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The Spatial Impacts of a Massive Rail Disinvestment Program: The Beeching Axe

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Abstract
Transport investment is a popular policy instrument and many recent studies have investigated whether new infrastructure generates economic benefits and has spatial economic impacts. Our work approaches the question differently and looks at what happens when a substantial part of a national railway network is dismantled, as happened during the 1950s, 60s and 70s in Britain. Part of this disinvestment occurred following controversial reports on railway profitability and structure in the early 1960s – a course of action known colloquially as 'the Beeching Axe' after the author of the reports. The removal of railways is often blamed for the decline of rural areas and peripheral towns in post-war Britain. This rail disinvestment program was targeted at removal of underused and unprofitable lines and not specifically targeted at local economic performance. Even so, we find that there is a relationship between pre-war population decline and the depth of the rail cuts in the post 1950 period. Conditional on these pre-trends, we show that loss of access by rail did cause relative population decline, decline in the proportion of skilled workers, and decline in the proportion of young people in affected areas. The elasticity of population with respect to changes in centrality (or market access) is around 0.3 in our main estimates. Instrumental variables estimates based on the network structure of the cuts yield higher elasticities. An implication of these findings is that rail transport infrastructure plays an important role in shaping the spatial structure of the economy.

Key words: rail, infrastructure, Beeching
JEL: H54; R1; R4

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1. Introduction

Theory and common sense suggest that transport plays an important role in shaping the spatial economy. It affects where people choose to live, where people choose to work, affects patterns of trade and potentially shifts productivity. Despite this, it is only quite recently that high quality evidence has emerged, using detailed spatial data and modern methods to provide credible estimates of the response of the economy to changes in transport networks. [1] Some of this work focusses on specific schemes within cities. Some turns to historical settings or developing countries in order to find contexts where there is a large expansion in the transport network on which to base estimation. However, there is a formidable empirical challenge in that transport is typically targeted towards places that are already growing, or are otherwise atypical, so it is hard to disentangle causal effects from pre-existing trends. Our work is unique in looking at the effects of disinvestment in rail infrastructure, which offers some advantages in that we are not studying the construction of infrastructure to serve specific local economic demands. Studying partial removal of a rail system also offers interesting insights into whether infrastructure locks in permanent changes in spatial structure, or whether whatever benefits it brings are conditional on the infrastructure staying in place.

The specific context we study is the decommissioning of railways that occurred over the 1950s, 1960s and 1970s in Britain. At this time, the railways were a nationalised industry, under control of British Rail, part of the British Transport Commission. The cutbacks to the rail network started early in this period, though are often blamed on a 1963 report *The Reshaping of British Railways* issued by the chairman of the British Railways Board, Dr. Richard Beeching (British Railways Board 1963). The report is commonly known as the 'Beeching report' and its

[1] Redding and Turner 2015 provide a recent review of this transport literature. For some specific examples related to rail, see Ahlfeldt 2015, Baum-Snow et al 2017, Bogart et al 2018, Donaldson 2018, Donaldson and Hornbeck 2016, Heblich, Redding and Sturm (2017, Garcia-López et al 2017, Gonzalez-Navarro and Turner 2016, Hornung 2015, Qin 2016.

consequences referred to as the 'Beeching Axe'. The main factor motivating the cuts was simply the dire financial situation of the rail transport industry, which was incurring losses of over £100 million per year by the early 1960s (Waller 2013). The reasons for these losses are complex, partly due to the changing patterns of demand with shifts towards buses and road transport, partly due to failed reinvestment programmes and poor management, and partly a legacy of the private sector development of the network during the 19th century which had resulted in some oversupply and redundancy. The bottom line was that over the 1950-1980 period 42% or the line (around 13,000 km from 31,000 km) and nearly 60% of the stations (3700 out of 6400) were closed. Subsequently, there has been intense and long running debate over the consequences of these cuts for the British economy, particularly rural areas (Loft 2013). However, to the best of our knowledge there has been no systematic assessment of the effects.

Our basic approach to filling this gap is to link small scale aggregated historical decennial census data from 1901 through to 2001 to a historical GIS of Britain's railway network that details the lines and stations open in each decade. We then use panel data regression-based methods to estimate whether changes in accessibility due to cuts in the railways – measured by a market access/network centrality index – were associated with changes in population and other demographic and socioeconomic area characteristics. An important point to emphasise here is that we are explicitly investigating the effects of changes in infrastructure on the distribution of population across space. A pervasive criticism of studies that look at outcomes like firm or regional productivity or employment is how to distinguish 'causal' effects from displacement and sorting of agents across space (see Redding and Turner 2015 for a recent exposition). In our setting, this criticism is not directly relevant, because we are explicitly looking at displacement and sorting, asking if cuts to transport in one location relative to another result in population changes in one place relative to another. We are not making any claims about the effects of transport cuts on national aggregate population, age or skills. The main empirical identification challenge we face is to distinguish local population decline that was caused by the cuts from population decline that was already occurring, or which would have occurred from other structural changes even in the absence of the rail cuts. For this reason, our primary identification strategy matches geographical units flexibly on pre-existing population trends to address the problem that the rail cuts were not randomly allocated and were more likely to occur in already-declining places. We also check carefully for the influence of other contemporaneous changes that might confound our estimates, including general urban-rural trends, the growth of specific towns due to planning and the evolution of the motorway network. We also devise two instruments for the depth of the rail cuts for use in an instrumental variables procedure, based on the network structure. These instruments exploit the fact that the cuts targeted non-trunk routes in the network, and as a by-product, lines running east-west were much more likely to be cut than lines running north-south down the spine of Britain towards London.

