk lines they connected to. Conversion of any line is costly, so it is plausible that the abandonment of those lines was due in part to the cost of adapting them to the new gauge. Thus a possible consequence of the historical railway gauge muddle is a more limited regional railway network in the current era than would have existed had the gauge been standardised from the beginning.

Previous research has studied the economic effects of regional railways in other countries. In contrast to the current paper, the previous work generally finds positive effects of railways on local economic growth. Donaldson (2018) found that colonial railways in India led to lower transport costs and higher welfare in the regions they connected. Bogart and Chaudhary (2013) showed that the productivity of the colonial railways in India increased more rapidly than other sectors, so they even had a direct effect on economic growth. Donaldson and Hornbeck (2016) found that US railroads in the late 19th century improved market access and caused large increases in agricultural land values. Bogart, You, Alvarez-Palau, Satchell and Shaw-Taylor (2022) studied the 19th-century railways in England and Wales and showed that they contributed strongly to local growth while having a negative effect on places 3 to 15 kilometres away. Büchel and Kyburz (2020) found that 19th-century railways in Switzerland led to population growth along the new lines while reducing the population in places 2 to 10 kilometres away. Berger and Enflo (2017) found that railways in Sweden had positive effects on regional population in the 19th century, though mostly as a reallocation from other regions, and that the regional population differences persisted through the 20th century despite further network development. Berger (2019) showed that Sweden's 19th-century railways also contributed to industrialisation in the areas they connected. Lindgren, Pettersson-Lidbom and Tyrefors (2021) studied Sweden's railways for 1860 to 1917 using an event-study design and found larger effects on regional development than in previous studies.

A related literature studies the economic effects of urban railways and transit systems. Baum-Snow and Kahn (2000) found positive effects of rail transit in US cities on nearby house values. Mayer and Trevien (2017) studied expansions to commuter rail lines in Paris and found significant positive effects on employment and the numbers of highly educated residents near the new stations. Gonzalez-Navarro and Turner (2018) estimated the effects of subway lines in cities around the world using night lights data and found that subways cause a city's population to spread along the lines and further from the centre, but not to significantly increase in total.

The economics of railway gauge has been studied extensively by Douglas Puffert (1991; 2000; 2002; 2009), who focused on the processes by which railway gauges are chosen. He thoroughly documented the history of railway gauge development around the world. He used a simple but realistic model to explain how different gauges may emerge in different regions, a local gauge may eventually persist despite incentives to use a different gauge, and the optimal gauge is not necessarily chosen as standard. Benmelech (2009) studied the financing of 19th-century US railroads and found that gauge differences reduced their ability to raise debt financing by making them less profitable.[3]

The main contribution of this paper is to connect railway gauge with regional development. The historical analysis of the economic effects of railways has mostly ignored the question of gauge, while research on railway gauge has generally not addressed the consequences for regional development. This paper focuses in particular on the issues arising from the lack of a uniform gauge. Multiple-gauge networks are now unusual, except in cases where the different gauges carry very different types of trains.[4] However, many historical railway networks lacked a uniform gauge and breaks-of-gauge are still required at many international borders, for example between China and most of its neighbours and between the European countries that use standard, Iberian, and Russian gauges (Puffert, 2002; Shang-Su, 2020). The findings presented in this paper suggest those breaks-of-gauge may have important implications for regional development.

[3]Note that the situation in Australia is different, as from the early days of railway construction until the late 20th century its mainline railways were publicly built and operated.

[4]Examples include the Shinkansen in Japan, which runs on a different gauge (4'8½") to the rest of the national railway network (3'6"), tourist railways, and small railways that service mines or power plants.

Indeed, the analysis presented here avoids the issues with separating the growth effects of breaks-of-gauge and international borders that would arise from studying those scenarios directly.

In addition, breaks-of-gauge represent a classic example of both a trade friction and a local economic shock, as they increase the costs of transport but also generate local economic activity. The available data for South Australia do not permit an analysis of historical trade, but the analysis presented here contributes to the work exemplified by Davis and Weinstein (2002) and Bleakley and Lin (2012) on the persistence of local economic shocks. Namely, it shows that the local economic activity induced by the breaks-of-gauge was unwound after those operations ceased.

There are several important limitations to the analysis presented here. Firstly, it is based on data for local population and employment levels, as no historical regional data on output, productivity, or trade were available. Secondly, the data on population and employment are unavoidably rough as they were inferred from data for regions that changed size and shape over time. Thirdly, the census periods are of uneven lengths, ranging from 5 to 14 years, which introduces potential inconsistencies and limits the precision of the results. Fourthly, railway lines are built, maintained, and operated to different standards, but the analysis does not distinguish between lines by type as there is not sufficient information to do so. Fifthly, the breaks-of-gauge also differ in terms of the scale of their operations, but the analysis does not differ between them.

The remainder of this paper is organised as follows. Section 2 describes the data, Section 3 details the methods used for the estimation, and Section 4 presents the estimation results. Concluding remarks are presented in Section 5. Appendix A provides background on the concept of railway gauge and the multiple-gauge situation in Australia and Appendix B presents some additional results.

2 Data

The data used for the analysis were assembled from several sources. Information about the railway network, including the breaks-of-gauge, is from cartographic data. Local economic activity is measured using population and employment figures from the Australian census.[5] Other data are from the Australian Bureau of Statistics (ABS) and the Bureau of Meteorology (BoM). The data are combined into a panel for the 13 census years from 1911 to 1996.

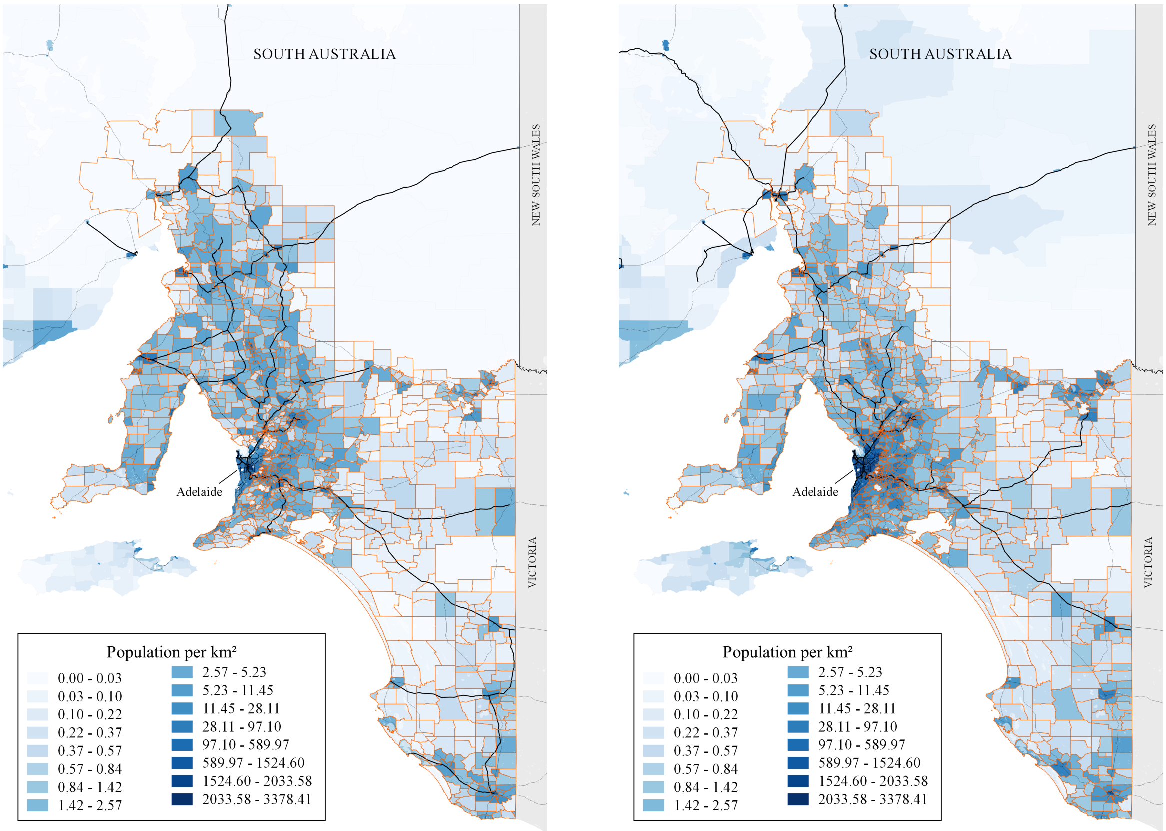
In the Australian census, there is no statistical unit for regions below the level of the state that has remained constant over time. Most regional data are simply given by local government area (LGA), the borders of which regularly change. To keep the geographical units consistent, the data are mapped to the 2016 version of the 'State Suburb' (SSC) defined by the ABS. The SSCs broadly correspond to postal locations, so in metropolitan areas they are usually suburbs and in rural areas they are usually towns or cities, often separated from one another and from their rural hinterlands. This makes the SSCs more representative of the local market of a town or city than for example county or even municipal boundaries. The mapping of LGAs to SSCs is done by identifying the proportions of the settled areas that overlap the contemporary LGAs using maps in the census documents.

The Australian census has been conducted in 1901, 1911, 1921, 1933, 1947, 1954, and then every 5 years from 1961 onwards. Each census since 1911 details the population by LGA and all but the 1911, 1976, 1981, and 1991 censuses also detail employment by LGA. The missing employment figures were approximated from employment in earlier and later censuses and the population growth rates. The population and employment data were then re-aggregated to the SSCs. The panel starts in 1911 as that was the first census with data by region. The panel ends in 1996 because by then all regional breaks-of-gauge in South Australia were closed and in 1997 there was a large realignment of the LGAs in South Australia that would mean inconsistencies if data from censuses after 1996 were approximated to the same set of regions.

The population of South Australia is heavily concentrated in the south-east of the state. As the analysis requires comparison between places that are similar except in whether they have railway infrastructure, the sample excludes the Adelaide metropolitan area and the more remote parts of the state. Adelaide is excluded as it is qualitatively different from the rest of the state in terms of industry and development and has none of the type of break-of-gauge locations studied

[5] It would be ideal to study the effects on other measures, for example output or productivity. However, population and employment are the best measures of the size of the local economy available in the historical censuses and there is no alternative source of regional economic data published consistently over the 20th century.

in the analysis. The remote areas excluded are the vast unpopulated areas in the north and west of the state as well as Kangaroo Island and the Eyre Peninsula, which are isolated from the core of the railway network and the major population centres. This leaves a sample of 1,018 SSCs, which are illustrated in the maps in Figure 1 along with the 1911 and 1996 population densities and railway networks.



(a) 1911

(b) 1996

Figure 1: Maps of the 1,018 sample 'State Suburbs' (SSCs), outlined in orange. The maps show the 1911 and 1996 population densities (in blue shading) and the railway lines (as black lines). As South Australia is vast and largely unpopulated, the sample is limited to the area in the south east of the state where the population is concentrated. It also excludes the Adelaide metropolitan area.

The routes of the railways in each gauge were constructed as Geographic Information System (GIS) data for the whole of South Australia. The gauges are 3'6" 'narrow' gauge, 4'8½" 'standard' gauge, and 5'3" 'broad' gauge. The sources were maps of the railway networks in 1910, 1915, 1930, 1972, and 1974 from the State Library of South Australia and the National Railway Museum in Port Adelaide, GIS data on the current network from OpenStreetMap, and the history of the South Australian railway network by Vincent (2019). The GIS data were converted to binary variables for railways by SSC and year. Figure 2 plots the approximate lengths of railway lines by gauge and the numbers of break-of-gauge locations in South Australia by year for 1911 to 1996. Maps that show the development of the South Australian railway network during the 20th century are in Appendix A.

