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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 increasing by around 50% within a decade of them opening. However, these effects were unwound within two decades of a break-of-gauge being closed. There is little evidence of gauge segmentation causing different paces of regional development. The gauge muddle also appears to have limited the extent of the railway network.

KEYWORDS
agglomeration; rail transport; railway gauge; trade frictions; transport infrastructure

JEL H54, L92, N77, N97, R42
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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. The breaks-of-gauge added to the costs of transport and limited goods flows, partially isolating places on either side of the gauge divides.[1] However, they also required local labour and capital and most were in rural or remote locations, so they may also have brought a local economic stimulus to regional areas. The railway gauge issues have been partly addressed in Australia by connecting all major cities to a single-gauge network, but significant gauge divides remain elsewhere in the world, notably between the main European and Russian networks, and at several international borders in East Asia and South America (Puffert, 2009).

This paper studies the regional economic implications of the historical railway gauge situation in Australia during the 20th century. It focuses on South Australia, the state where the intersections between conflicting railway gauges were the most heavily concentrated. The analysis addresses three questions in particular: How did break-of-gauge operations affect economic activity in the communities that hosted them? Did the segmentation of the railway network into different gauges affect regional economic development? What were the implications of the gauge situation for the configuration of the railway network?[2] The analysis is conducted using historical data on the railway network and regional population and employment aggregated to all census years from 1911 to 1996.

Railway equipment can only operate on track of a specific gauge. Typically, a unique gauge is chosen for a railway network, often with compatibility across an entire country or region. Australia is peculiar in that 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″ (1435 mm) and a 'broad' gauge of 5′3″ (1600 mm). South Australia then adopted 5′3″ to conform with its nearer neighbour Victoria. In the late 1850s, a 'narrow' gauge of 3′6″ (1067 mm) was chosen by Queensland because of claimed lower construction costs and suitability to rugged terrain. Its success led to it being used in other remote or mountainous parts of the country, including part of the network in South Australia. Efforts were eventually made to unify the gauge of major lines to the 'standard' of 4′8½″, which led to

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standard-gauge lines connecting Adelaide with other states and territories and the conversion of some regional lines. These events led to South Australia having substantial networks of railways in all three of the gauges 3′6″, 4′8½″ and 5′3″, with all three networks being used for general traffic including the transport of passengers and goods, for most of the 1900s. Appendix A in the supplemental data online gives more detail on the development of the railway network and the gauge situation in Australia.

The breaks-of-gauge in South Australia used three techniques: moving passengers or goods from one vehicle to another, interchanging bogies compatible with different gauges, or placing the vehicles on flat wagons that run on a different gauge. Each technique required substantial time and work to carry out and the breaks-of-gauge were thus significant points of friction in the transport network.[3] The natural expectation is that these activities would positively affect the local economy, as other transport activities locate near breaks-of-gauge, industries that rely on transport benefit from access, and railway employees spend their salaries at local businesses. There was also an advantage of relatively low transport costs to both sides of the gauge divide. On the other hand, the frictions in the transport network should have negative overall effects and thus negatively affect some other regions.

This paper studies the effects of breaks-of-gauge on local economic activity by testing whether population and employment in regions with breaks-of-gauge grew relative to other regions, using ordinary least squares (OLS), propensity score matching (PSM) and synthetic controls (SC) techniques. The OLS analysis shows how breaks-of-gauge correlate with local growth, but likely not their causal effects as they may simply be built where growth is planned or anticipated. Public debates from the era when breaks-of-gauge were being established suggest the most prevalent concern in choosing their locations was which market or port could be accessed without a gauge transfer, while there was a common belief that breaks-of-gauge would cause local growth (e.g., *South Australian Register*, 1884; *The Advertiser*, 1911; *The Chronicle*, 1925; *The Observer*, 1927). These observations leave open the possibility that locations with good conditions for growth would be chosen. The PSM and SC methods are used to identify the causal effects. Both function by comparing each 'treated' (break-of-gauge) region with another region that is similar except in that it does not have the treatment – a real region for the PSM and a hypothetical synthetic region for the SC – to isolate the effects of the treatment.

The main OLS result is that population and employment in regions with breaks-of-gauge grew around 2% faster than other regions. The PSM results suggest a somewhat smaller causal effect of roughly 1–2%. The SC results show that the aggregate effect of the breaks-of-gauge is large – with population and employment levels rising by around 50% within a decade of a break-of-gauge being opened. However, the local population and employment levels dropped to near the original growth path within two decades of a break-of-gauge being closed.

The question of whether the gauge segmentation of the network affected regional development is also addressed using OLS, PSM and SC techniques. The core of the railway network in South Australia, including the capital city Adelaide, was built in broad gauge and lines to Adelaide and the other state capitals were eventually built in standard gauge. The essence of the question is whether regions on narrow-gauge lines, which required gauge transfers to access most markets, experienced smaller benefits from railways than those with broad- or standard-gauge lines that could access markets at lower cost. The results for railways by gauge are unclear, as the effects of narrow- and broad-gauge lines on local growth are ambiguous and standard-gauge lines appear to have had positive effects.

The effects of the gauge muddle on the configuration of the railway network are inferred by analysing the development of the network over time. As gauge standardisation occurred in South Australia, many regional lines were abandoned. Higher proportions of the lines that were or would become gauge-isolated were abandoned. It is likely that the costs of gauge transfers or adaptation to the new gauge contributed to these lines being abandoned. A possible consequence of the railway gauge muddle is thus 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 railways and, in contrast to this paper, it 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. Donaldson and Hornbeck (2016) found that US railroads in the late 19th century increased market access and agricultural land values. Bogart et al. (2022) showed that 19th-century railways in England and Wales strongly increased local growth but negatively affected places 3–15 km away. Büchel and Kyburz (2020) found that 19th-century railways in Switzerland caused population growth along the new lines but reduced populations 2–10 km away. Berger and Enflo (2017), Berger (2019) and Lindgren et al. (2021) found that 19th-century railways in Sweden had positive effects on regional populations, incomes, land values and industrial development. Ciccarelli et al. (2021) found that the establishment of the Italian railway network in the late 19th century led to industrial growth, particularly in the north and over the long term. Franch et al. (2013) identified positive effects of 20th-century railways in Spain on population growth in certain regions. Alvarez-Palau et al. (2021) studied railway expansion on the European periphery between 1870 and 1910 and found a stronger association with gross domestic product (GDP) growth in northern than southern areas.

The history and economics of railway gauge have been studied extensively by Puffert (1991, 2000, 2002, 2009). He used a simple model to explain how different gauges can emerge in different regions, a different local gauge may persist despite the advantages of conformity, and the optimal gauge is not necessarily chosen as standard. An important implication for this paper is that the diversity of gauges in South Australia does not mean that situation was optimal. Benmelech (2009) studied the financing of 19th-century US railroads and found that gauge differences reduced their profitability.[4]

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 this paper contributes to the work exemplified by Davis and Weinstein (2002) and Bleakley and Lin (2012) on the persistence of local economic shocks. Indeed, it contrasts with their findings, as the local economic activity induced by the breaks-of-gauge was unwound after those operations ceased.