The overall conclusion is that places experiencing large reductions in rail centrality experienced falls in population, the number of educated and skilled workers and an increase in the proportion of older workers, relative to places that were less affected. The elasticity of population with respect to network centrality (or market access) is around 0.3, with instrumental variables estimates higher but less precisely measured. The population results indicate that, as theory would suggest, transport has a major role to play in changing patterns of land use. As the national population grew, it was redistributed towards places where rail access was preserved and towards places that gained road access through growth in the motorway network.

In the next section we outline our methods. Following that, we present our key results and conclusions.

2. Methods

2.1 Specification

We estimate the effect, on a number of population and employment outcomes, of changes in the network centrality (or market access) of areas in Britain arising as a result of cuts to the railway network and closures of stations. The focus specifically is on the changes in centrality occurring between the 1951 and 1981 census years. The methods and data for constructing these changes in centrality are described in Sections 2.2 and 2.3. The fundamental challenge to estimation is that the places subject to cuts were potentially on very different population trends prior to the cuts. This pattern does not arise through targeting of cuts specifically to areas in economic decline, but as a by-product of the fact that the cuts were targeted to unprofitable rail lines, with low passenger traffic. An important reason for line unprofitability was the unregulated oversupply of railways due to speculative railway mania in the 19th century, rather than the economic conditions in the mid-20th Century (Bogart, Shaw-Taylor and You 2018).

Our context does not offer many obvious quasi experimental approaches. The bureaucratic nature of the plans to cut the railways based on railway passengers and ticket revenue suggests potential regression discontinuity designs, but information on the precise rules adopted for the cuts is absent. Instead we adopt a number of methods to try to match on the population pre-trends in a careful and flexible way. To do this we either: 1) include lags of historical census population variables back to 1901; 2) control directly for population pre-trends using dummies for quantiles of the distribution of these trends; or 3) use pairwise differences in a semi-parametric estimator to difference out population pre-trends. A number of placebo and robustness tests are available exploiting planned station closures which were not enacted, and we rule out effects from simultaneous growth in the Motorway network. We also devise an instrumental variables approach using the rail line orientation as a robustness check, described in the Results section.

More formally, we estimate flexible time differences specifications for geographical units *i*, with the following form

$$\ln y_{i81} = \beta(\ln cent_{i81} - \ln cent_{i51}) + \gamma \ln cent_{i51} + \delta \ln y_{i51} + x_i'\lambda + \varepsilon_i \quad (1)$$

The dependent variable is one of a number of variables describing the population and is taken from the Census. The variable $cent$ is the centrality of place *i* in the rail network in the corresponding year, constructed as described in Section 2.2. Note that the estimate of β in (1) is identical to that which would be obtained from a regression of the 1951-1981 change in log y on the 1951-1981 change in log centrality, conditional on log rail centrality and log y in 1951.

The vector of control variables x_i includes: 1) log population in 1921, 1931, 1911 and 1901 and squares of these log populations; or 2) sets of dummies for 5 percentile intervals in the distribution of the pre-1951 population trends, for 1901-51, 1911-51, 1921-51and 1931-51. In the pairwise-difference estimator we rank observations by an index of the population pre-trends, then transform (1) into differences between adjacent ranked observations (so we are comparing places which are on nearly identical pre-trends). The index used for this ranking is either: a) the 1901-1951, 1911-1951, 1921-51 or 1931-51 log population change; or b) the linear prediction a regression of the 1951 to 1981 parish rail centrality change on a flexible polynomial in the population growth in preceding decades:

$$(\ln cent_{i81} - \ln cent_{i51}) = \pi_1 \ln pop_{i01} + \pi_2 \ln pop_{i01}^2 + \sum_{t=11}^{51} (\sigma_{1t} \Delta \ln pop_{it} + \sigma_{2t} (\Delta \ln pop_{it})\ ) + v_i \quad (2)$$

In (2), the Δ represents a difference between census period *t* and the previous available census. The advantage of this pairwise differencing method is to control flexibly for non-linearities in the relationship between the outcome variables and the pre-trends. This kind of estimator has been proposed for partially linear models (Yatchew 1997; Honore and Powell 2005; Aradillas-Lopez, Honore and Powell 2007) although in our context we do not wish to estimate the non-linear part, only control for it.