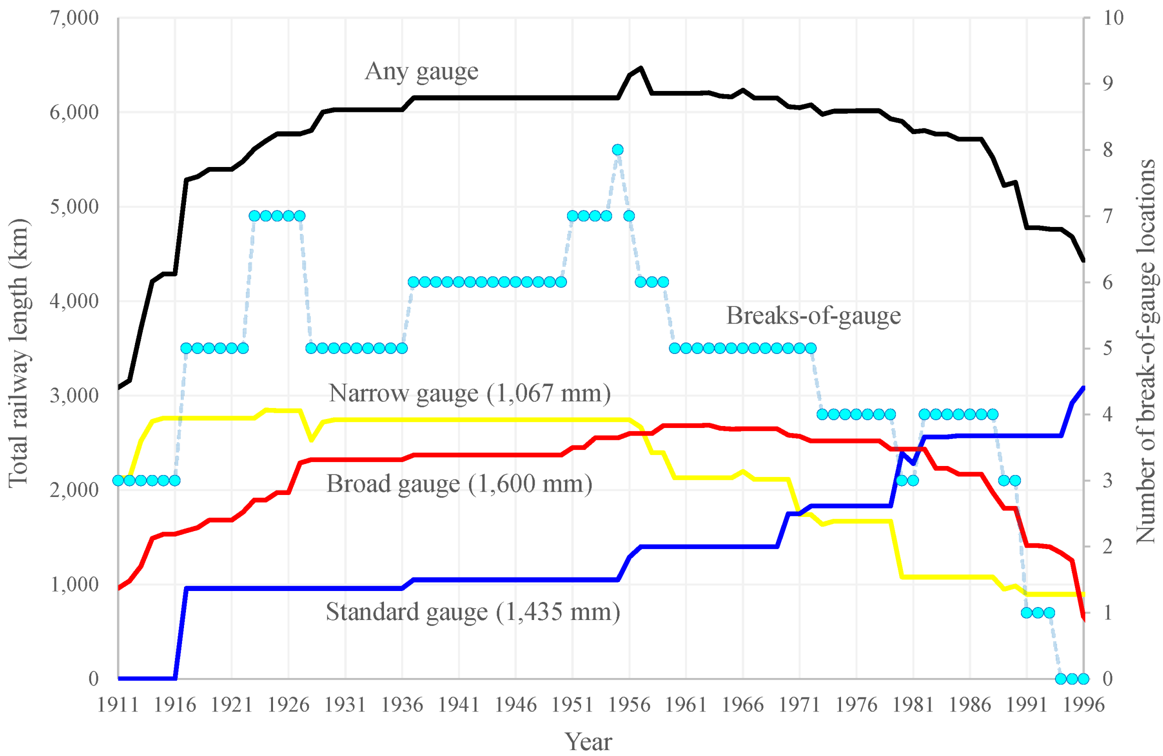


Figure 2: Approximate lengths of railway lines by gauge and the number of break-of-gauge locations in South Australia by year from 1911 to 1996. The lengths of railway lines are the 'system kilometres', which do not separately count double track, sidings, or yards. The breaks-of-gauge are for the whole state except the Adelaide metropolitan area.

The same sources were used to identify the break-of-gauge locations. Some locations where different gauges meet are not classified as breaks-of-gauge for the purposes of this study. Adelaide has had multiple railway gauges since 1982, when the standard-gauge connection to the Perth-Sydney line was completed. However, the gauge transfers of passengers and goods in Adelaide have only ever been a small proportion of the transport activity in the city. Whyalla has had both narrow and standard gauges since 1972, but they are effectively separate connections to the steelworks. Also excluded are junctions with tourist railways and disused track. The remaining breaks-of-gauge in South Australia are listed in Table 1.

Location	Break-of-gauge start	end	Gauges
Bowmans	1923	1927	$3'6''$ & $5'3''$
Brachina	1955	1956	$3'6''$ & $4'8\frac{1}{2}''$
Gladstone	1927	1990	$3'6''$ & $5'3''$ to 1970, then $3'6''$, $4'8\frac{1}{2}''$, & $5'3''$
Hamley Bridge	1879	1927	$3'6''$ & $5'3''$
Kadina	1982	1990	$4'8\frac{1}{2}''$ & $5'3''$
Marree	1957	1980	$3'6''$ & $4'8\frac{1}{2}''$
Mount Gambier	1917	1956	$3'6''$ & $5'3''$
Naracoorte	1951	1959	$3'6''$ & $5'3''$
Peterborough	1970	1988	$3'6''$, $4'8\frac{1}{2}''$, & $5'3''$
Port Augusta	1917	1972	$3'6''$ & $4'8\frac{1}{2}''$
Port Pirie	1937	1982	$3'6''$, $4'8\frac{1}{2}''$, & $5'3''$ to 1970, then $4'8\frac{1}{2}''$ & $5'3''$
Snowtown (NG-BG)	1923	1927	$3'6''$ & $5'3''$
Snowtown (SG-BG)	1982	1993	$4'8\frac{1}{2}''$ & $5'3''$
Terowie	1881	1970	$3'6''$ & $5'3''$
Wolseley	1884	1955	$3'6''$ & $5'3''$

Table 1: Summary of the break-of-gauge locations in South Australia.

The data on the railway network and local population and employment are combined into a balanced panel dataset, aggregated to the 1,018 sample SSCs and spanning the 13 census years from 1911 to 1996. The dataset also includes data on mean land elevation, mean temperature, and annual rainfall by SSC from the BoM. Table 2 presents summary statistics for the dataset and Table 3 presents the characteristics of the SSCs by railway and break-of-gauge status.

	Mean	Std. dev.	Minimum	Maximum
Data by SSC and census year (13,234 observations in balanced panel of 1,018 SSCs):				
Railway of any gauge	0.300	0.458	0	1
Narrow-gauge railway	0.048	0.213	0	1
Standard-gauge railway	0.032	0.177	0	1
Broad-gauge railway	0.232	0.422	0	1
Break-of-gauge location	0.004	0.061	0	1
Population	277.2	787.7	0	20,195
Employment	112.1	317.3	0	8,901
Data by SSC (1,018 observations):				
Land area (km^2)	110.4	197.6	0.04	2,866.9
Distance from Adelaide (km)	136.7	95.1	7.7	401.7
Distance from Coast (km)	51.4	48.7	0.2	227.1
Distance from Murray River (km)	100.8	80.2	0.1	324.0
Mean elevation (m)	160.7	160.8	0.1	703.5
Mean temperature (℃)	15.7	1.2	13.0	19.4
Annual rainfall (mm)	470.0	173.9	200.8	988.1

Note: the railway and break-of-gauge variables are binary and indicate the SSC having any amount of railway or being a break-of-gauge location in the given census year

Table 2: Summary statistics for the dataset, which is a panel for the 1,018 sample SSCs over the 13 census years from 1911 to 1996.

SSC status for 1911–1996	Never had railway	Had railway	Had break-of-gauge
Distance from Adelaide (km)	130.7	147.6	214.5
	(95.0)	(94.4)	(87.3)
Distance from coast (km)	47.7	58.3	43.4
	(47.9)	(49.3)	(35.6)
Distance from Murray River (km)	98.3	105.3	175.8
	(80.8)	(79.1)	(60.0)
Population in 1911	101.8	357.4	1,644.3
	(210.8)	(637.2)	(1,678.0)
Employment in 1911	43.8	154.2	712.6
	(90.5)	(274.8)	(723.0)
Population in 1996	193.0	699.8	3,601.4
	(386.2)	(1,663.9)	(5,904.8)
Employment in 1996	80.1	291.0	1,465.1
	(158.2)	(705.4)	(2,601.6)
Number of SSCs	660	358	11

Note: the value given for each variable is the mean across all SSCs in the given subset, with the standard deviation in parentheses

Table 3: Summary statistics for the sample SSCs by railway and break-of-gauge status between 1911 and 1996.

3 Method

The main aim of the empirical analysis is to understand how railways and break-of-gauge operations affected local economic activity throughout the 20th century. Local economic activity is measured as either population or employment and is denoted $Y_{r,t}$ for region r in census year t, applied in log terms as $y_{r,t} \equiv \ln(Y_{r,t})$. The annual growth between census years t and $t+1$ is denoted $\Delta y_{r,t} \equiv \frac{y_{r,t+1} - y_{r,t}}{\tau_{t+1} - \tau_t}$, where τ_t is the calendar year for census year t. The presence of a railway line or break-of-gauge is represented by the binary variable $infr_{r,t}$. The DiD and PSM estimates are generated by fitting the following equation:

$$\Delta y_{r,t} = \beta_{infr} infr_{r,t} + \gamma X_{r,t} + \delta_t + \varepsilon_{r,t} \tag{1}$$

In equation (1), β_{infr} is the coefficient on the binary variable for a railway line or break-of-gauge operation, $X_{r,t}$ is a vector of controls with coefficients γ, δ_t is a fixed effect for census year t, and $\varepsilon_{r,t}$ is an independent and identically distributed error term. We are primarily interested in the estimates of β_{infr}, which relates local growth to the presence of a railway line or break-of-gauge. Alternative specifications are run with $infr_{r,t}$ as either the railway line or break-of-gauge, with both variables included separately in the same regression, and with separate binary variables for railways of each of the three gauges.

Equation (1) is estimated using the DiD and PSM techniques. The DiD technique is applied by estimating (1) with the full sample of regions. The PSM technique is applied by estimating (1) with a subset of the regions selected such that for each region with the railway infrastructure there is another region without it but that is determined to be otherwise similar based on an estimation process described below.

The SC technique functions by comparing the outcomes in a region where a railway line or break-of-gauge is opened with the outcomes in a 'synthetic' region constructed to be similar to the 'treated' region except that it does not have that type of infrastructure. The approach is based on the framework detailed in Abadie, Diamond and Hainmueller (2010) and Abadie (2021). In contrast to the DiD and PSM techniques as applied here, it is centred around the period in which the infrastructure is opened. Using the notation r for the 'treated' region, t for the census year, T_0 for the census year in which the infrastructure was opened, $I_{r,t}^{infr}$ as a binary variable for the infrastructure having been opened in region r by period t, $Y_{r,t}$ for the actual population or employment in region r in census year t, and $Y_{r,t}^N$ for the population or employment there would have been in the absence of the infrastructure. The $Y_{r,t}^N$ are the levels measured in the synthetic regions, which are constructed as weighted combinations of the 'untreated' regions using the approach described below. The following relationship is then estimated:

$$Y_{r,t} = Y_{r,t}^N + \alpha_{r,t-T_0} I_{r,t}^{infr} \quad (2)$$

The effects of the infrastructure on economic activity are inferred by estimating the parameters $\alpha_{r,t-T_0}$, which quantify the difference between the actual and synthetic levels of economic activity $Y_{r,t}$ and $Y_{r,t}^N$. The idea is that as the synthetic levels reflect what would have occurred in the absence of the infrastructure, any difference between $Y_{r,t}$ and $Y_{r,t}^N$ in the period after the infrastructure is opened can be attributed to the infrastructure. The parameters $\alpha_{r,t-T_0}$ have time subscripts because they are estimated separately for each interval of census years after the infrastructure is opened. To study the effects of railway lines and breaks-of-gauge being closed, versions of the analysis are run with the actual and synthetic levels compared around the census year when the infrastructure was closed.