Breaks-of-gauge are related to other storage and transfer facilities that form nodes in transport networks. Rodrigue (2006, 2008) notes that concentrating transfer operations can lead to efficiency gains, in particular if the work required to carry out the transfers is minimised by design and technology as in the 'thruport' model, and that some facilities are required for transfers between railway owners or operators. Breaks-of-gauge differ in that they are additional points of friction in the network necessitated only by the lack of a uniform gauge. A greater obstacle to transport is 'missing' or 'broken' links – where transport infrastructure is not completed between major destinations. Maggi et al. (1992) argued that missing links were a barrier to the benefits of European integration. Peters (2003) and Schindler and Kanai (2021) highlighted poor transport links at national borders as a source of inefficiency. Liu and Zhou (2017) and Liu (2019) studied the missing links in the intercity highway system in China and Bian and Yeh (2020) estimated their effects on regional development.

The main contribution of this paper is to connect railway gauge diversity 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 effects on regional development. Multiple-gauge networks were common in the past but are now unusual, except in cases where the different gauges carry very different types of trains.[5] However, 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, 2009). The findings in this paper suggest those breaks-of-gauge may have important implications for regional development. Furthermore, the analysis avoids the issues with separating the growth effects of breaks-of-gauge and international borders that would arise from studying those scenarios directly.

There are several limitations to the analysis in this paper. First, it uses population and employment to represent local economic activity, as no historical regional data on output, productivity or trade are available. Second, the population and employment data are unavoidably rough as they were inferred from data for regions that changed size and shape over time. Third, the census periods are of uneven lengths, from five to 14 years, which introduces potential inconsistencies and limits the precision of the results. Fourth, railway lines are built, maintained and operated to different standards, but the analysis treats all railway lines as identical as no data adequate to distinguish them by quality or type are available. Fifth, the breaks-of-gauge differ in the scale of their operations, but the analysis does not differentiate 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. Section 4 presents the estimation results. Conclusions are presented in section 5. The supplemental data online provides additional background, details on the method and results.

2. DATA

The data used for the analysis were assembled from several sources. Information about the railway network is from cartographic data and related documents. Local economic activity was measured using population and employment figures from the Australian census.[6] Other data are from the Australian Bureau of Statistics (ABS), Geoscience Australia (GA) and the Bureau of Meteorology (BoM). The study is limited to South Australia because of its diversity of railway gauges as well as the work required to construct historical regional data for any part of Australia. The data were combined into a panel for the 13 census years from 1911 to 1996, which spans the period from the first Australian census to the closing of the last break-of-gauge in South Australia.

The analysis uses population and employment data by census year. The Australian census has been conducted in 1911, 1921, 1933, 1947, 1954 and then every five years from 1961. It has no statistical unit for regions below the level of the state that has remained constant over time. The most consistent regional data are populations by local government area (LGA), the borders of which regularly change. Employment is also given by LGA for all censuses except 1911, 1976, 1981 and 1991. The missing employment numbers were approximated from employment in earlier and later censuses and population growth rates – the imputation should be reasonable but makes the analysis for employment somewhat less reliable than that for population. To keep the geographical units consistent, the data were aggregated to the 2016 version of 'state suburbs' (SSCs) defined by the ABS. The SSCs broadly correspond to postal locations, so in rural areas they are usually towns or cities and thus good representations of local markets. The data given by LGA in each census were mapped to the 2016 SSCs according to the proportions of the settled areas of the LGAs that overlap the SSCs, identified from maps in the census documents.[7]

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 has more than two-thirds of South Australia's population and is thus qualitatively different from the rest of the state in terms of industry and density. The remote areas excluded are Kangaroo Island and the Eyre Peninsula, which are isolated from the core of the railway network and the major population centres, and the vast unpopulated areas in the north and west of the state. This leaves a sample of 1018 SSCs, which are illustrated in Figure 1 along with the 1911 and 1996 population densities and railway networks.

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″ (1067 mm) 'narrow' gauge, 4′8½″ (1435 mm) 'standard' gauge and 5′3″ (1600 mm) '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 any amount of railway by SSC and year. Figure 2 plots approximate lengths of railway lines by gauge and numbers of break-of-gauge locations in South Australia by year for 1911 to 1996. Maps showing the development of the South Australian railway network during the 20th century are given in Appendix A in the supplemental data online.

The same sources were used to identify the breaks-of-gauge, listed in Table 1. Some locations where different gauges meet were not classified as breaks-of-gauge for the purposes of this study. Adelaide has had multiple railway gauges since 1982, but gauge transfers are a relatively small part of its transport operations and this is an additional reason for Adelaide being excluded from the sample. Whyalla has had both narrow and standard gauges since 1972, but only as separate connections to its steelworks and it is also outside of the sample geography. Other junctions not classified as breaks-of-gauge are those with tourist railways and disused track. The activities carried out at the breaks-of-gauge listed in Table 1 included the transfer of passengers and goods between wagons of different gauges, exchanging bogies of different gauges, 'piggy-back' operations where wagons were loaded on flat wagons of another gauge, and storage of goods and railway vehicles (Vincent, 2019).

The data on the railway network and local population and employment were combined into a balanced panel

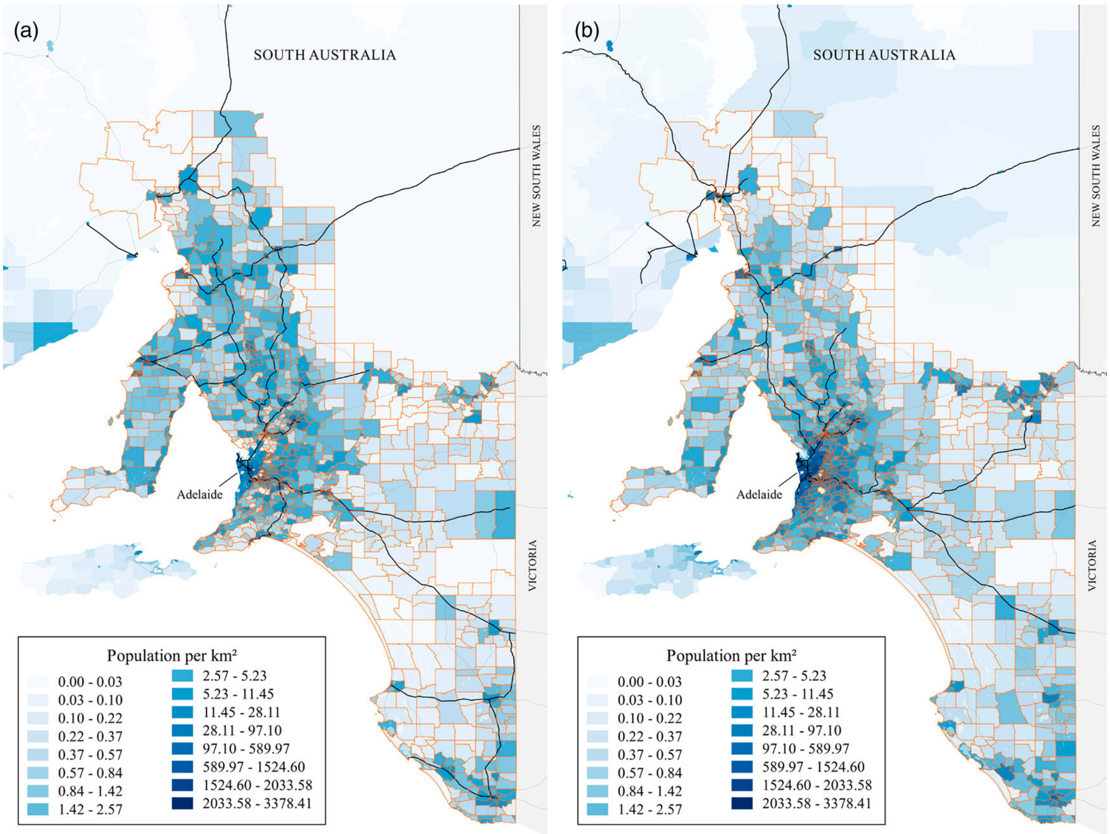

Figure 1. Maps of the 1018 sample 'state suburbs' (SSCs), with shading for the (a) 1911 and (b) 1996 population densities, and contemporary railways illustrated as lines.
Note: The sample is limited to the south-east of South Australia where the population is concentrated and it excludes the Adelaide metropolitan area.