2.2 Measuring centrality and market access

This section describes the construction of the centrality or market access indices. The main index we use is an unweighted network closeness centrality index. We also show results using a node population weighted centrality index, which is also known as a population accessibility index in the transport literature, or more recently as market access in the trade and spatial economics literature. Centrality indices of this type have long been used in the transport literature to measure accessibility, and recent applications in analysing the impact of transport on the economy include Gibbons et al (2012), Donaldson and Hornbeck (2016), Gibbons and Wu (2017), Baum-Snow at al (2016). In the current application, these indices are constructed first at rail station level. The station-specific indices are then aggregated to the geographical units of analysis (parishes or Local Government Districts (LGDs)) using inverse distance weighting. Formally, the indices have the structure:

$$cent_{it} = \sum_{j \in J_{it}} \left(\sum_{k \, K_t} m_k \times railtime_{jk}^{-0.5} \right)_j \times roadtime_{ij}^{0.5} \qquad (3)$$

In this expression, *i* represents a geographical unit, *j* represents an origin station amongst a set J of stations local to place *i*, *k* represents other stations on the network amongst the set K of stations currently open on the network. For our main estimates, we set J=3 so that parish centrality is a weighted average of the rail network centrality of the three nearest stations.

The cost variable $railtime_{jk}$ is an imputed shortest path rail time between station *j* and station *k*, derived by network analysis of a historical GIS of the rail network. The cost variable $roadtime_{ij}$ is an imputed shortest path road journey time between a point chosen at random within zone *i*, and the local station *j*. Road times are based on 'Manhattan' distances, i.e. 1.4* the straight-line distance between zone *i* and station *j*. To estimate the distance from a zone to a station, a set of points are drawn randomly within each zone and the distances from each point to station *j* are averaged. Weights m_k are station node weights. In our preferred unweighted centrality indices these are set to 1. Alternatively, the weights can be set to the 1951 populations in the parish in which the station *k* is located, yielding a market or population access index. The distance decay exponents are set to -0.5, such that if there was only one nearby station, the index in (2) yields a standard centrality index, with the cost of travelling between two parishes represented by the geometric mean of the rail and road stages of the journey.[2]

Conceptually, the index in (3) is based on an assumption that the centrality of a parish in the rail network can be represented as a weighted average of the rail network centrality of the stations near to that parish. Other formulations are of course possible, and a more standard approach would be to simply allocate a parish to the nearest station or point in the rail network and calculate parish-parish origin destination least cost paths, assuming people always choose the minimum travel time route. The structure of (3) is less restrictive, in that it avoids assigning a specific station to a parish when there are multiple stations that are almost equidistant from that parish. However, it will assign much greater weights to proximate stations that more distant ones. Another advantage of this index structure is that it can be easily decomposed into components due to changes in the network (the set of stations K and associated rail links), holding the set of local stations constant, and changes in the set of local stations J holding the global set K constant. This allows us to estimate to what extent the impacts on local economies are due to removal of local stations, or spatially differentiated patterns due to changes occurring elsewhere on the network.

2.3 Data

Outcome variables are taken from historical census data, at either the parish level, for populations, covering the whole of Great Britain, or Local Government District (LGD) level covering only England and Wales. Data prior to 1971 have been digitised from paper records by

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[2] We also tried exponents of -1. The results we report later are not highly sensitive to this parameter, within the range typically found in the literature.

the Vision of Britain project (http://www.visionofbritain.org.uk/) and we are limited to the records that have been published and digitised. At the present time it is not possible to recover any more comprehensive data from the historical census micro data during the 20th century because these are subject to 100 year confidentiality rules. From 1971 onwards, more detailed small-area census data is readily available in electronic form, though for different geographical units. We use data from 1901, 1911, 1921, 1931, 1951, 1961, 1971, 1981, 1991 and 2001 and re-weight all the data to parish and LGD units as defined for 1951. There was no census in 1941 for obvious reasons. Our key variables are those that we can reasonably make consistent across the census years of interest: population; the number of 'qualified' workers, which means educated to at least age 20 in earlier censuses, or educated to degree or higher in later years; social class groups; broad age categories. At parish level, the only useful data available is total population although we have this for the whole of Great Britain. All other variables are at LGD level and available for England and Wales only. There are around 1,470 LGDs in England and Wales, and 13,350 parishes in Britain.

Our rail network data was kindly provided to us by Jordi Marti Henneberg, whose team has painstakingly digitised it from historical atlas of British railways (Cobb 2003). The data provided to us lists stations and lines closed by decade from 1900 to 2000. We made a few corrections, added in the London underground network and cleaned the data to make it useable for a GIS Network Analysis. We then used the network analyst tools in ArcGIS to calculate station-to-station minimum distance origin-destination matrices. This network does not distinguish between goods and passenger lines, or goods and passenger stations, and in the majority of cases there was no distinction between the two in reality. Good services were typically run on the same lines as passenger services. We are therefore unable to distinguish the effects of rail cuts arising from changes to passenger travel versus those attributable to freight transport.