The SC technique as described thus far generates a single deterministic growth path for each synthetic control region that is compared with the respective treated region to infer the effects. In order to run statistical tests of the effects of the infrastructure, it is necessary to generate a measure of the variation that would be expected were the infrastructure actually to have no effect. To do this I apply the approach developed by Cavallo, Galiani, Noy and Pantano (2013), in which a large number of 'placebo' treatments are selected at random from the regions that never had railway lines, a synthetic control region is constructed for each, then the differences between the placebo treated and synthetic control growth paths are aggregated to create a distribution of the differences in growth paths that would occur amongst regions that were never actually 'treated'. The p-value for each region or set of regions where railway infrastructure has been built is calculated by evaluating where the actual difference in growth paths fits on the relevant distribution.

3.1 Estimating and matching the propensity scores

Formally, the propensity scores are the probabilities of the regions having railway lines given their inherent characteristics. They are estimated from the data on the geography of the regions and locations of railway lines using a set of logistic regressions. The estimation is done separately for each census year. Using p_r to denote the probability of region r having a railway line in the given census year, X_r to denote a set of characteristics of region r with vector of coefficients ζ, and ε_r as the logistic error term, the following relationship is estimated:

$$\ln\left(\frac{p_r}{1-p_r}\right) = \zeta X_r + \varepsilon_r \tag{3}$$

The propensity scores are the fitted values $\hat{p}_r$ generated from the estimation of (3). The estimation is run separately for each census year. The X_r only include factors inherent to the regions and nothing that is affected by economic development, so the propensity scores do not reflect the development that would be driven by railway infrastructure.

Table 4 shows the results from the estimation for 1971, with a range of specifications to illustrate the roles of the variables in the regressions and the sample selection. The factors are the log distances from region r to Adelaide, the coast, and the Murray River, the mean elevation, mean temperature, and annual rainfall. These are introduced in turn in Columns 1 to 5. The remaining columns test alternative sample selections: the Adelaide metropolitan area and the remote areas that were excluded from the main sample, then combinations of the main sample and these other areas. The specification in Column 5, which uses the main sample and full set of factors, is used to run the matching.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
ln(area)	0.316^a	0.308^a	0.157^a	0.128^b	0.095	0.132	0.094	0.152^a	0.084^b	0.131^a
	(0.047)	(0.051)	(0.061)	(0.061)	(0.062)	(0.174)	(0.072)	(0.052)	(0.041)	(0.038)
ln(dist from Adelaide)		0.029	−0.168	-0.322^b	-0.406^a	−0.298	−1.445	-0.216^a	-0.606^a	-0.325^a
		(0.096)	(0.108)	(0.130)	(0.145)	(0.214)	(0.991)	(0.076)	(0.129)	(0.064)
ln(dist from coast)			0.476^a	0.618^a	0.771^a	0.164	0.239	0.288^a	0.384^a	0.144^b
			(0.091)	(0.114)	(0.121)	(0.298)	(0.185)	(0.082)	(0.082)	(0.063)
ln(dist from Murray)			0.378^a	0.501^a	0.628^a	10.283^b	1.406^c	0.415^a	0.422^a	0.249^a
			(0.078)	(0.097)	(0.105)	(4.023)	(0.772)	(0.077)	(0.087)	(0.063)
Elevation				-0.001^a	−0.000	0.013^b	−0.001	0.000	-0.001^c	−0.000
				(0.001)	(0.001)	(0.006)	(0.001)	(0.001)	(0.001)	(0.000)
Temperature					0.479^a	1.610^b	-0.561^a	0.191^c	-0.253^a	-0.245^a
					(0.132)	(0.738)	(0.196)	(0.111)	(0.082)	(0.076)
Rainfall					0.001	−0.008	-0.009^a	-0.002^b	-0.003^a	-0.004^a
					(0.001)	(0.005)	(0.003)	(0.001)	(0.001)	(0.001)
Main sample area	Y	Y	Y	Y	Y			Y	Y	Y
Adelaide metro						Y		Y		Y
Remote areas							Y		Y	Y
Pseudo R^2	0.04	0.04	0.07	0.08	0.10	0.13	0.10	0.07	0.06	0.04
Number of observations	1,018	1,018	1,018	1,018	1,018	347	315	1,365	1,333	1,680

Note: robust standard errors clustered by SSC in parentheses; *a*, *b*, *c* denote significance at 1%, 5%, 10%

Table 4: Propensity-score estimation results for the 1971 census year. Columns 1 to 5 progressively introduce the geographical controls and Columns 6 to 10 use alternative sample selections. The estimation of the propensity scores for all census years uses the specification in Column 5.

The idea with the matching process is to pair each region that had a railway line with a region that never had a railway line, such that the two regions had characteristics that made them similarly likely to have the railway line. This is achieved by pairing the regions to minimise the sum of the differences between the values of $\hat{p}_r$ for each pair, with treated regions that cannot be matched to within 0.05 of an untreated region excluded from the sample. The matching is carried out separately for each census year, as the distribution of railway lines changed over time, so the pairings do not remain constant between periods. As there were many more regions that never had railway lines than that had them in each census year, the process is effective at assigning good matches and more than 95% of the treated regions are successfully matched. Figure 3 illustrates the propensity scores for matched pairs of regions in all census years.

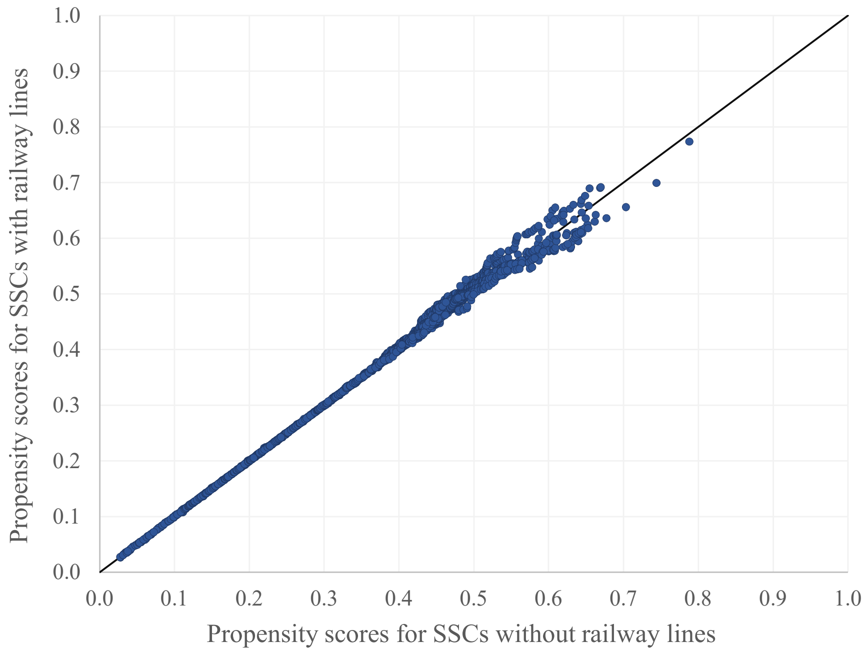


Figure 3: Comparison of the propensity scores for all SSCs paired in the matching process. Each point represents a pair of SSCs, with the SSC without a railway line on the horizontal axis and the SSC with a railway line on the vertical axis. The plot includes the matches for all census years.

3.2 Identifying the synthetic control regions

The first step in implementing SC method is the construction of the synthetic regions. One synthetic region is created for each region where a railway line or break-of-gauge was opened. Each synthetic region is created such that it matches the region where the railway line or break-of-gauge was opened as closely as possible in terms of a number of factors that reflect the inherent characteristics of the regions and the rate of population or employment growth in the period before the infrastructure was opened.

The synthetic regions are constructed by summing weights – that by definition add to one – of a set of the regions that never had the infrastructure during the sample period. Thus the synthetic regions for new railway lines are constructed from SSCs that never had a railway line. To create the cleanest comparison for the breaks-of-gauge, their synthetic regions are constructed from the SSCs that had railway lines at the time but never had breaks-of-gauge. Regions within 25 kilometres are excluded from the potential controls to prevent bias from what Abadie (2021) calls 'interference' between the treated and control regions, as nearby places may directly benefit from the infrastructure or be within the 'growth shadow' that it draws economic activity from.

The factors used in the synthetic matching are the same as the controls used for the estimation of the propensity scores: the log distances to Adelaide, the coast, and the Murray River and the mean elevation, mean temperature, and annual rainfall. The matching of the population or employment growth rates in the period before the opening of the railway line or break-of-gauge is done using data from up to four previous census years, with fewer used where limited by the sample beginning in 1911. The matching is carried out using the R package *Synth* created by Abadie, Diamond and Hainmueller (2011). Once the synthetic weights have been identified for a 'treated' region, the synthetic growth paths are calculated by summing the weighted population and employment densities of the constituent regions.

Figure 4 shows an example of a synthetic control region in a map. The example is the town and SSC of Stanley Flat, which gained a railway line in 1922. The matching is therefore conducted using 1933 as the first census year that it had a railway line. The map shows the SSCs included in the synthetic region for Stanley Flat, shaded to represent the weights for each.

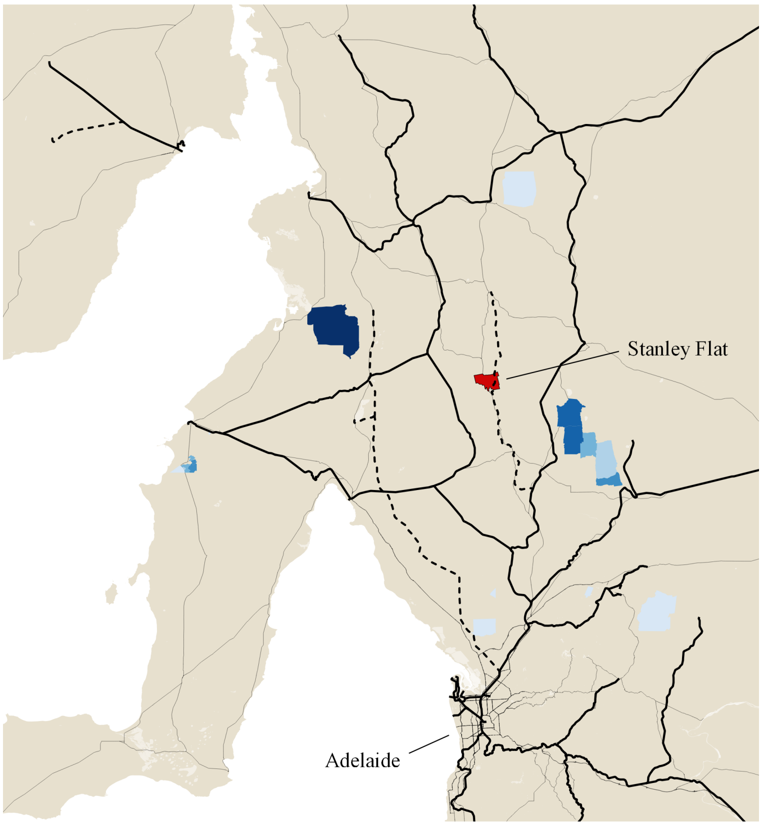


Figure 4: Map showing an example outcome of the synthetic matching process. The Stanley Flat SSC is illustrated in red and the SSCs that comprise its synthetic control region are illustrated in blue, with shading that indicates the weights assigned to each. The railway line to Stanley Flat was opened in 1922, so the matching is conducted using 1933 as the first census year it was in place. The railway lines that existed in 1933 are illustrated as black lines, with those that were new since 1921 as dotted lines.

4 Results

This section presents the results of the analysis. The DiD, PSM, and SC results are presented in separate subsections, followed by an analysis of line closures. The estimation is run using both population and employment as measures of local economic activity. However, as the results generated using the two measures are largely similar and the employment figures are partly based on approximated data (for the censuses where they were not given explicitly), some results are given for population only and the results for employment are given in Appendix B.