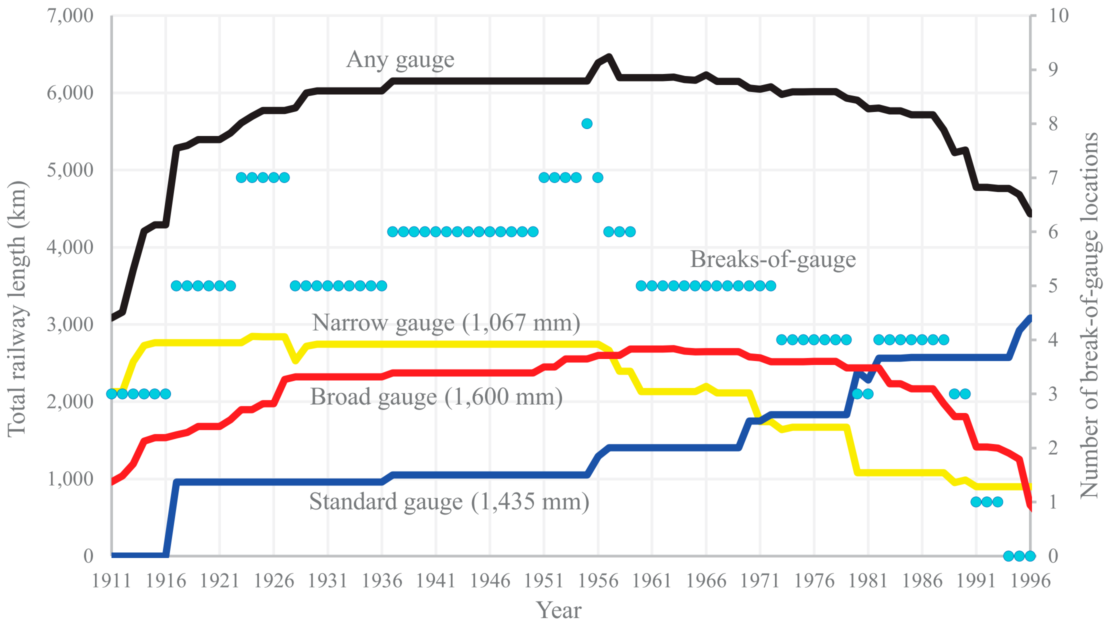

Figure 2. Approximate lengths of railway lines by gauge and the number of break-of-gauge locations in South Australia by year from 1911 to 1996.
Note: The lengths of railway lines are the 'system kilometres', which do not separately count double track, sidings or yards.

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

Location	Break-of-gauge		Transfer				
	Start	End	Passenger	Goods	Bogie exchange	Piggyback	Gauges (feet and inches)
Bowmans	1923	1927	×	×			3′6″ and 5′3″
Brachina	1955	1956		×		×	3′6″ and 4′8½″
Gladstone	1927	1990	×	×			3′6″ and 5′3″ to 1970, then 3′6″, 4′8½″ and 5′3″
Hamley Bridge	1879	1927	×	×			3′6″ and 5′3″
Kadina	1982	1990	×	×			4′8½″ and 5′3″
Marree	1957	1980	×	×		×	3′6″ and 4′8½″
Mount Gambier	1917	1956	×	×			3′6″ and 5′3″
Naracoorte	1951	1959	×	×			3′6″ and 5′3″
Peterborough	1970	1988	×	×	×		3′6″, 4′8½″ and 5′3″
Port Augusta	1917	1972	×	×		×	3′6″ and 4′8½″
Port Pirie	1937	1982	×	×	×		3′6″, 4′8½″, and 5′3″ to 1970, then 4′8½″ and 5′3″
Snowtown (NG-BG)	1923	1927	×	×			3′6″ and 5′3″
Snowtown (SG-BG)	1982	1993	×	×			4′8½″ and 5′3″
Terowie	1881	1970	×	×		×	3′6″ and 5′3″
Wolseley	1884	1955	×	×			3′6″ and 5′3″

Note: BG, broad gauge; NG, narrow gauge; SG, standard gauge.

dataset, aggregated to the 1018 sample SSCs and the 13 census years from 1911 to 1996. The dataset also includes data on mean land elevation from GA and mean temperature and annual rainfall by SSC over the period 1961 to 1990 from the BoM. Table 2 presents summary statistics for the main variables in the dataset. Table 3 presents the characteristics of the SSCs by railway and break-of-gauge status, which shows how regions with railways and breaks-of-gauge differ from other regions in terms of location and size.

Table 2. Summary statistics for the dataset, which is a panel for the 1018 sample 'state suburbs' (SSCs) over the 13 census years from 1911 to 1996.

	Mean	SD	Minimum	Maximum
Data by SSC and census year (13,234 observations in balanced panel of 1018 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	8901
Data by SSC (1018 observations)				
Land area (km^2)	110.4	197.6	0.04	2866.9
Distance from Adelaide (km)	136.7	95.1	7.7	401.7
Distance from the coast (km)	51.4	48.7	0.2	227.1
Distance from the Murray River (km)	100.8	80.2	0.1	324.0
Mean elevation (m)	160.7	160.8	0.1	703.5
Mean temperature (°C)	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.

3. METHOD

The main aim of the empirical analysis is to understand how railways and breaks-of-gauge affected local economic activity during the 20th century. Local economic activity is measured as either the local population or employment and denoted $Y_{r,t}$ for region r in census year t, applied in log terms as $y_{r,t} \equiv \ln(Y_{r,t})$. 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. The presence of railway lines or breaks-of-gauge is represented by $infr_{r,t}$, a vector of binary variables defined such that for example $infr_{r,t} = 1$ if region r had a break-of-gauge in census year t and $infr_{r,t} = 0$ if it did not. The OLS and PSM estimates are generated by fitting the following equation:

$$\Delta y_{r,t} = \beta_{infr} infr_{r,t} + \beta_y y_{r,t} + \eta_r + \theta_t + \varepsilon_{r,t} \qquad (1)$$

where $y_{r,t}$ controls for the current level of population or employment, with parameter β_y. Factors for local growth other than the railways are captured by the SSC fixed

Table 3. Summary statistics for sample 'state suburbs' (SSCs) by railway and break-of-gauge status between 1911 and 1996.