Straight line distances from a set of random points within parishes to stations, needed to impute road distances, are also computed with ArcGIS. The random points were generated such that the number of points is proportional to parish land area but with a minimum of six points.

Converting rail network and parish-station distances into journey times necessarily requires some assumptions. We do not have data on service frequencies or complete data on timetables, so take no account of these features in our estimation of journey times. Our assumption is that people would time their journeys in accordance with timetables in order to minimise delays. As such, the empirical results we present later should be interpreted as 'intent to treat' estimates relating to the provision of rail infrastructure, rather than the timetabled services that are run on that infrastructure. Even so, hard data on potential road and rail journey times for Britain in the 1950s is not easy to find, and we infer appropriate speeds from historical rail and bus timetables. Our baseline assumptions for rail speeds are 65 km per hour for journeys above 75km and 40km per hour for journeys below 75km, plus 6 minutes on all journeys (for transfers and waits). Road travel speeds – which are for our purposes short journeys to local stations – are set to 20km per hour, plus 12 minutes (for transfers and waits) on all journeys. [3] Note, private car use was relatively rare in Britain in the 1950s and the majority of journeys of this type would be by bus or bicycle. These station-station origin destination rail travel times and parish-station road travel times are used to compute station-level centrality indices as described in Section 2.2 above. Although speeds will have changed over the decades of the analysis, we fix them at these assumed 1950s levels, so that all changes in centrality indices come about through changes in the network structure, not through any arbitrary changes in the assumed speeds along the network. The analysis does not appear to be particularly sensitive to these assumptions, since the estimates are driven by changes in physical network structure rather than any of the speed assumptions.

[3] One additional data point other than bus timetables – though from an earlier period – is the figure of 12 miles per hour (19.2 km per hour) reported for average off-peak speeds of a 'motor driven cab' in 1904 – House of Commons 1999.

For part of the analysis, we also use a centrality index based on the Motorway network, the construction of which is described where we present the corresponding results.

3. Results

3.1 Descriptive statistics and figures

The railway line network as it was in 1950 and as it became by 1980, is shown in Figure 1. Evidently, the cuts to lines were severe, but as Figure 2 illustrates, the changes in the distribution of stations were even more dramatic. Clearly, looking at the effects of cuts based on line length alone – as is common in many studies of rail and road infrastructure – is inadequate. Many areas retained lines, but lost all their stations. Instead, our analysis makes full use of both the cuts in lines and the cuts in stations, through the network centrality index defined in Section 2.

Figure 3 shows the lines that were cut over the 1950 to 1980 period, and the resulting changes in rail centrality, computed as in equation (3) without population destination node weights. The picture with parish population weights in the numerator is broadly similar, and as the descriptive statistics in the Appendix shows, the standard deviation in the two variant indices is similar, although with different means. The correlation between the changes in the 'market access' indicator using population weights and a pure, unweighted closeness centrality index (with numerator weights of one) is 0.99, so the results we present later are nearly identical whichever index we use. In what follows we report results only for the unweighted centrality index. As expected, there is a strong link between the locations of the cut lines and the magnitude of the cut in centrality. Note, most, but not all of the places experiencing the least decline in centrality (the darkest areas) are central and urban. However, some places, such as the north of Scotland, experienced little decline in centrality because they were already poorly connected and peripheral. Note, we retain the outlying islands of Scotland in our main estimation samples, but the results that follow are robust to dropping these (and to dropping

Scotland as a whole). The numbers on the scale indicate the change in log centrality. Additional descriptive statistics are in the Appendix.

Figure 4 illustrates the general patterns in parish population over the 20th Century, split by quintiles for the strength of the rail cuts that occurred over the 1950-1980 period. The darkest lines are the deepest cut areas; the light dotted line represented least affected areas. Populations are in natural logs normalised to zero in 1951. This figure illustrates the fundamental empirical challenge we are facing: the 20% of parishes facing the least cuts (the dotted line) were already on stronger population growth trends than the remainder, because these are predominantly core city areas. The pre-1950s population trends in the remaining 80% of parishes that experienced stronger cuts are less differentiated according to the severity of the cuts, though not exactly parallel. The empirical challenge is to disentangle whether there are impacts from the rail cuts that go above and beyond what we would have expected based on the pre-trends.

3.2 Baseline regression results for 1981 populations, controlling for population pre-trends

Table 1 shows results from our base specifications for residential populations in parishes in Britain in 1981. The table shows regression coefficients and robust standard errors, corresponding to equation (1), estimated as discussed in Section 2.1. We experimented with clustering at higher levels of geographical aggregation (LGDs) but the results are broadly similar, and we look at alternative clustering schemes based on grid squares later in this section.