4.1 Difference-in-differences

Table 5 presents the results from the estimation of (1) using DiD and with population as the measure of local economic activity. The table has seven columns, showing results from regressions with different sets of binary variables for railway infrastructure. Column 1 uses a variable for a railway of any gauge. Columns 2 to 4 use each of the three gauges and Column 5 uses all three in the same regression. Columns 6 and 7 use a variable for a break-of-gauge, with and without the variable for a railway of any gauge.

The results in Table 5 show that the presence of a railway line correlates negatively with local population growth. The coefficients that relate population growth to a railway line of any gauge – in Columns 1 and 7 – are negative and significant at 10% and 5%. The coefficients for the broad-gauge railway lines are also negative and significant, though those for narrow- and standard-gauge lines are positive and some are significant.

The most likely explanation for the negative coefficients on railway lines appears to be the overall pattern of development in South Australia, reflected in the maps of population density in Figure 1. Regional development in South Australia before 1911 was largely in rural areas and heavily dependent on railway lines. During the 20th century, the increased prevalence of motor vehicles allowed the population to spread more evenly across the state. There was also a trend for urbanisation, with growth in and around Adelaide and declines in population for many rural towns and cities. Thus the railway lines correlated with lower growth during the sample period, but were not necessarily negative factors for growth. The controls partly capture this overall growth pattern – for example in the negative coefficients on current log population – but a component remains that is reflected in the negative coefficients on the railway lines.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Railway	-0.001^{c}						-0.001^{b}
	(0.001)						(0.001)
Narrow-gauge railway		0.005^{a}			0.004^{a}		
		(0.001)			(0.001)		
Standard-gauge railway			0.003		0.003^{c}		
			(0.002)		(0.002)		
Broad-gauge railway				-0.002^{a}	-0.002^{a}		
				(0.001)	(0.001)		
Break-of-gauge						0.019^{a}	0.019^{a}
						(0.003)	(0.003)
ln(population)	-0.002^{a}	-0.002^{a}	-0.002^{a}	-0.001^{a}	-0.002^{a}	-0.002^{a}	-0.002^{a}
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ln(area)	0.001^{a}	0.001^{a}	0.001^{a}	0.001^{a}	0.001^{a}	0.001^{a}	0.001^{a}
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ln(dist from Adelaide)	-0.008^{a}	-0.008^{a}	-0.008^{a}	-0.008^{a}	-0.009^{a}	-0.008^{a}	-0.008^{a}
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
ln(dist from coast)	0.001^{a}	0.001^{a}	0.001^{a}	0.001^{a}	0.001^{a}	0.001^{a}	0.001^{a}
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ln(dist from Murray)	-0.002^{a}	-0.002^{a}	-0.002^{a}	-0.002^{a}	-0.002^{a}	-0.002^{a}	-0.002^{a}
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Elevation	-0.000^{a}	-0.000^{a}	-0.000^{a}	-0.000^{a}	-0.000^{a}	-0.000^{a}	-0.000^{a}
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Temperature	0.004^{a}	0.004^{a}	0.004^{a}	0.004^{a}	0.004^{a}	0.004^{a}	0.004^{a}
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Rainfall	0.000^{a}	0.000^{a}	0.000^{a}	0.000^{a}	0.000^{a}	0.000^{a}	0.000^{a}
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
R^2	0.18	0.18	0.18	0.18	0.18	0.18	0.18

Note: 12,216 observations for each regression, representing 1,018 SSCs; robust standard errors clustered by SSC in parentheses; *a*, *b*, *c* denote significance at 1%, 5%, 10%; all regressions include census-year fixed effects; the dependent variable in all regressions is the change in log population

Table 5: Results from the difference-in-differences estimation of the relationships between railway lines or breaks-of-gauge and (log) annual population growth at the SSC level between 1911 and 1996.

The coefficients in Table 5 for the relationships between breaks-of-gauge and local growth – in Columns 6 and 7 – are positive and strongly significant. This indicates that population growth was relatively high in regions that hosted breaks-of-gauge. The magnitude of the coefficient is not affected by the inclusion of the railway variable.

The estimated coefficients for log employment growth, detailed in Appendix B, are similar in sign and magnitude to those for population growth in Table 5. There are only slight differences in the magnitudes and significant levels of the railway variables, though the estimation for log employment growth achieves slightly higher R^2 values.

Due to the identification issues described above, the coefficients from the DiD estimation should not be used to infer the causal effects of the railway infrastructure. The PSM technique is used to shed light on the causal effects, as it addresses the main identification issues, and the results from it are presented in the following subsection.

4.2 Propensity-score matching

Table 6 presents the results from the PSM estimation of (1) with log population growth as the outcome. These results show the effects of railway infrastructure. The railway variables in the seven columns correspond to those in the DiD estimation in Table 5. The principal technical difference with the PSM analysis is that the samples used in Table 6 are limited to the pairs of SSCs with and without railway infrastructure paired according to the propensity scores. The results using log employment growth as the outcome are presented in Appendix B.

Limiting the samples of SSCs has two important implications. The first is that the sample sizes vary between regressions, depending on how many SSCs have the relevant type of infrastructure. The second is that the matching used in Column 7 is suboptimal for the breaks-of-gauge, as that regression compares pairs of SSCs with and without railway lines and only a small share of the former have breaks-of-gauge.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Railway	−0.001						−0.001
	(0.001)						(0.001)
Narrow-gauge railway		0.001			0.007^a		
		(0.002)			(0.001)		
Standard-gauge railway			0.004		0.002		
			(0.003)		(0.002)		
Broad-gauge railway				-0.002^c	-0.001^c		
				(0.001)	(0.001)		
Break-of-gauge						0.011^c	0.018^a
						(0.007)	(0.003)
ln(population)	-0.002^a	-0.001^a	0.001	-0.002^a	-0.002^a	0.000	-0.002^a
	(0.000)	(0.001)	(0.001)	(0.000)	(0.000)	(0.002)	(0.000)
ln(area)	−0.000	0.001	−0.000	−0.000	−0.000	0.000	−0.000
	(0.000)	(0.001)	(0.001)	(0.000)	(0.000)	(0.003)	(0.000)
ln(dist from Adelaide)	-0.007^a	0.001	-0.014^a	-0.007^a	-0.008^a	−0.007	-0.007^a
	(0.001)	(0.002)	(0.002)	(0.001)	(0.001)	(0.005)	(0.001)
ln(dist from coast)	0.000	0.001	0.002	0.000	0.001	0.002	0.000
	(0.001)	(0.001)	(0.002)	(0.001)	(0.001)	(0.003)	(0.001)
ln(dist from Murray)	-0.002^a	−0.002	−0.001	-0.003^a	-0.003^a	0.003	-0.002^a
	(0.000)	(0.001)	(0.002)	(0.001)	(0.000)	(0.003)	(0.000)
Elevation	-0.000^a	-0.000^a	-0.000^a	-0.000^a	-0.000^a	-0.000^a	-0.000^a
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Temperature	0.003^a	0.002	0.001	0.003^a	0.002^a	−0.002	0.003^a
	(0.001)	(0.002)	(0.002)	(0.001)	(0.001)	(0.006)	(0.001)
Rainfall	0.000^a	0.000^a	0.000	0.000^a	0.000^a	0.000	0.000^a
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
R^2	0.18	0.22	0.23	0.18	0.18	0.38	0.18
Number of observations	7,208	1,154	548	5,796	7,208	98	7,208

Note: robust standard errors clustered by SSC in parentheses; *a*, *b*, *c* denote significance at 1%, 5%, 10%; all regressions include census-year fixed effects; the dependent variable in all regressions is the change in log population

Table 6: Results from the propensity-score matching estimation of the effects of railway lines or breaks-of-gauge on (log) annual population growth at the SSC level between 1911 and 1996.

The coefficients on the presence of a railway of any gauge in Table 6 are not significant.

This contrasts with the negative and significant coefficients from the DiD estimation in Table 5. Therefore, though there was a negative correlation between railways and local growth, there was no clear causal effect.

The results for railways by gauge in Table 6 show a similar picture. The coefficients for narrow-gauge and standard-gauge railways are not significant, while the coefficient on broad-gauge railways is negative and weakly significant. When all three gauges are included in the same regression – in Column 5 – the coefficient on narrow-gauge railways is also positive and significant.

The results in Table 6 indicate a positive effect of a break-of-gauge on local population growth. The coefficient on breaks-of-gauge in Column 6 is positive though only weakly significant, though it should be noted that limiting the sample to pairs of SSCs where one of them had a break-of-gauge leads to a small sample size. The regression in Column 7 has a positive and strongly significant coefficient on the breaks-of-gauge. However, as noted above, the matching in that regression is not fully appropriate to analysing the breaks-of-gauge as it includes all pairs of SSCs where one had a railway line. Though the evidence is not entirely clear, this does suggest a positive effect of breaks-of-gauge on local growth.

The PSM results for the effects of railway infrastructure on log employment growth, presented in Appendix B, are similar to those for population growth in Table 6. The first main difference is that the effect of the broad-gauge railways appears to be weaker for employment growth. The second is that, as with the DiD results, the model explains more of the variation in employment growth than it does for population growth, as the R^2 are generally higher.

4.3 Synthetic controls

The SC analysis goes further than the PSM in addressing the identification issues with measuring the effects of railway infrastructure, as it matches the growth trend in the period before the infrastructure was opened. In addition, as the development patterns related to railway infrastructure may vary depending on its age, the SC gives a clearer temporal picture of the effects of the infrastructure.

The SC analysis is conducted by comparing the actual and synthetic population and employment densities. The growth paths are defined with a timescale of the number of census years prior to or following the treatment, so that year 0 is the first census year that the relevant infrastructure was operational.[6]

The analysis is run on sets of treated regions – for example all regions where railways were opened or only those of a certain gauge – so it is necessary to aggregate the growth paths for each set. This is done by taking the means of the growth rates for the treated and synthetic control regions between each pair of consecutive census years, then combining them in sequence to create aggregate growth paths indexed such that the census year when the infrastructure is opened has value 1. The growth paths are calculated from a series of single-period growth rates because not all regions have the same number of census years prior to or following the treatment, due to the limits of the sample and because in some cases the infrastructure is removed. However, the placebo scenarios are constructed to match the period of treatment for each treated region in the set, so the benchmark used in constructing each *p*-value is appropriate to that set.

Figure 5 plots the actual and synthetic population and employment growth paths for all SSCs where railways were opened during the sample period. The lower part of the figure shows the *p*-values for the differences between the actual and synthetic growth paths, inferred from the distribution created from the placebo trials.

[6] The intervals between the Australian censuses have not been constant but rather have varied between 5 and 14 years. However, there is no convenient way of converting these to intervals of actual numbers of years for this type of analysis. Note that the longer time intervals also occurred around the time of the Great Depression and the Second World War, so it is unclear how well the observations from that era would compare with the later period even if it were possible to adjust the time periods appropriately.