SSC status for 1911–96	Never had a railway	Had a railway	Had break-of-gauge
Distance from Adelaide (km)	130.7	147.6	214.5
	(95.0)	(94.4)	(87.3)
Distance from the coast (km)	47.7	58.3	43.4
	(47.9)	(49.3)	(35.6)
Distance from the Murray River (km)	98.3	105.3	175.8
	(80.8)	(79.1)	(60.0)
Population in 1911	101.8	357.4	1644.3
	(210.8)	(637.2)	(1678.0)
Employment in 1911	43.8	154.2	712.6
	(90.5)	(274.8)	(723.0)
Population in 1996	193.0	699.8	3601.4
	(386.2)	(1663.9)	(5904.8)
Employment in 1996	80.1	291.0	1,465.1
	(158.2)	(705.4)	(2601.6)
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 (SD) in parentheses.

effects η_r and the census-year fixed effects θ_t. The term $\varepsilon_{r,t}$ is a set of independent and identically distributed errors. Of primary interest is the vector of parameters β_{infr}, which relates local growth to the presence of a railway line or break-of-gauge. Alternative specifications were run with different combinations of railway or break-of-gauge variables in $infr_{r,t}$.

The OLS technique was applied by estimating (1) with the full sample of regions. The PSM technique was applied by estimating (1) with a subset of the regions selected so for each region with the railway infrastructure there is another region without it but that was determined to have been similarly likely to have had it based on the estimation process described in Appendix B in the supplemental data online.

The SC technique functions by comparing outcomes in a region where a railway line or break-of-gauge was opened with outcomes in 'synthetic' region designed to be similar to the 'treated' region except that it does not have that type of infrastructure. Each synthetic region was constructed as weighted combinations of the 'untreated' regions using the approach of Abadie et al. (2010) and Abadie (2021) as described in Appendix C in the supplemental data online.

In contrast to the OLS and PSM techniques as applied here, the SC technique is centred around the period when the infrastructure was opened. Using r for the 'treated' region, t for the census year, and T_0 for the census year the infrastructure was opened, $I_{r,t}^{infr}$ is a binary variable for the infrastructure being open, $Y_{r,t}$ is actual population or employment, and $Y_{r,t}^{N}$ is the hypothetical population or employment in the absence of the infrastructure as represented by the synthetic region. The following relationship was fitted:

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

The effects of the infrastructure on economic activity were inferred from the parameters $\alpha_{r,t-T_0}$, which quantify the differences 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 $Y_{r,t}^{N}$ after the infrastructure was opened can be attributed to the infrastructure. The parameters $\alpha_{r,t-T_0}$ are defined separately for each interval of census years $t - T_0$ after the infrastructure was opened.[8] To study the effects of railway lines and breaks-of-gauge being closed, versions of the analysis were run with the actual and synthetic levels compared around the census year the infrastructure was closed.

The SC technique as described thus far generates a single deterministic growth path for each SC region to compare with the respective treated region. To test the statistical significance of the effects, I used the approach developed by Cavallo et al. (2013). That is, a large number of 'placebo' treatments were selected at random from the regions that never had railway lines, a SC region for each was constructed, then the differences between the placebo treated and SC growth paths were 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 set of regions where railway infrastructure was built was calculated by evaluating where the actual difference in growth paths fits on the relevant distribution.

4. RESULTS

This section presents the OLS, PSM and SC results in separate subsections, followed by an analysis of line closures. The OLS and PSM results for the local population are also presented. For brevity and because the employment data are less reliable, the OLS and PSM employment results are presented in Appendix D in the supplemental data online. The SC results are presented for both population and employment.

4.1. Ordinary least squares (OLS)

Table 4 presents the results from the estimation of (1) using OLS and with population as the measure of local economic activity. The columns show results from regressions with different sets of binary variables for railway infrastructure. Column 1 uses a variable for a railway of any gauge, columns 2–4 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 4 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 1%. The coefficients for the broad-gauge railway lines are also negative and significant, though those for narrow-gauge lines are positive and for standard-gauge lines are not 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 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. Thus railway lines correlated with lower growth during the sample period, but were not necessarily negative factors for growth. The population variable partly captures this overall growth pattern, as its coefficient is negative, but a component remains that is reflected in negative coefficients on railways.

The coefficients in Table 4 for the relationships between breaks-of-gauge and local growth – in columns 6 and 7 – are positive and significant at 1%. 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 D in the supplemental data online, are similar in sign and magnitude to those for population growth in Table 4. There are only slight differences in the

Table 4. Results from the ordinary least squares (OLS) estimation of the relationships between railway lines or breaks-of-gauge and (log) annual population growth at the 'state suburb' (SSC) level between 1911.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Railway	−0.008[b]						−0.008[b]
	(0.002)						(0.002)
Narrow-gauge railway		0.012[a]			0.008[a]		
		(0.002)			(0.002)		
Standard-gauge railway			−0.004		−0.002		
			(0.002)		(0.003)		
Broad-gauge railway				−0.010[a]	−0.007[a]		
				(0.001)	(0.002)		
Break-of-gauge						0.018[a]	0.018[a]
						(0.005)	(0.005)
ln(Population)	−0.013[a]	−0.014[a]	−0.013[a]	−0.013[a]	−0.013[a]	−0.013[a]	−0.013[a]
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
R^2	0.34	0.34	0.34	0.34	0.34	0.34	0.34
Number of observations	12,216	12,216	12,216	12,216	12,216	12,216	12,216

Note: Robust errors are shown in parentheses; [a, b, c]significance at 1%, 5% and 10%, respectively; all regressions include SSC and census-year fixed effects; the dependent variable in all regressions is the change in log population.

magnitudes and significance levels of the railway variables, though the employment estimation has slightly higher R^2 values.

4.2. Propensity score matching (PSM)

Table 5 presents the results from the PSM estimation of (1) with log population growth as the outcome. The railway variables in the seven columns correspond to those in the OLS estimation in Table 4. The sample sizes vary by column because only SSCs with infrastructure or matched to them are included in each regression.

As with the OLS results presented above, the coefficients on the presence of a railway of any gauge in Table 5 are negative and significant. Though the OLS results can only be interpreted as reflecting a negative correlation between railways and local growth, the PSM results suggest they had a negative causal effect. The results for railways by gauge in columns 2–5 show mixed evidence for the effects of narrow-gauge railways, no effect of standard-gauge railways and negative effects of broad-gauge railways.

The results in Table 5 indicate positive effects of breaks-of-gauge on local population growth. The relevant coefficient in column 6 is not significant, though note the small sample size for that regression. The regression in column 7 has a positive and strongly significant coefficient on the breaks-of-gauge. However, the matching in that

Table 5. Results from the propensity score matching (PSM) estimation of the effects of railway lines or breaks-of-gauge on (log) annual population growth at the 'state suburb' (SSC) level between 1911 and 1996.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Railway	−0.010[a]						−0.010[a]
	(0.003)						(0.003)
Narrow-gauge railway		−0.016[a]			0.006[a]		
		(0.006)			(0.002)		
Standard-gauge railway			−0.015		−0.000		
			(0.024)		(0.003)		
Broad-gauge railway				−0.009[a]	−0.007[a]		
				(0.003)	(0.002)		
Break-of-gauge						0.022	0.016[a]
						(0.018)	(0.005)
ln(Population)	−0.013[a]	−0.012[a]	−0.035[a]	−0.014[a]	−0.013[a]	−0.030[c]	−0.013[a]
	(0.001)	(0.003)	(0.009)	(0.002)	(0.001)	(0.016)	(0.001)
R^2	0.39	0.68	0.61	0.42	0.39	0.90	0.39
Number of observations	7208	1154	548	5796	7208	98	7208

Note: Robust standard errors are shown in parentheses; [a–c]significance at 1%, 5% and 10%, respectively; all regressions include SSC and census-year fixed effects; the dependent variable in all regressions is the change in log population.

regression is not fully appropriate to analysing the breaks-of-gauge as it includes all SSCs with railway lines and their paired control regions. Though not clear evidence, 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 D in the supplemental data online, are similar to those for population growth in Table 5. The main difference is that more of the variation in employment growth is explained in the model.