Column 1 is a simple regression of the change in log population on the change in centrality, and includes no control variables other than initial log centrality in 1951 and parish land area. Column 2 adds in controls for log population and log population squared for 1901, 1911, 1921 and 1931. Column 3 controls instead for dummies for 5 percentiles bins in the distribution of the changes in log populations in previous decades and Columns 4-8 implement the pairwise difference approach to eliminating these pre-trends (see Section 2.1). In the ranked pairwise difference, the standard errors are robust to the autocorrelation induced by the pairwise differencing, using a Bartlett kernel with lag length 2 (implemented using ivreg2 in Stata). Note, that the coefficients show the effect of an implied increase in centrality: a positive sign indicates that the rail cuts reduced the outcome variable under investigation.

The most striking feature of Table 1, is that – although controlling for population pre-trends makes some difference, between column 1 and 2 - the method by which we do this makes almost no difference to the estimated coefficients. In all cases, the elasticity of population with respect to centrality is around 0.3, e.g. a 10 percent decrease in centrality in a parish is associated with a 3 percent decrease in population relative to a parish where centrality is unchanged. It is worth emphasising at the outset that the centrality measure is simply an index of transport accessibility, so the scale of this elasticity – though not its qualitative implications – depends on assumptions about its structure. We return to this issue when we discuss alternative measures of exposure to the rail cuts later in the results.

As a check for the effectiveness of the pairwise differencing strategy in Table 1, columns 4-8, we estimated placebo pre-trend regressions of the specification in column 8, but replacing the dependent variable in equation (1) with either a) 1951 population, controlling for 1921 population; or 1931 population, controlling for 1901 population; or simply c) the 1951 population. As expected, the coefficient on the 1981-1951 centrality change variable is zero in all cases (0.001, with a standard error of 0.008 and 0.003 with a standard error of 0.008, and -0.013 with a stanard error of 0.031 respectively – see Table 12 in the Appendix). Evidently this matching on pre-trends does reliably eliminate the differences in trends as exhibited in Figure 4. This result is a somewhat mechanical outcome of the estimation method, but demonstrates it effectiveness. We would ideally have other pre-1951 variables on which to base this test, but unfortunately none are available from the census records that are currently digitised.

There are potential confounding factors, affecting post-1951 population trends, and correlated with the centrality changes for other reasons than rail accessibility. This is an issue we focus on in the remainder of the paper. As a first step to address this concern, we re-estimate the specification of Table 1, column 8, with fixed effects to control for arbitrary spatial trends at the level of grid squares, obtained by rounding the parish coordinates to 20km (667 groups), 50km (146 groups) and 100km (53 groups). These fixed effects control for unobservables affecting population growth at the grid square level. The results are in Table 2, columns 1-3. The coefficients remained almost completely unchanged once we include these grid square fixed effects. In column 4, we drop the grid square fixed effects but add in controls for demographic characteristics – age structure, education and social class - at the Local Government District level. This specification controls for differential population growth that is correlated with these initial demographic conditions. The sample size is smaller here, because the sample is limited to England and Wales. Again, the coefficient of interest remains largely unchanged and is similar too to what we get if we estimate on this sample without the LGD control variables.

There are also concerns about the standard errors in the estimates in Table 1, given the spatial interpolation implicit in the construction of the centrality indices, and the likely spatial correlation in unobservables across space. Table 2, columns 1-3, assess the severity of this threat to inference by clustering the standard errors at the level of the grid squares used to define the fixed effects, so that the standard errors are robust to autocorrelation in unobservables within the grid squares, and heteroscedasticity at the grid square level. The standard errors, though around 50% larger with clustering at the larger spatial scales, still imply t-statistics at least 9, so Type I errors seem unlikely.

3.3 Robustness to contemporaneous confounding factors: rural/urban, centrality and motorways

Although our methods have, we argue, convincingly ruled out pre-trends in population as potential threats to our identification, the other crucial question is whether these population changes really relate to the rail cuts, or whether they relate to some other contemporaneous changes that were correlated with the rail cuts. One alternative explanation is that there was some general change in spatial structure that favoured central and urban areas in Britain, or those initially well connected by rail, given the cuts disproportionately impacted on peripheral locations. A second explanation is the planned growth of specific 'New Towns', starting with the New Towns Act (1946) but extending throughout our study period. Planned population in these towns, with retention of the railways serving them, might bias our estimates. A third is the growth of the road network, especially since one of the justifications for closing the railways was that roads were seen as the future of transport. The main change in the road network over this period was the construction of the motorways, which coincided with the rail cuts, the first opening in 1958. Table 3 explores these alternative hypotheses.