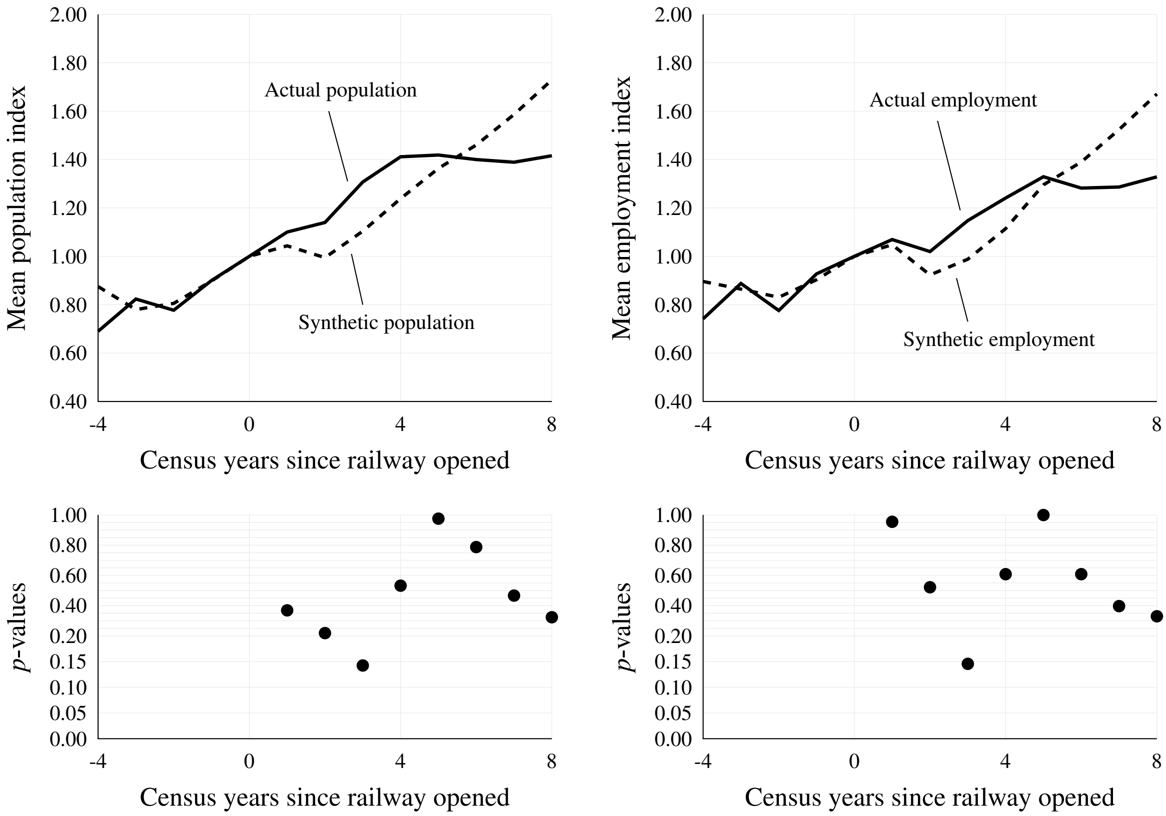


Figure 5: Plots of indexed population and employment growth in regions where railway lines were opened compared with the equivalent 'synthetic' regions. The horizontal axis is the difference between the current census year and the census year in which the railway line was opened. The diagram below each plot shows the *p*-values for the differences between the actual and synthetic growth paths.

The differences between the actual and synthetic population and employment levels in Figure 5 appear to indicate that new railway lines initially lead to somewhat higher local growth. The indexed growth paths for the actual population and employment levels are above the synthetic growth paths for five census periods, though the differences are only significant in a few cases. In addition, the effect may eventually either level out or be unwound even while the railway line remains in operation. Overall, this represents weak evidence that the railway lines lead to increased local economic activity.

Figure 6 plots the actual and synthetic population growth paths for the opening of railway lines in each of the three gauges. Note that there was only one narrow-gauge line opened during the sample period, which served two new SSCs, so those plots are based on relatively little information. The *p*-values are omitted from the figure to save space, though in most cases the differences between the actual and synthetic growth paths are not significant.

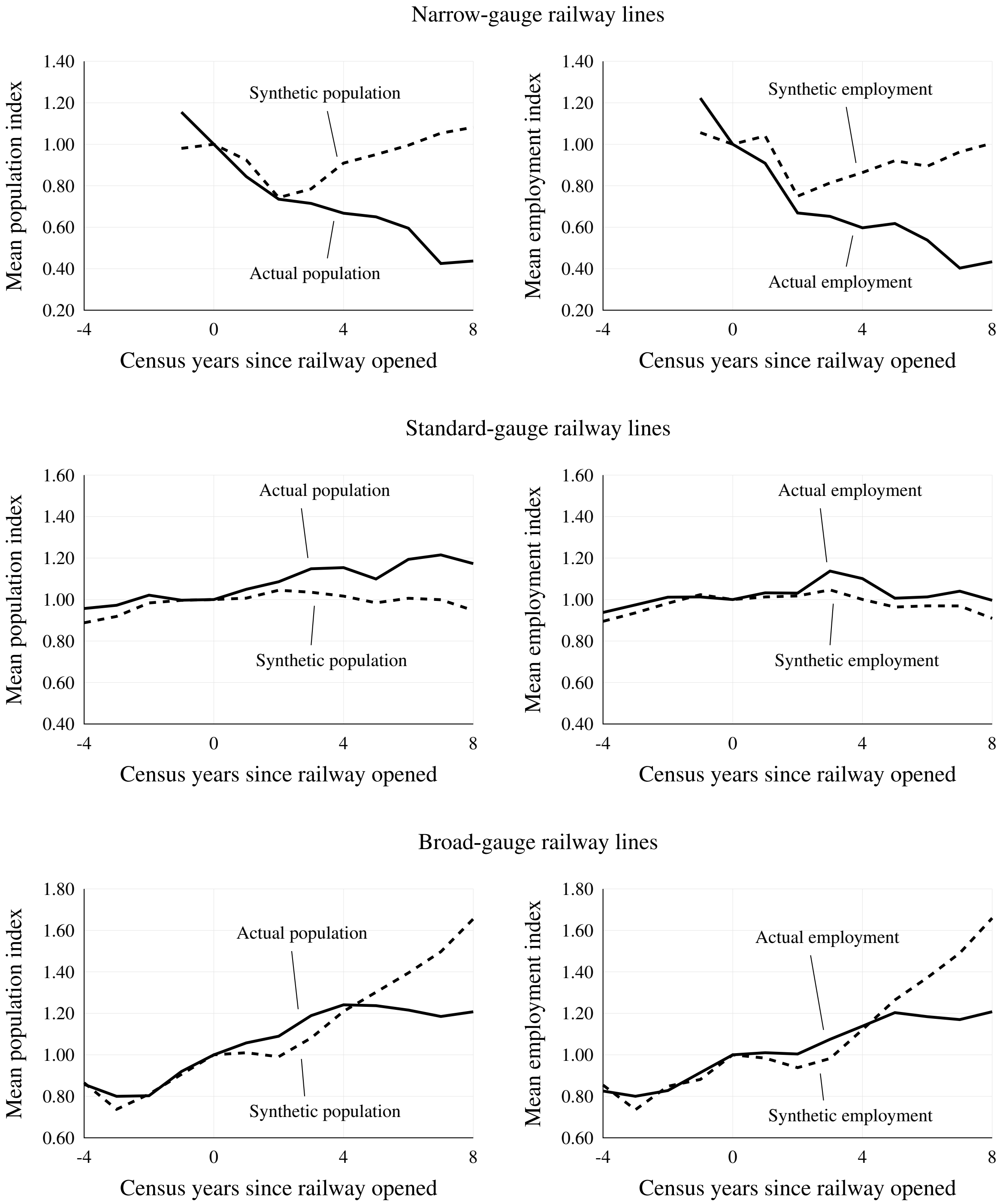


Figure 6: Plots of indexed population and employment growth in regions where railway lines in each gauge were opened compared with the equivalent 'synthetic' regions. The horizontal axis is the number of census years relative to the opening of each railway line. The *p*-values are not shown to save space, but the only differences significant at 10% are for the population in five of the eight periods after the opening of standard-gauge lines.

The results in Figure 6 are mostly not significant, though certain trends are apparent from the plots. The pattern for the new narrow-gauge line is of the regions it served growing similarly to the synthetic regions for two census periods and being in relative decline for decades thereafter, though none of the differences are significant. The SSCs with standard-gauge lines grow somewhat more than the synthetic regions, though the differences are only significant for five of the periods for the population levels and none of the employment differences. The weak effects of standard-gauge railways could be because they were built more as thoroughfares than the existing lines, as they were built primarily to connect large cities and ports and have fewer stations along their routes. The results for the broad-gauge lines resemble those for railway lines of any gauge in Figure 5, with slightly higher growth for SSCs with the actual regions for a few census periods and then lower growth.

Figure 7 illustrates the actual and synthetic growth paths for the period around the closing of a railway line. The population and employment levels in it were constructed by aggregating the SSCs where railway lines were closed to time periods relative to the closing of the lines. Note that the synthetic regions are still those constructed based on the trends before the opening of the railway lines – they are not recalculated to fit the trends before the railway lines are closed.

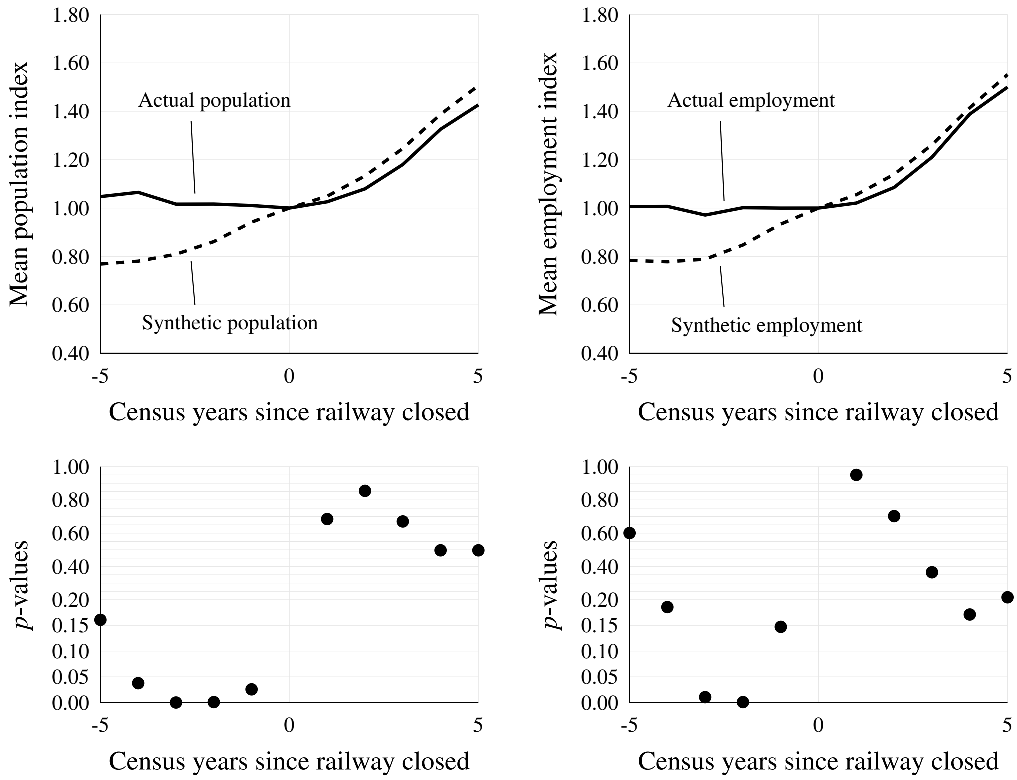


Figure 7: Plots of indexed actual and synthetic population and employment growth around the closing of a railway line. The horizontal axis is the number of census years relative to the closing of the railway. The diagram below each plot shows the *p*-values for the differences between the actual and synthetic growth paths.

Figure 7 shows that the SSCs where railway lines were closed had on average been in decline before they were closed but not thereafter. In the period before the railway lines were closed, the growth in population and employment was lower in the SSCs with railway lines than in the synthetic regions and many of the differences are significant. The growth paths after the railway lines were closed are similar and no differences in levels are significant. This suggests that (1) the railway lines may have been abandoned in response to the regions they serve going into decline and (2) the utility of the railway lines may have been negligible by the time they were abandoned. Note, however, that it is possible the abandonment of the lines did cause lower growth, but that they remained idle for a period before being removed.