4.3. Synthetic controls (SC)

The SC analysis is conducted by comparing the actual and synthetic population and employment densities in the period around the opening or closing of a given type of infrastructure. The idea is to infer the causal effects of the infrastructure by matching the characteristics of the actual and synthetic regions. It constructs growth paths defined with a timescale of the number of census years before or following the treatment, so year 0 is the first census year that the relevant infrastructure was either opened or closed.

The analysis is run on sets of several treated regions, so it is necessary to aggregate the growth paths for each set. This is done by creating a growth index for each treated or control region, with value 1 assigned to the census year the infrastructure was opened or closed and then the value for each earlier or later census year calculated in sequence based on the mean growth rate for all regions with valid observations for that interval. The growth paths are calculated from a series of single-period growth rates because not all regions have the same number of census years before or after the treatment, due to the limits of the sample and the infrastructure sometimes being removed. Each placebo scenario is constructed to match the periods of treatment for the set of treated regions.

Figure 3 plots the actual and synthetic population and employment growth paths for all SSCs where railways were opened during the sample period. The lower part 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 3 appear to indicate that new railway lines initially led to somewhat higher local growth, though the differences are not significant. Overall, this does not represent evidence that the railway lines influenced local economic activity.

Figure 4 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.

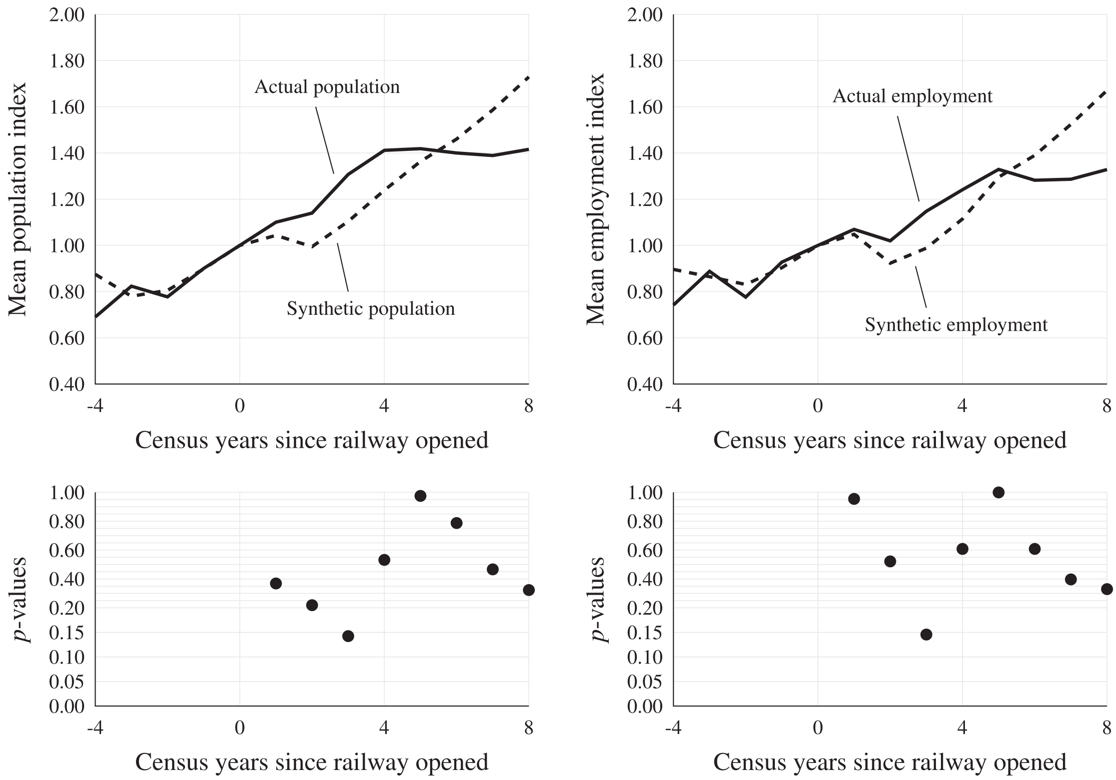

Figure 3. Plots of the indexed population and employment growth in regions where railway lines were opened compared with the equivalent 'synthetic' regions. The horizontal axis is the difference between the current census year and the census year in which the railway line was opened.
Note: The diagram below each plot shows the p-values for the differences between the actual and synthetic growth paths.