Firstly, we look at the role of the initial centrality of a parish on the rail network. The main specifications already controlled linearly for rail centrality in 1951. Column 1 extends the specification by including a dummy for above/below median rail centrality in 1951 and its interaction with the 1951-1981 change in rail centrality. Evidently, initial rail centrality matters (3rd row column 1), with parishes above median rail centrality experiencing 22 percentage points higher population growth than those below the median. However, the coefficient on the interaction between initial centrality and the 1951-1981 changes in centrality is small and insignificant and the coefficient on the change in centrality is unchanged at 0.3. Column 2 takes this further, by controlling for an indicator that a parish is remote from rail in that there is no station within 10km in both the 1951 and 1981 periods, and its interaction with the rail centrality change index. The idea here is to distinguish the effects of the cuts in the peripheral parishes which were evidently not targeted by the cuts – they were remote from rail both before and after the cuts – but that nevertheless experienced centrality changes. Appendix Figure A1 illustrates the geographical distribution of these areas, which are as we would expect rural and peripheral. As the results in column 2 show, the effects of the cuts were quite general within both remote-from-rail and less remote areas.

Column 3 does something similar to column 1, but with an indicator for above/below median general spatial centrality rather than rail centrality. By spatial centrality, we mean a standard closeness centrality/population potential index $a_i = \sum_j m_j distance^{-1}{}_{ij}$ using parish populations as the numerator and straight line distances between parish pairs as the denominator. The idea here is to see if it is a parish's location in the core or periphery of Britain that is driving population change, rather than the rail cuts per-se. Interestingly, spatial centrality in itself is not strongly related to population change – but then the major metropolitan areas in Britain which experienced growth over this period, apart from Birmingham, are not centrally located. There is no evidence of a significant interaction between this spatial centrality and the impact of the cuts, though the implied effect of the cuts in spatially peripheral areas – the first row in column 2 – are 20% larger than on average in the sample. Columns 4 looks closer at urban/rural differences, controlling for an indicator of above/median distance to major urban areas, defined as Local Government Districts with populations of 80,000 plus. As we would expect, parishes further away from cities experienced relative population decline (-19% from column 3, row 3) but there is no evidence that places closer to cities were more or less affected by the rail cuts than those further away (column 3 row 2). The main effect of the cuts is unchanged at 0.3. The results are also almost unchanged if we drop potential outlying cases like London, the remote islands of Scotland, or Scotland as a whole.

In column 5 we consider whether planning on New Towns could be driving our findings. We classify parishes according to whether they are in New Towns that developed during the study period.[4] As expected, parishes in New Towns experienced much higher population growth than others. There is also a strong and significant interaction between rail centrality and New Town location, implying that rail centrality had a much bigger impact on population in areas where

[4] Specifically: Basildon, Bracknell, Central Lancashire, Corby, Harlow, Hatfield, Hemel Hempstead, Milton Keynes, Newton Aycliffe, Peterlee, Redditch, Runcorn, Skelmersdale, Stevenage, Telford, Washington, Cumbernauld, East Kilbride, Glenrothes, Irvine, Livingston, Cwmbran, Crawley, Northampton, Peterborough, Warrington.

there was planned population growth – or in other words, New Towns that were affected by rail cuts over the 1950s-80s period experienced much less population growth than they would have done without the cuts. The effect of the rail cuts outside of New Towns, is, however, unchanged relative to previous estimates at around 0.3.

In column 6 and 7 we consider the impact of motorways and their interaction with rail. In column 6 we include a measure of the change in accessibility induced by the construction of motorways over the 1950-1980 period. Note that there were no motorways in 1950, and their construction over the 1960s, 70s and beyond resulted not in reductions in distances, but increases in speed. We construct the index of closeness centrality/market access using a standard population weighted inverse travel time-weighted centrality index. Unfortunately, we do not have a road network for 1950 or for 1980. Instead, we construct the road network for 1980 by, in effect, deleting motorways constructed after 1980 based on web-sourced information on the years of construction. Although this method does not take into account improvements on A-roads and new non-motorway links, these are relatively minor changes in the physical network in comparison to the motorways. Increases in road accessibility would have come about through increases in speeds rather than reductions in distance. We assume vehicle speeds of 60 miles per hour on motorways (97km per hour), 30 miles per hour (48 km per hour) on A-roads, and 30 km per hour on the imputed links between parishes and their nearest A-road network connections in 1980. These figures are based, approximately, on data available from the Department for Transport for current average speeds. These speeds have remained stable in recent decades. For 1950, we use the same road network but assume travel times throughout are limited to 30 km per hour everywhere. The implied change in journey times and increases in road-based centrality might be higher than the reality, but our aim is to give roads the best shot at explaining changes in population. A map in the Appendix shows these imputed market access/centrality changes in relation to the motorway network as it was at the end of the 1970s.