Figure 8 plots the actual and synthetic control population growth paths for the opening of breaks-of-gauge. The synthetic control regions in this analysis are constructed from the SSCs that had railway lines at the time but never had a break-of-gauge.

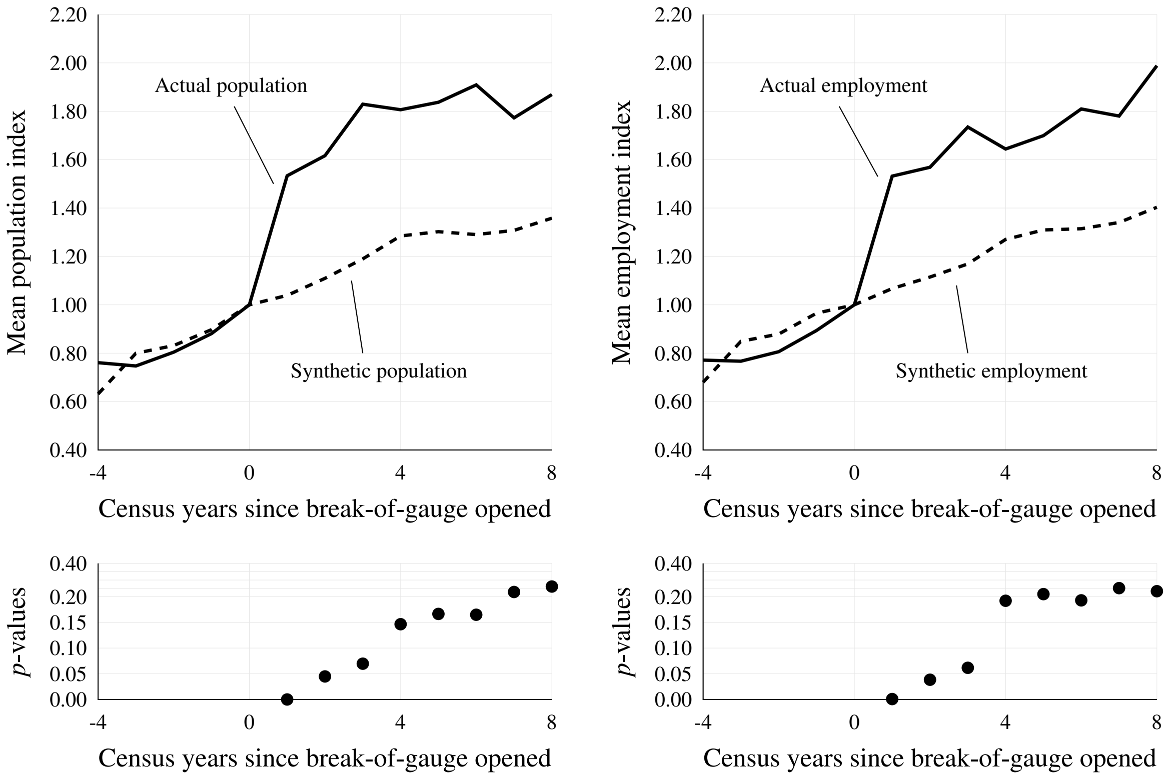


Figure 8: Plots of indexed population and employment growth in regions where breaks-of-gauge were opened compared with the equivalent 'synthetic' regions. The horizontal axis is the number of census years relative to the opening of the break-of-gauge. The diagram below each plot shows the p-values for the differences between the actual and synthetic growth paths.

The plots in Figure 8 show that the average break-of-gauge led to its host SSC having around

50% higher population and employment levels within one census period of being opened than it would have had without the break-of-gauge. The relative increase appears to be maintained for as long as the break-of-gauge is in operation, even if that is for several decades, though the differences are not significant after around three census periods.

The substantial sizes of the effects of breaks-of-gauge on local population and employment make sense for at least three reasons. Firstly, break-of-gauge operations required a substantial amount of labour to be employed by the railway and in related activities. Secondly, the fact that goods must be loaded and unloaded at breaks-of-gauge means there are frictions in the transport network at those points that also makes them relatively advantageous locations for freight forwarders or firms that use or sell traded goods. Thirdly, there should be a multiplier effect on local employment due to the demand for local goods and services by railway employees and their families as well as labour supplied by their families. The statistics on employment by sector in the 1971 census support the latter two explanations, as no more than a quarter of employment in the LGAs with triple-gauge breaks-of-gauge was in *transport and storage*.[7]

All of the breaks-of-gauge in South Australia were closed during the sample period. To understand the effects of breaks-of-gauge on regional development, it is also important what happens after their closing. Figure 9 shows the actual and synthetic growth paths around the time each of the breaks-of-gauge was closed. This is done by indexing the growth paths for each scenario to the census year in which the break-of-gauge was closed. Placebo scenarios are run to calculate appropriate p-values for the differences between actual and synthetic levels.

The results in Figure 9 suggest that practically all of the local population and employment gains due to the breaks-of-gauge are unwound within three or four census years. In other words, the regions appear to return within twenty years to the growth path they would have been on were they never to have had a break-of-gauge. The actual and synthetic growth paths track together before the breaks-of-gauge are closed, then they diverge with the actual growth paths falling behind those of the synthetic regions. It should be noted, however, that the differences are only significant for employment.

[7] In the 1971 census, the *transport and storage* industry employed 39 of 415 workers in Gladstone (District Council), 299 of 1,136 workers in Peterborough (Municipality), and 593 of 4,876 workers in Port Pirie (City).

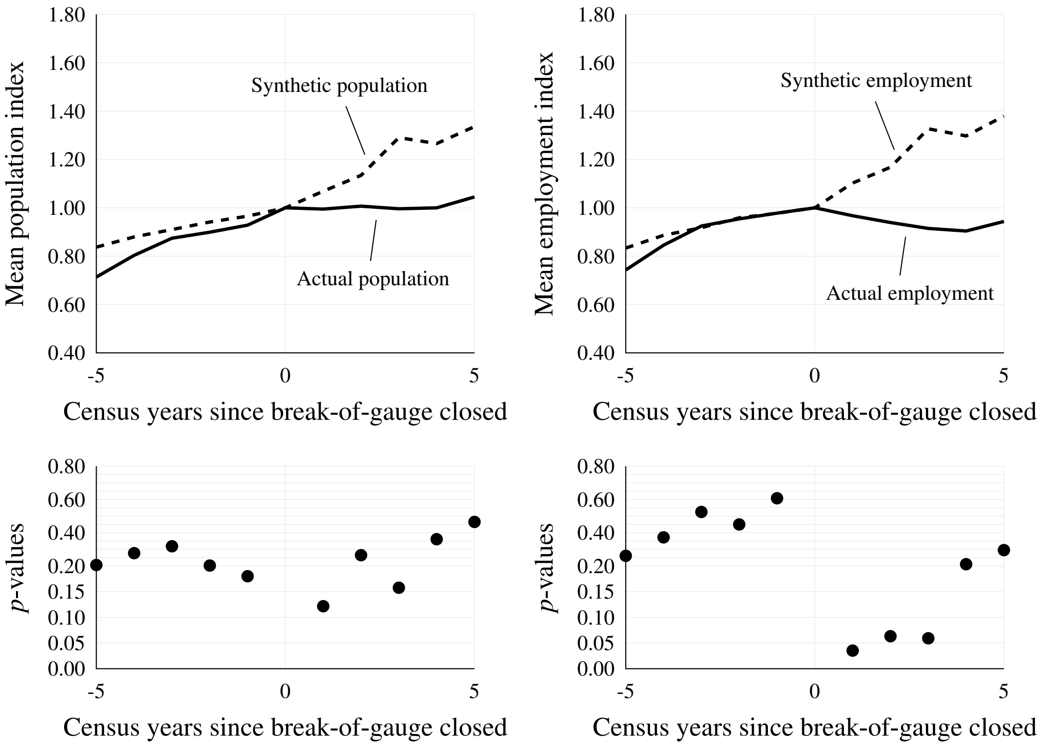


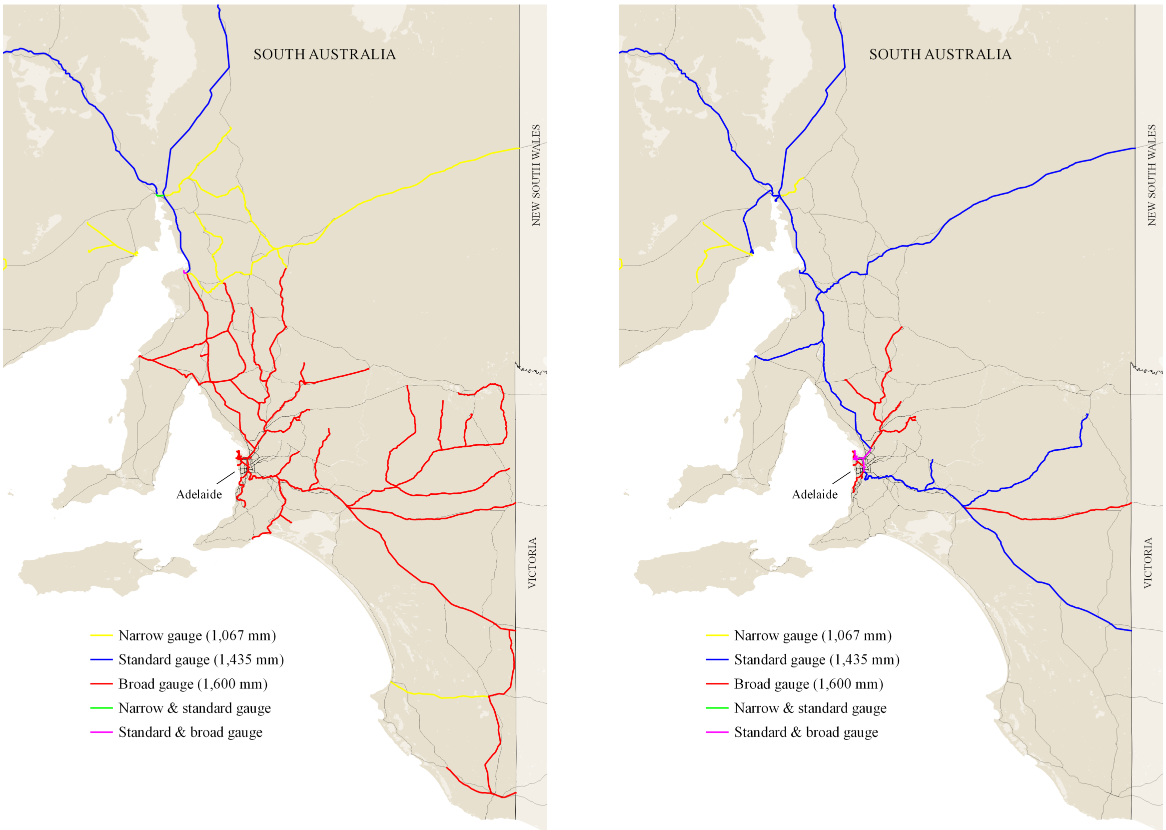
Figure 9: Plots of indexed actual and synthetic population and employment growth around the closing of a break-of-gauge. The horizontal axis is the number of census years relative to the closing of the break-of-gauge. The diagram below each plot shows the *p*-values for the differences between the actual and synthetic growth paths.