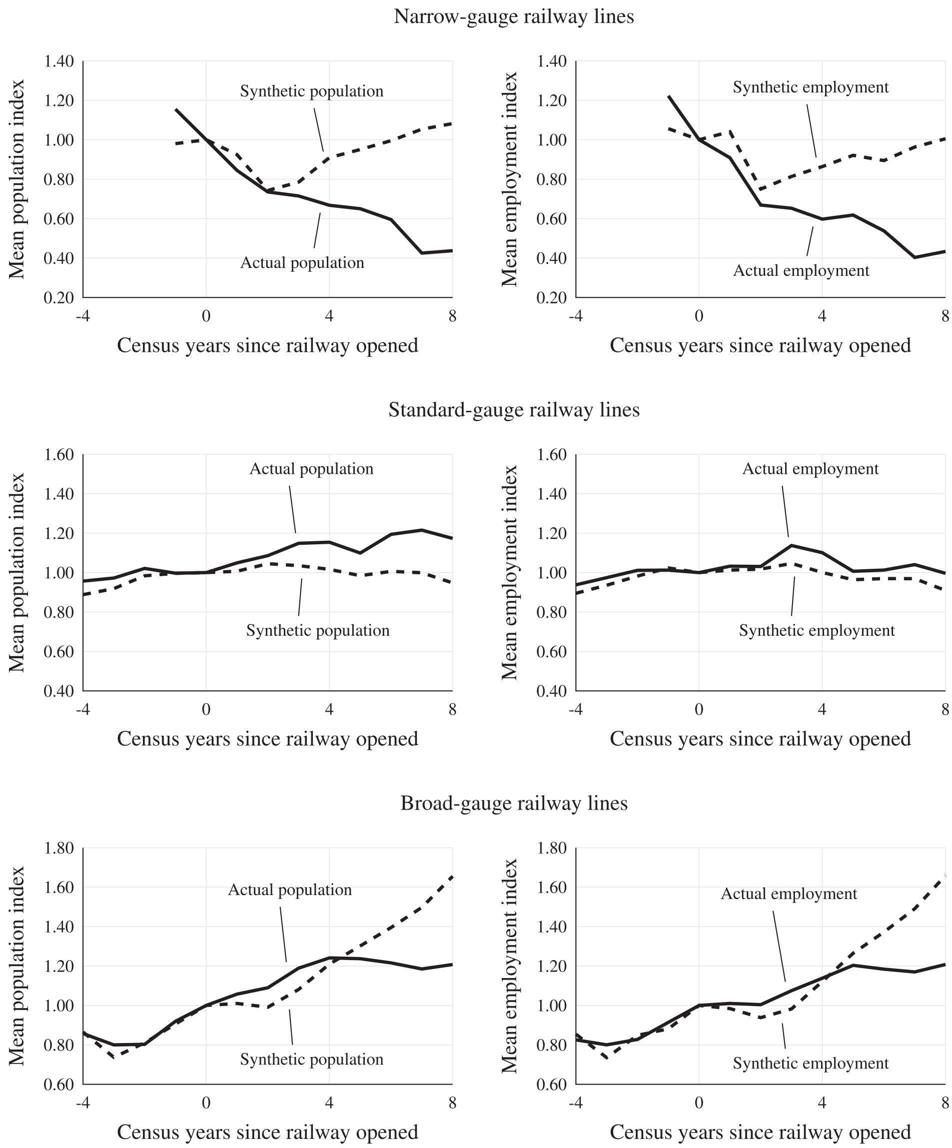

Figure 4. Plots of the indexed population and employment growth in regions where railway lines in each gauge were opened compared with the equivalent 'synthetic' regions.
Note: The horizontal axis is the number of census years relative to the opening of each railway line. The only differences significant at 10% are for the population in five of the eight periods after the opening of standard-gauge lines.

Though the results in Figure 4 are mostly not significant, certain trends are apparent from the plots. The pattern for the new narrow-gauge line is of similar growth to the synthetic regions for two census periods and then relative decline for decades thereafter, though none of the differences are significant. The SSCs with standard-gauge lines grew 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 had fewer stations along their routes. The results for the broad-gauge lines resemble those for railway lines of any gauge in Figure 3, with slightly higher growth for SSCs with the actual regions for a few census periods and then lower growth.

Figure 5 illustrates the actual and synthetic growth paths for the period around the closing of a railway line. The population and employment levels 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 those constructed based on the trends before the opening of the railway lines, rather than being recalculated to fit the trends before the railway lines were closed.

Figure 5 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 line closings appear similar and the differences are not significant. This suggests that either (1) lines were abandoned in response to the regions they served being in decline or (2) the utility of

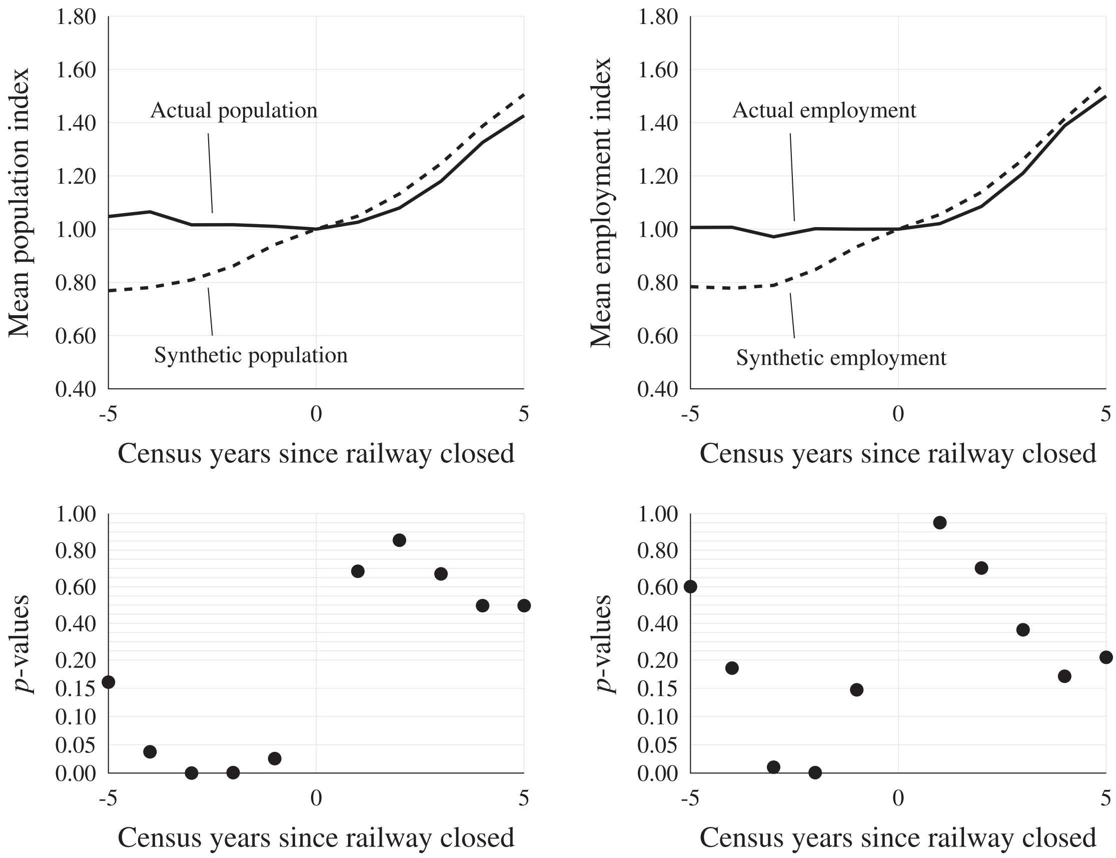

Figure 5. Plots of the indexed actual and synthetic population and employment growth around the closing of a railway line. Note: The horizontal axis is the number of census years relative to the closing of the railway. The diagram below each plot shows the *p*-values for the differences between the actual and synthetic growth paths.

the lines became negligible or indeed they may have been left idle before they were abandoned.

Figure 6 plots the actual and SC population growth paths for the opening of breaks-of-gauge. The SC regions in this analysis are constructed from the SSCs that had railway lines at the time but never had a break-of-gauge.

The plots in Figure 6 show that the opening of the average break-of-gauge led to around 50% higher local population and employment levels within one census period 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 for several decades, though the differences are not significant after 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. First, break-of-gauge operations required a substantial amount of labour to be employed by the railway and in related activities. Second, as goods had to be loaded and unloaded at breaks-of-gauge, there were frictions in the transport network at those points that also made them relatively advantageous locations for freight forwarders or firms that used or sold traded goods. Third, a multiplier effect on local employment due to the demand for local goods and services and 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*.[9]

All the breaks-of-gauge in South Australia were closed during the sample period. What happened after the breaks-of-gauge were closed is also important to understanding their effects on regional development. Figure 7 shows the actual and synthetic growth paths around the closing of the breaks-of-gauge. Placebo scenarios are run to calculate appropriate *p*-values for the differences between actual and synthetic levels.

The results in Figure 7 suggest that practically all the local population and employment gains from the breaks-of-gauge were unwound within three or four census years of them being closed. That is, the regions appear to return, within 20 years, to the growth path they would have been on if they had never had breaks-of-gauge. The actual and synthetic growth paths track together before the breaks-of-gauge are closed, so the growth rates do not appear to have been affected in advance of them being closed. It should be noted, however, that the differences are only significant for employment and for three census years.