Introducing this control for the improvement in road transport and the growth of the motorway network in column 6 makes no difference to our estimate of the effects of the change in the rail network. The reason for this is that, conditional on 1951 rail centrality, 1951 population, and the population pre-trends, there is almost no correlation between the motorway and rail-based centrality changes: if we regress our log motorway centrality change variable on the log rail centrality change variable, the coefficient is only 0.01 (although statistically significant, not tabulated). Interestingly, the coefficient on the change in motorway centrality in the population regression in column 6 is itself very similar to that on rail. Given that there is no reason to expect the impacts of access by one mode to be markedly different according to mode of travel, this result provides some degree of confidence that our results have an economically meaningful causal interpretation (though as we note later, the magnitude of the rail centrality variable is sensitive to what we assume about the relevant number of local stations).

The final specification in column 7 adds in an interaction between the changes in road centrality and changes in rail centrality. The main effect of rail centrality in row 1, corresponding to parishes that experienced little growth in motorway centrality, is twice as large as in previous columns. The coefficient on the interaction term (row 2) is also large and significant. The implication is that the rail cuts had a much bigger impact on population decline in places which did not benefit from the growth of the motorway network and improvement in road speeds. The effects of the rail cuts are mitigated by motorway road centrality. Conversely, motorways had a much more limited effect on population change in areas that were unaffected by the rail cuts (row 3), but their effects was enhanced by the decline or railways.

3.4 Robustness: Alternative treatment definitions and non-linearities

In Table 4 we experiment with different definitions of rail access. The first panel looks at simpler measures based on changes in the distance to the nearest station. In column 1, this measure is just the change in log distance from the parish to the nearest station, due to station closures.

Column 2 uses a simple indicator of whether or not a parish lost its nearest station, and column 3 is an indicator of whether the distance to the nearest station doubled as a result of the cuts. In all cases, in line with the results using the centrality index, an increase in station distance (reduction in centrality) is associated with a reduction in population. Note that although the coefficients are smaller in magnitude than those obtained from the more complex rail centrality index, the qualitative implications are similar: the effect of a one standard deviation change in the rail centrality index is around 0.11, while the effect of a one standard deviation change in log station distance is 0.094.

The second panel reverts to using the rail centrality index of equation 3, but with modified assumptions. In column 1, we use destination node parish population weights. There is little difference between this coefficient and that from the unweighted index of column 8, Table 1. Evidently, it is changes in network structure and loss of stations that matters here and the specific weights placed on destinations in the centrality index are irrelevant. Column 2 assigns to parishes the centrality index of its nearest station (inversely weighted by assumed parish-station road travel time), rather than averaging over three stations. The coefficient estimate is now considerably smaller than when using the index averaged over the nearest three stations. Conversely, when we average over four stations in column 3, the effect is larger. The reason why the coefficient varies according to the number of stations is that averaging over local stations smooths out the variation in rail centrality across space, reducing its variance. Again, the implications in terms of the effects of the rail cuts are the same – it is just that the scaling of the index has changed. To see this, the third panel of Table 4 splits the centrality index changes into quintiles, for each of the 1-station, 3-station and 4-station variants. Two features are evident from these results. Firstly, the patterns of population change from the most cut to the least cut places are broadly similar regardless of the index. The top 1 in 5 parishes in terms of rail cuts experienced 25 percentage points less population growth than parishes in the least cut, in line with the raw figures plotted in Figure 4 (i.e. populations grew by about 25% in the least cut parishes from 1951 to 1981, whereas in the most cut there was little change). Secondly, the effects on populations are seen throughout the distribution of cuts, so assuming a log-linear relationship in the main results has little cost. However, there is some non-linearity, with the marginal effects more marked in the parishes experiencing deeper cuts. The gap in population growth is around 8-10 percentage points between the 5th, 4th and 3rd quintiles, compared to around 4-6 percentage points between the 3rd, 2nd and 1st quintiles.

3.5 Robustness: Instrumental variables estimates

Various features of the rail cut programme set out in the British Railway Board reports in the 1960s suggest potential identification strategies and instruments. The decisions about which lines to cut in the 1963 Beeching report (British Railways Board 1963) were based on station ticket sales and line usage, implying a potential regression discontinuity design based on pre-policy service levels. Unfortunately, the rules on which the decisions were based are not set out precisely in any public information, and the information on historical ticket sales and service frequencies is unavailable at a suitable level of detail. Instead we turn to other features of the report to devise potential instruments.

A key element of subsequent British Railway Board plans was to preserve trunk routes. The sketch map from this report are shown in the Appendix. The decision rules are set out in the 1965 British Railways Board report (British Railways Board 1965, p37): "The process of selection involved consideration of the following factors:- (i) the extent to which existing routes coincide with the principal traffic flows of the future, (ii) the comparison of the workable capacity of the alternative routes with the number and type of trains expected to arise from the future area to area flows, (iii) the service of important intermediate centres, (iv) recent expenditure on route modernisation, such as track improvement, electrification and resignalling projects, (v) the necessity for large items of future expenditure on trunk routes, (vi) physical characteristics of the routes: the incidence of bridges, tunnels, viaducts, of ruling gradients, and features likely to restrict speeds permanently, (vii) 'network' considerations: the way in which routes selected fit into the future railway trunk network, (viii) the extent to which changes in the trunk system may result in greater lengths of haul." Evidently, (i) suggests that the decision might be related to future population growth in the areas served by the network, although most of the other criteria are based on network structure. The relationship of the observed cuts in the network to the trunk routes therefore provides potential instruments, conditional on the past population trends and other factors which might have been used to predict potential future traffic.