4.4 Network development

Another interpretation that can be made from the historical development of the railway network in South Australia is that the gauge muddle may have led to a less extensive railway network in the current era than would otherwise have been the case. As shown in Figure 2, the total length of railways in the state has generally been declining since its peak in 1957. If continuing to operate a line requires a gauge conversion because the trunk line that connects it to the broader network is converted, then that would imply an additional cost that may make it not worthwhile to retain the line. The decline in break-of-gauge locations may also imply that the costs of gauge transfers have increased, meaning it is less worthwhile to keep gauge-isolated lines.

The maps in Figure 10 show the South Australian railway networks in 1957 and 1996. If we ignore the isolated sections of railway on the Eyre Peninsula and around Whyalla, there were 21 branch lines at the peak of the railway network in 1957. Only 8 of those branch lines remained in operation at the end of the sample period in 1996. Of the 21 branch lines in 1957, 4 were in narrow gauge, always required a gauge transfer to access Adelaide, and all 4 were abandoned by 1996. A further 11 were broad-gauge lines connected to Adelaide via trunk lines that were converted to standard gauge in the 1980s or 1990s, so they would either require gauge transfers or conversion to standard gauge, and only 3 of those branch lines were converted to standard gauge while the remaining 8 were abandoned by 1996. Of the 6 branch lines that were in broad gauge and were off broad-gauge trunk lines that were not converted, 5 of them had been shortened but remained in operation in 1996.

The pattern in these branch line closings is clear: those that would have required gauge conversion or transfers were more likely to be closed. The corollary is that the current railway network would be more extensive if it had been built in a uniform gauge from the beginning.



(a) 1957 **(b)** 1996

Figure 10: Maps of the South Australian railway network in 1957 and 1996. The colours indicate the gauge of each line. The state railway network was at its peak in terms of total line kilometres in 1957.

The apparent abandonment of gauge-isolated lines raises a further question of whether fewer lines were built in the first place due to the gauge muddle. A similar logic could apply to potential new lines, either because the lack of a single-gauge connection to important destinations or the prospect of future gauge conversion meant they were not worthwhile to build. The result of such decisions would be that a network with fewer or shorter lines would be built.

5 Conclusion

The railway gauge question has fuelled debate and political wrangling in Australia since its constituent colonies entered the railway era in the 1850s. The colonies chose different gauges for their railways, despite criticism that a lack of compatibility would eventually be costly. Gauge unification was a political cause from the beginning and several large public inquiries were conducted to study its feasibility, though the steadily increasing costs of unification kept it out of reach. Sydney and Melbourne were only linked with a railway line of constant gauge in 1962, after almost 80 years of passengers and goods changing trains at the state border. The first railway connection between Sydney and Perth, completed in 1917, required three gauge transfers and a single-gauge connection between those cities was not established until 1970.

Critics predicted that the lack of a uniform railway gauge would be a negative factor for trade between the states, due to the cost of transferring passengers and goods at the breaks-of-gauge. Though historical data on trade within Australia are scarce, this prediction appears to have come true (Smith, 1963). This paper shows that the lack of a uniform gauge also had some positive effects, as the regions that hosted breaks-of-gauge had increased economic activity as a result. Furthermore, there is no evidence that regions served by railways that are isolated in gauge from the core of the network experience less growth than regions with railways connected to Adelaide or the other capital cities with a single gauge.

The analysis in this paper focuses on South Australia as it had railways in all three of Australia's mainline gauges and the highest concentration of break-of-gauge locations of any of its states or territories. The analysis uses a range of estimation techniques and a panel of regional data for all census years from 1911 to 1996.

In contrast to the existing literature, there is only weak evidence of any effect of railway lines on local growth. This may be due to the lower levels of detail and precision in the Australian historical data, which implies additional noise in the observations. The abandonment of railway lines appears to occur in response to relatively slow growth but is not a cause of slower growth once the lines are abandoned.

Break-of-gauge activities are found to have had positive effects on the local population and employment. Relative to otherwise similar places, an area that hosts break-of-gauge activities experiences an average of around 1% higher annual population and employment growth than otherwise similar places. A detailed treatment of the timing of the effects reveals that the effects are in fact roughly 50% increases in population and employment within a decade of a break-of-gauge opening, with the levels maintained as long as the break-of-gauge is in operation.

When a break-of-gauge is removed, the local population and employment levels return to their original growth paths within two decades. This contrasts with the finding of Bleakley and Lin (2012) that settlements built at river portage sites in the US remained relatively large in population many decades after the portage operations became obsolete. It is not obvious why this did not occur with breaks-of-gauge in South Australia. However, a possible explanation is that many of the places that hosted breaks-of-gauge, being in largely agricultural regions lacking conditions favourable for other industries, simply had too little potential to maintain a base of economic activity in the absence of the railway.

The magnitude and timing of the SC results suggest that the 1% annual difference in growth rates in the PSM results could be a misleading simplification, as it averages a few years of a large effect and then many years of little to no effect. The SC result also appears to be larger, even though most breaks-of-gauge were in operation for many years.

The most obvious potential cost of the railway gauge muddle is that higher transport costs would have negatively affected the producers and consumers of traded goods. The available evidence does not permit an evaluation of these effects, as there is little detailed information about the historical costs of transport and trade flows. It would have been useful to compare these costs with the local benefits of the breaks-of-gauge. A comparison between the regional gains and the costs of trade would in any case be somewhat subjective, as the overall effects may be positive in some regions and negative in others. Nevertheless, it seems safe to conclude that the positive regional effects of the breaks-of-gauge traded off against the negative trade effects of the higher transport costs.

An additional cost of gauge diversity appears to be that it has led to a sparser railway network in the current era than would otherwise have existed. Converting the gauge of an existing line is costly, which can lead to regional lines being abandoned when the trunk lines they depend on are converted. As discussed in Section 4, this would explain the abandonment of regional lines around the converted trunk lines in South Australia. The resulting network is sparser than those in New South Wales, Victoria, and Queensland, none of which required the same degree of gauge conversion. The natural conclusion is that there are currently regions in Australia not served by rail that would have been in the absence of the gauge muddle.

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A Railway gauge and the gauge situation in Australia

The gauge of a railway is the distance between the inside edges of the rails. The choice of gauge is somewhat arbitrary, as similar gauges differ only slightly in performance, but it is essential for a single gauge to be chosen for a network of rails and compatible equipment. In general, a broader gauge yields more stability and can be used to operate longer trains, while a narrower gauge allows for tighter bends and is cheaper to build and maintain (Puffert, 2009).

Railways around the world have been built in a wide variety of gauges, mostly between 2 feet and 7 feet. By convention, a railway gauge of 4'8½" (1,435 mm) is termed 'standard gauge'. Any gauge of less than 4'8½" is classified as 'narrow gauge' and any gauge wider than 4'8½" is classified as 'broad gauge'. The gauge of 4'8½" was adopted as the standard in the United Kingdom in the 19th century, spread to other parts of Europe and to the United States for the compatibility of equipment, and is now used for a majority of the railway track in the world (Puffert, 2000; 2002).

Places where passengers and goods can be transferred between railway lines of different gauges are known as 'breaks-of-gauge'. Breaks-of-gauge usually function using one of three techniques: by unloading the passengers or goods from one vehicle and loading them into another, by changing out the bogies on the vehicles for bogies compatible with the other gauge, or by placing the vehicles of one gauge on special flat carriages that run on the other (usually broader) gauge. South Australia had breaks-of-gauge of all three types.[8] Each technique has its advantages, but they all require substantial amounts of capital and labour to operate.[9]

A.1 History of railway construction and railway gauge in Australia

The construction of railways in Australia began in the mid-19th century, when the country was governed as separate colonies. Many of Australia's first railway lines were privately built, but within a few years each of the colonies had a publicly owned rail corporation that built and operated most of its railways. During the era when construction began, the policy of the government

[8] Another technology has bogies and axles that can be adjusted to fit different gauges, used for example on *Talgo* trains in Spain. To the best of the author's knowledge, this technology has not been employed in South Australia.

[9] Lacking information on the relative costs, the analysis in this paper does not treat the types of break-of-gauge operations differently. However, the fact that all were in use in South Australia suggests that their costs were reasonably similar.

of the United Kingdom was to interfere less in the affairs of its colonies and so the choice of railway gauge was not imposed from London (Hansard, 1849; Mills, 2010).

In 1850, on the recommendation of its chief engineer, the colony of New South Wales chose a broad gauge of 5'3" for its railways, which differed from the standard gauge of 4'8½" used in Britain but matched the gauge in Ireland. Victoria became a separate colony in 1851, formed from part of New South Wales, and inherited the choice of 5'3" gauge. New South Wales lost its chief engineer over a pay dispute and his replacement, installed in 1852, insisted on a gauge of 4'8½" for the colony. He argued that it performed equally well to the broader gauge and had the advantage that it was becoming the world standard. The legislative council of New South Wales accepted this recommendation, changed to 4'8½" gauge, and informed the other colonies of its decision in February 1853 (Pratt, 1912; Puffert, 2002; 2009).

Victoria had already begun planning for railways in 5'3" gauge and its first lieutenant-governor, Charles La Trobe, approved orders for equipment in that gauge in April 1853. La Trobe petitioned Earl Grey, the colonial secretary in London, to enforce the original choice of gauge by denying assent for New South Wales's change to 4'8½". Grey's response followed the *laissez-faire* colonial policy on two fronts: by allowing New South Wales to switch to 4'8½" and by allowing Victoria to retain 5'3" (Puffert, 1991; 2009; Mills, 2010). Gauge-specific investments meant there would have been costs associated with either colony conforming to the other's choice, though proponents of a common gauge argued that the benefits would eventually vastly outweigh the initial costs (Pratt, 1912; Puffert, 2009). Railway construction began in Victoria in 1854 and in New South Wales in 1855, with each colony using its chosen gauge. As the networks developed, the estimated costs of gauge unification increased rapidly and soon made it infeasible for the gauge to be unified (Puffert, 2002; Martin, 2018).

South Australia had been a separate colony from New South Wales since 1836. Despite being the first colony in Australia to adopt a railway gauge, its legislative council having decided on a gauge of 4'8½" in 1847,[10] it played a relatively minor role in the initial railway-gauge dispute. Railway construction began in South Australia in 1856 and the colony adopted 5'3" to conform to the gauge in Victoria, which it borders (Pratt, 1912; Puffert, 2009; Martin, 2018).

[10]The decision to adopt a gauge of 4'8½" for the colony was reported in "Proceedings of the Legislative Council: Tuesday, October 5" on page 211 of the 8 October 1847 edition of *The South Australian*.

The government of Queensland decided in 1863 to build its railways in a narrow gauge of 3'6" (1,067 mm). The decision was based largely on the recommendation of its chief engineer. He argued that (1) a narrower gauge would be cheaper per mile and well suited to mountainous terrain, which was persuasive due to Queensland's vast distances and mountains separating the interior from the coast, (2) Queensland had too sparse a population to require high-capacity lines, and (3) gauge uniformity had already been ruled out in Australia by other states using two different gauges (Knowles, 1981; Kerr, 1990; Puffert, 1991).

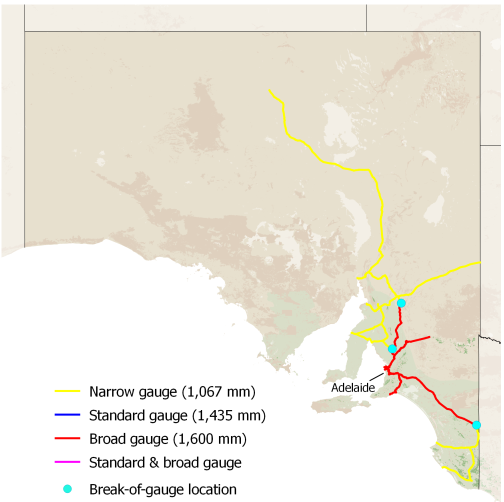
Though the cost savings of narrow-gauge railways were and are still disputed, they were highly popular around the world in the late 19th century (Puffert, 2000). South Australia followed Queensland in using 3'6" for some new and relatively remote parts of its network starting in the 1870s (Puffert, 2009). When the narrow- and broad-gauge networks met at Hamley Bridge in 1879, South Australia had its first break-of-gauge location (Vincent, 2019).