4.4. Network development

Some aspects of how the gauge muddle has affected the extent and composition of the railway network in South Australia can be understood by observing its historical development. As shown in Figure 2, the total length of

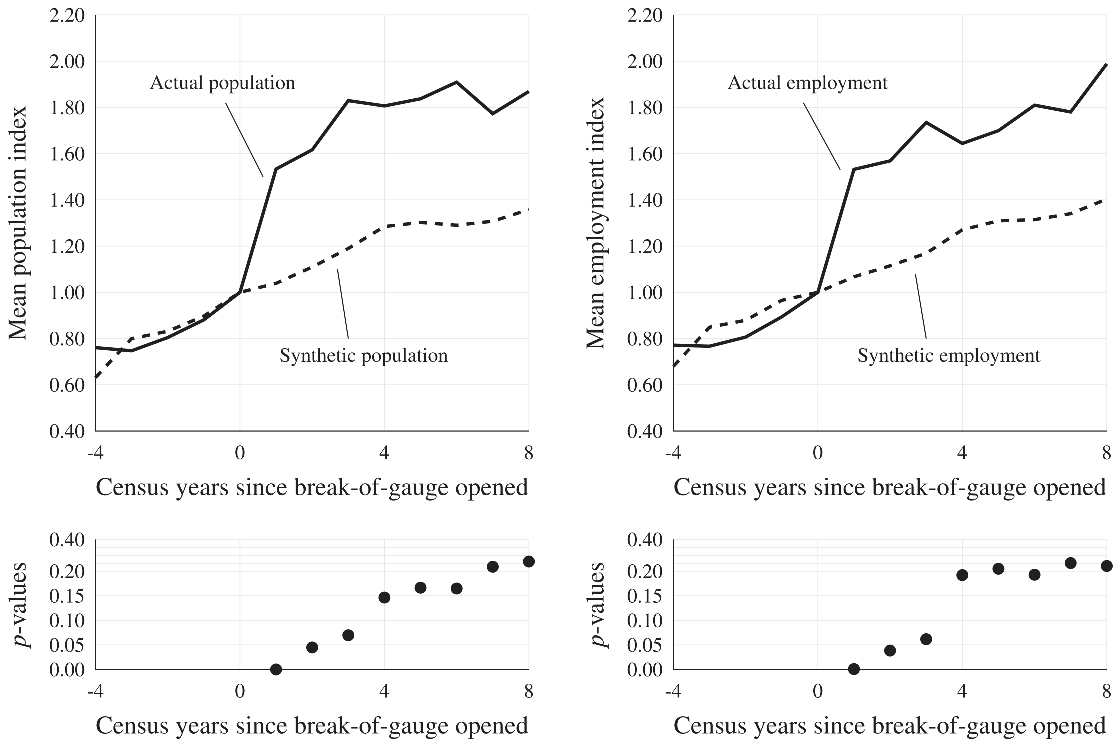

Figure 6. Plots of the indexed population and employment growth in regions where breaks-of-gauge were opened compared with the equivalent 'synthetic' regions.
Note: The horizontal axis is the number of census years relative to the opening of the break-of-gauge. The diagram below each plot shows the *p*-values for the differences between the actual and synthetic growth paths.

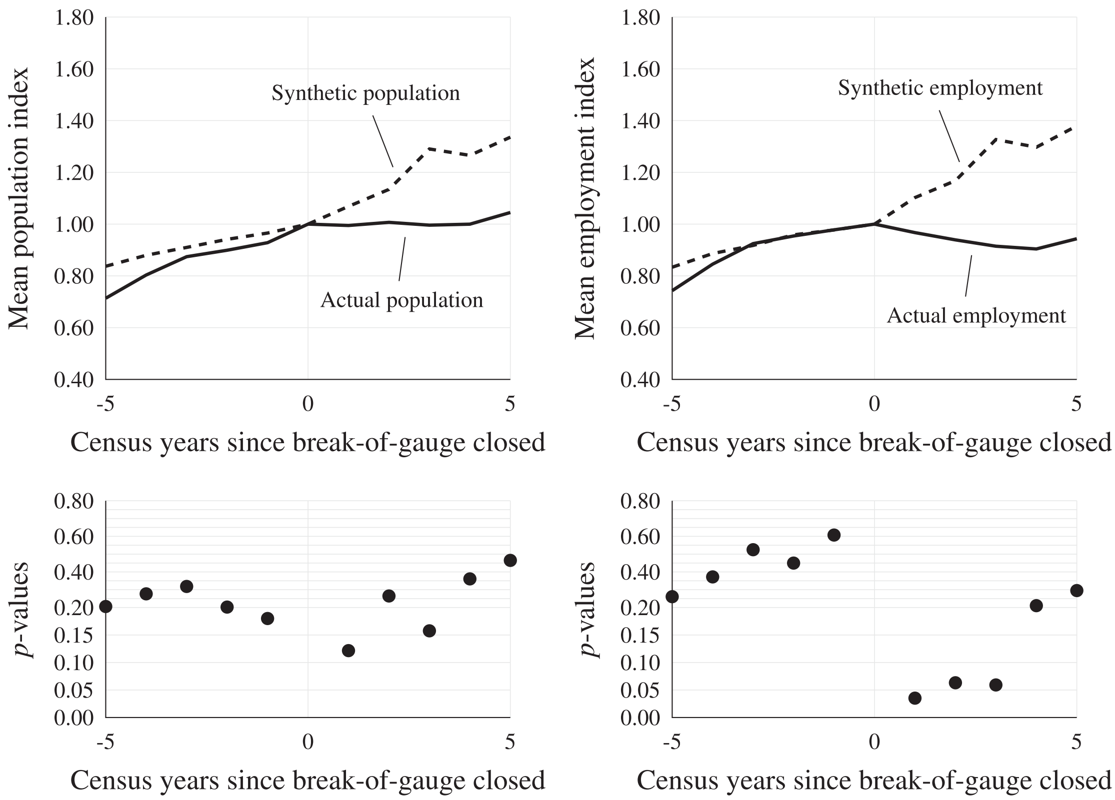

Figure 7. Plots of the indexed actual and synthetic population and employment growth around the closing of a break-of-gauge.
Note: The horizontal axis is the number of census years relative to the closing of the break-of-gauge. The diagram below each plot shows the *p*-values for the differences between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

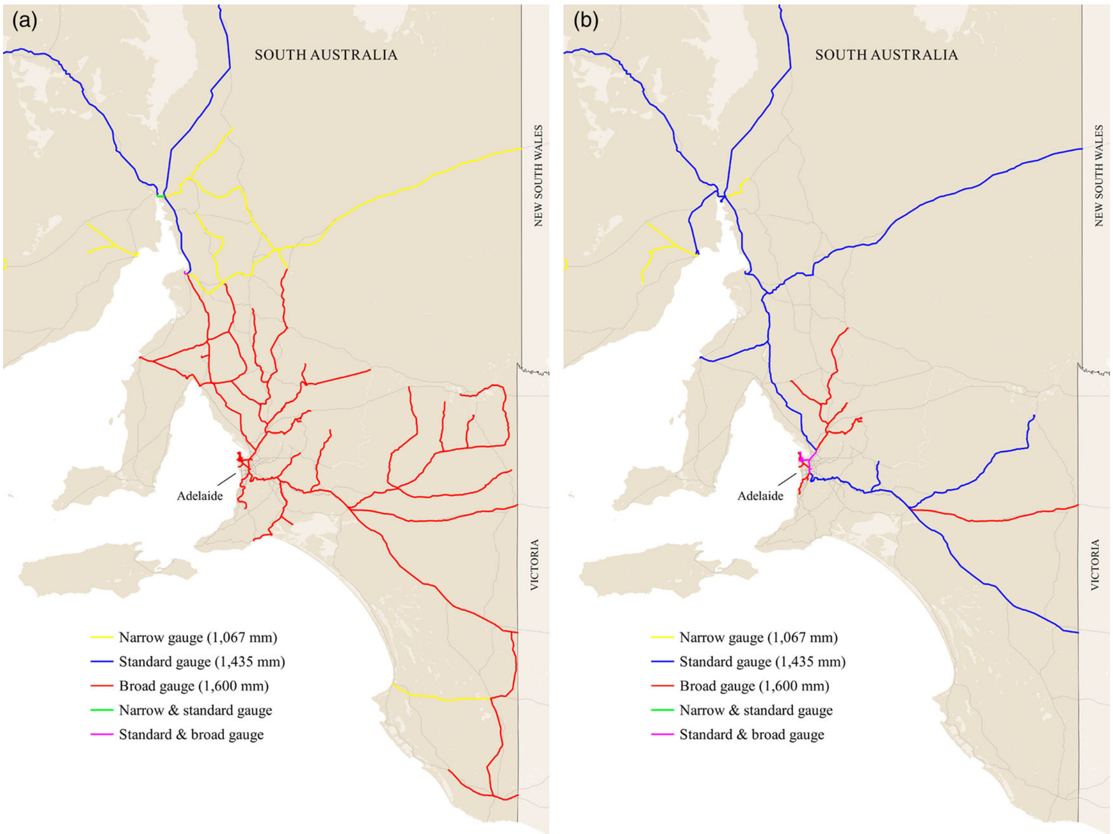

Figure 8. Maps of the South Australian railway network in (a) 1957 and (b) 1996. The state railway network was at its peak in terms of total line-kilometres in 1957.

railways in the state has generally been declining since its peak in 1957. If keeping a line in operation requires a gauge conversion because the trunk line that connects it to the broader network is converted, then there would be 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 8 show the South Australian railway networks in 1957 and 1996. Ignoring 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 eight of those branch lines remained in operation in 1996. Of the 21 branch lines in 1957, four were in narrow gauge, always required a gauge transfer to access Adelaide, and all four 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, would thus either require gauge transfers or conversion to standard gauge, and only three of those branch lines were converted to standard gauge while the other eight were abandoned by 1996. Of the six branch lines that were in broad gauge and connected to broad-gauge trunk lines that were not converted, five 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.

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. CONCLUSIONS

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. Despite the efforts of politicians and other advocates over the years, the steadily increasing costs of gauge unification have 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; a single-gauge connection between them 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 between gauges. Though the scarcity of historical data on trade within Australia prevented it from being analysed here, Smith (1963) and many news accounts have confirmed this prediction. The costs of these obstacles in the railway network limiting trade are also logical given the clear findings about the impact of missing transport links (Bian & Yeh, 2020; Maggi et al., 1992; Schindler & Kanai, 2021) and about the benefits of trade-facilitating transport infrastructure (Allen & Arkolakis, 2022; Donaldson, 2018; Donaldson & Hornbeck, 2016; Jaworski & Kitchens, 2019). The main finding of this paper represents a trade-off against the costs of higher transport costs: the breaks-of-gauge also had positive economic effects on the regions that hosted them.

The effects of the breaks-of-gauge on local economic activity are measured in population and employment terms. The PSM analysis shows that regions with breaks-of-gauge experienced around 1–2% higher annual population and employment growth than otherwise similar regions. The SC analysis reveals that the effects of the average break-of-gauge were in fact roughly 50% increases in population and employment within a decade of the break-of-gauge opening, with the relative increases maintained as long as it was in operation.[10] The increases in population and employment exceeded the additional workers employed directly in railway operations.

When breaks-of-gauge were removed, the local population and employment levels returned to their original growth paths within two decades. In contrast, Bleakley and Lin (2012) found that settlements built at US river portage sites remained relatively large in population many decades after the portage operations became obsolete. It is not obvious why this did not occur with the breaks-of-gauge in South Australia. As with the US river portage sites, the jobs involved in the breaks-of-gauge disappeared and the infrastructure was either dismantled or idled when the operations closed. A possible explanation is that many of the places in South Australia that hosted breaks-of-gauge, being in remote and largely agricultural regions lacking conditions favourable for other industries, simply had too little potential to maintain a base of economic activity without the break-of-gauge. Another explanation could be that as the railways in South Australia were run by the government, which posted a pool of workers to locations around the state according to current need, a critical mass of workers and consumers were immediately removed from the community as soon as the facility was closed.[11]

The analysis finds no evidence that regions in South Australia suffered from being served by railways gauge-isolated from the core of the network. The PSM analysis suggests that broad-gauge railways, which represented the core of the network for most of the 20th century, caused lower rates of growth than the other two gauges. The SC analysis shows that the standard-gauge railways, which were only connected to Adelaide in 1982, had weakly larger effects on growth than the other gauges.

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, due to the costs of operating gauge transfers or converting the gauges of existing lines. As discussed in section 4, this would explain the abandonment of many regional 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 South Australia not served by rail that would have been in the absence of the gauge muddle.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the author.

NOTES

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 km by rail. Smith (1963) found that goods trade by rail between New South Wales and Victoria had a large discontinuity at the gauge divide at Albury. Historical newspaper accounts confirm the substantial costs of gauge transfers in South Australia, for example, *South Australian Register* (1880), *The Adelaide Observer* (1904), *The Observer* (1914) and *The Mail* (1952).
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.
3. Since at least the early 1900s, several technologies for variable-gauge wheelsets have been proposed to facilitate railway gauge transitions, including in Australia (*The Argus*, 1918). Such a technology is used on the Talgo trains that run between Spain and France, but has not been applied in Australia (Puffert, 2009).
4. In Australia, from the early days of railway construction until the late 20th century, mainline railways were publicly built and operated.

5. 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.
6. 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.
7. An additional reason for ending the sample in 1996 is that in 1997 there was a large realignment of the LGAs in South Australia, which would introduce substantial inconsistencies if data from censuses after 1996 were approximated to the same set of regions.
8. The intervals between the Australian censuses have varied between five and 14 years. Unfortunately, there is no practical way of converting them to intervals of constant length. 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.
9. In the 1971 Census, the *transport and storage* industry employed 39 of 415 workers in Gladstone (district council), 299 of 1136 workers in Peterborough (municipality) and 593 of 4876 workers in Port Pirie (city).
10. The magnitude and timing of the SC results suggest that the 1–2% effect in the PSM results could be a misleading simplification, as it averages a few years of a large effect and many years of little to no effect. Though most breaks-of-gauge were in operation for many years, the SC effects do indeed appear to be larger.
11. *The Chronicle* (1927) observed the following about the closing of the break-of-gauge at Hamley Bridge:

The railway station was the scene of many farewells this morning, as a large number of railway employees affected by the transfer of the break-of-gauge left for their new stations. … The station seems deserted since all the engines, coaches, etc. have been taken away. … The remainder of the men affected will leave by train on Monday morning for their respective destinations.

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