Gauge unification in Australia has been a political issue since before the gauge dispute of the 1850s (Pratt, 1912; Puffert, 2009). Action to unify the gauge began with the construction of the line from Kalgoorlie to Port Augusta in a gauge of 4'8½", completed in 1917, as a first step to building a trans-continental railway in that gauge (Appleton, 1962). This was the first standard-gauge railway in South Australia and since its construction the state has had three railway gauges: a narrow gauge of 3'6", the standard gauge of 4'8½", and a broad gauge of 5'3".

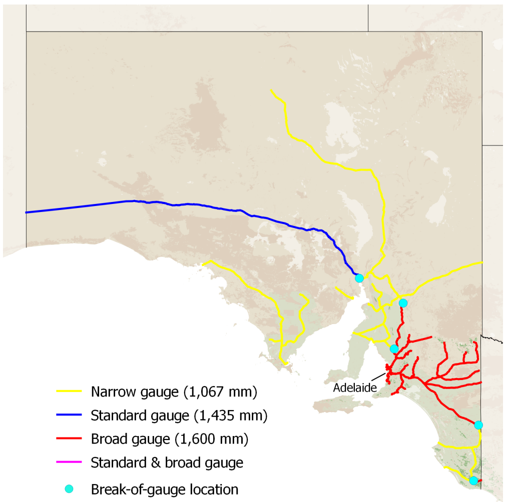
Following the recommendation of a Royal Commission in 1921, the commonwealth and state governments agreed to create a network in 4'8½" gauge to link the states' capital cities, though a requirement for unanimous consent for each section of line contributed to the project taking several decades to complete (Puffert, 2009; Martin, 2018). The standard-gauge line linking Western Australia to Port Augusta was extended to Port Pirie in 1937, making it the state's first triple-gauge junction. The last link in the standard-gauge trans-continental railway was completed when the line from Port Pirie to Broken Hill was converted to 4'8½" in 1970, which added triple-gauge junctions at Gladstone and Peterborough. In 1982 the broad-gauge line from Port Pirie to Adelaide was converted to 4'8½" and in 1995 the line from Adelaide to Melbourne was converted to 4'8½". In the 1980s and 1990s, most of the narrow- and broad-gauge country lines in South Australia were abandoned (Vincent, 2019).

While there are still sections of dual-gauge track and facilities that are serviced by multiple gauges in South Australia, particularly in and around Adelaide, the last regional break-of-gauge operation closed in 1993. The broad-gauge network in South Australia is now limited to suburban Adelaide and a handful of regional lines, while the narrow-gauge network is limited to isolated rails on the Eyre Peninsula, the lines that link iron ore mines to the Whyalla Steelworks, and a tourist railway (Vincent, 2019).

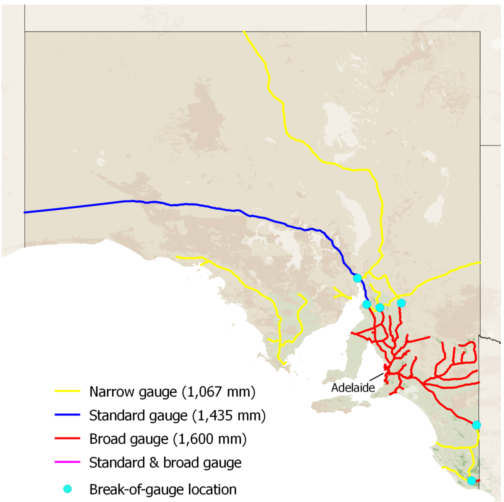
The maps in Figure A1 show the development of the railway network in South Australia over the 20th century. The maps show the gauge of each line and the locations of the breaks-of-gauge.



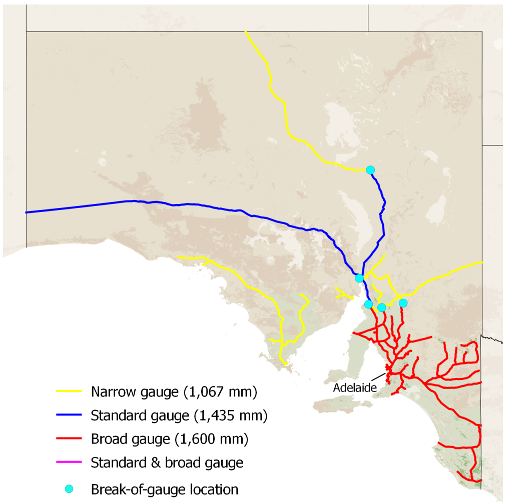
(a) Railway network in 1900



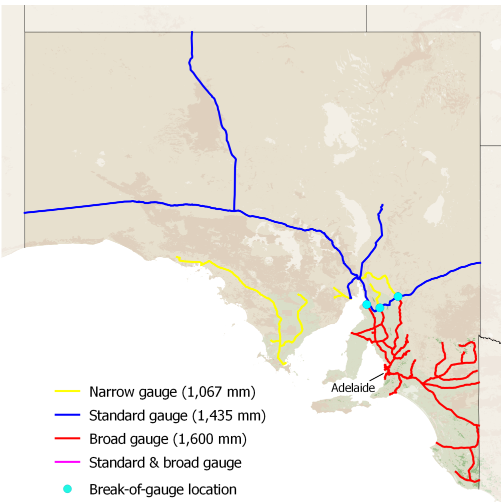
(b) Railway network in 1920



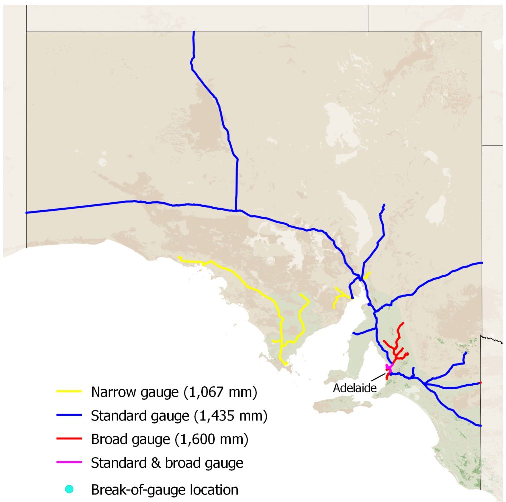
(c) Railway network in 1940



(d) Railway network in 1960



(e) Railway network in 1980



(f) Railway network in 2000

Figure A1: Maps showing the development of the South Australian railway network from 1900 to 2000. The colours indicate the gauges of the lines and the dots indicate the break-of-gauge locations. Only the railway lines and breaks-of-gauge in South Australia are illustrated.

B Additional results for employment

Tables A1 and A2 present the DiD and PSM results for the estimation of (1) using employment as the measure of local economic activity. These correspond to Tables 5 and 6 in the main text.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Railway	-0.002^b						-0.002^b
	(0.001)						(0.001)
Narrow-gauge railway		0.004^a			0.004^a		
		(0.001)			(0.001)		
Standard-gauge railway			−0.001		−0.001		
			(0.002)		(0.002)		
Broad-gauge railway				-0.002^a	-0.002^a		
				(0.001)	(0.001)		
Break-of-gauge						0.017^a	0.018^a
						(0.003)	(0.003)
ln(employment)	-0.001^a	-0.002^a	-0.001^a	-0.001^a	-0.001^a	-0.002^a	-0.001^a
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ln(area)	0.001^b	0.001^b	0.001^b	0.000^c	0.000^b	0.001^b	0.001^b
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ln(dist from Adelaide)	-0.008^a	-0.008^a	-0.008^a	-0.008^a	-0.008^a	-0.008^a	-0.008^a
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
ln(dist from coast)	0.002^a	0.002^a	0.002^a	0.002^a	0.002^a	0.002^a	0.002^a
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ln(dist from Murray)	-0.001^a	-0.002^a	-0.002^a	-0.001^a	-0.001^a	-0.002^a	-0.001^a
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Elevation	-0.000^a	-0.000^a	-0.000^a	-0.000^a	-0.000^a	-0.000^a	-0.000^a
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Temperature	0.004^a	0.003^a	0.004^a	0.003^a	0.003^a	0.004^a	0.004^a
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Rainfall	0.000^a	0.000^a	0.000^a	0.000^a	0.000^a	0.000^a	0.000^a
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
R^2	0.21	0.21	0.21	0.21	0.21	0.21	0.21

Note: 12,216 observations for each regression, representing 1,018 SSCs; robust standard errors clustered by SSC in parentheses; *a*, *b*, *c* denote significance at 1%, 5%, 10%; all regressions include census-year fixed effects; the dependent variable in all regressions is the change in log employment

Table A1: Results from the difference-in-differences estimation of the relationships between railway lines or breaks-of-gauge and (log) annual employment growth at the SSC level between 1911 and 1996.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Railway	−0.001						−0.001
	(0.001)						(0.001)
Narrow-gauge railway		−0.000			0.007^a		
		(0.002)			(0.001)		
Standard-gauge railway			0.007^c		0.000		
			(0.003)		(0.002)		
Broad-gauge railway				−0.001	-0.001^c		
				(0.001)	(0.001)		
Break-of-gauge						0.013^c	0.017^a
						(0.007)	(0.003)
ln(employment)	-0.001^a	-0.001^a	0.001	-0.002^a	-0.002^a	−0.000	-0.002^a
	(0.000)	(0.001)	(0.001)	(0.000)	(0.000)	(0.002)	(0.000)
ln(area)	−0.000	0.002^c	−0.001	−0.000	−0.000	0.001	−0.000
	(0.000)	(0.001)	(0.001)	(0.000)	(0.000)	(0.003)	(0.000)
ln(dist from Adelaide)	-0.007^a	0.000	-0.013^a	-0.007^a	-0.008^a	−0.010	-0.007^a
	(0.001)	(0.002)	(0.003)	(0.001)	(0.001)	(0.006)	(0.001)
ln(dist from coast)	0.002^a	0.001	0.004^c	0.002^a	0.002^a	0.001	0.002^a
	(0.001)	(0.001)	(0.002)	(0.001)	(0.001)	(0.004)	(0.001)
ln(dist from Murray)	-0.002^a	−0.002	−0.002	-0.002^a	-0.002^a	0.004	-0.002^a
	(0.000)	(0.001)	(0.002)	(0.001)	(0.000)	(0.003)	(0.000)
Elevation	-0.000^a	-0.000^a	-0.000^a	-0.000^a	-0.000^a	-0.000^a	-0.000^a
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Temperature	0.002^a	0.001	0.001	0.003^a	0.002^a	−0.002	0.002^a
	(0.001)	(0.002)	(0.002)	(0.001)	(0.001)	(0.006)	(0.001)
Rainfall	0.000^a	0.000^a	0.000^b	0.000^a	0.000^a	0.000	0.000^a
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
R^2	0.22	0.24	0.27	0.23	0.22	0.41	0.22
Number of observations	7,208	1,154	548	5,796	7,208	98	7,208

Note: robust standard errors clustered by SSC in parentheses; *a*, *b*, *c* denote significance at 1%, 5%, 10%; all regressions include census-year fixed effects; the dependent variable in all regressions is the change in log employment

Table A2: Results from the propensity-score matching estimation of the effects of railway lines or breaks-of-gauge on (log) annual employment growth at the SSC level between 1911 and 1996.