We infer what might have been considered 'trunk' routes based purely on the network structure and population patterns (in 1950). To do this, we used the network analysis algorithms in ArcGIS to deduce the least-length network path between London and all Local Government Districts with populations greater than or equal to 80,000 plus, and the least-length route required to traverse these same populous Local Government Districts. Lines in our network that are not on this inferred trunk route path are deemed non-trunk routes, and we use straight line distance from each parish to these non-trunk routes as an instrument for the 1951 to 1981 centrality change, conditional on straight line distance from each parish to the network in general and controls for pre-policy centrality, population and population trends (in this case we simply control for 1901-1951 population, rather than pairwise differencing to remove the pre-trends). In principle, what we are trying to do here is mimic the decision rules evident in (i), (ii), (iii), (vii) and (viii) but using only pre-existing geometric aspects of the network and population, both of which we can directly condition out in our regressions.

The results from this exercise are shown in Table 5, columns 1 and 2. Column 2, excludes parishes within 40km of London and parishes within 10km of other LGDs with populations of 80,000 or more to ensure we are not picking up the potential population growth in the main network nodes that have been used to define the trunk route path. The first stage of this IV regression has an acceptable F-statistic, implying the instrument works well in predicting which places lost rail connections. The IV estimates of the effect of centrality are substantially larger than our previous estimates, with an elasticity of 0.85-0.94, although not statistically different from the estimate in Table 1, column 8 based on a Hausman test (p-value = 0.194). There are undoubtedly potential problems with this approach, namely that we could be picking up more general population trends that are related to peripherality from the spine of Britain, although the regressions control for 1951 centrality, and we saw from Table 3 that there was not much heterogeneity in terms of general spatial centrality and proximity to the central core of Britain. A possible explanation for the higher IV coefficient is that we are, by this methodology, smoothing out a lot of the idiosyncratic variation in the rail centrality change, and population responds more to these broader spatial patterns of accessibility, than to the localised patterns. In other words, our raw centrality index change is a noisy measure of the underlying changes in accessibility which affect population patterns and our main estimates are downward biased.

A by-product of the decision rules outlined above, and one that is obvious to anyone who travels in Britain is that today, in most of the country it is hard to make cross country journeys without travelling via London. This is because many of the lines that were cut in the 1950-1980 period in the centre and north of the country were those not running down the length of the country towards London, as inspection of Figure 3 will confirm. This East-West pattern does not appear to have been intentional policy, but simply a by-product of cutting the least profitable lines which ran across the country, rather than along its length on its N-S axis. Based on this empirical observation, we devise another instrument which predicts loss of rail centrality based on the length of local lines running in an east-west orientation (Michaels 2008 uses a similar instrument based on the orientation of US highways). Specifically, we select line segments for which the difference in the south and north end points is less than 10km, and then aggregate the length of lines meeting this criterion which cut across each parish. This east-west parish line length provides our instrument. The identifying assumption is that, conditional on 1951 population, rail centrality, and pre-1951 population trends, that future population growth in a parish is unaffected by it having east-west running train lines in 1951, except through the fact that these lines were likely to be cut after 1950.

Figure 5a illustrates the relevance of this instrument visually, by overlaying the 1950-1980 cut lines with the parishes shaded according the length of east-west lines. Visually line orientation appears to predict the cuts quite well, although not in the South West (where north-south lines were likely to be cut, because the axis of this part of the country is east-west) and it over-predicts cuts in London (where services were preserved as commuter lines). Table 5 column 3 presents the results of this IV approach. Note, as before, we include pre-1951 population trends, log 1951 population, log 1951 rail centrality and parish land area. The first stage of this IV regression has a high F-statistic suggesting that the instrument, again seems good at predicting the cuts, bearing out the visual evidence from Figure 5a. The coefficient on the change in log centrality is now reasonably close to that in our main estimates in Table 1, though less precisely estimated. The last column combines both instruments, giving an estimate midway between those using the instruments separately. In summary, these IV results indicate that the main OLS and pairwise differenced estimates are likely a conservative estimate of the impacts of the rail cuts on population patterns.

3.6 Robustness: stations proposed for closure, but not closed

The 1963 British Railways Board reports provide a lot of detail on the stations that were proposed for closure. Rail enthusiasts have combined this information with historical records to provide various atlases of the stations and lines that were listed in the report and closed, listed and not closed, and those that were closed for other reasons either before the report or afterwards. We use the information from one of these atlases (Waller, P. 2013) to isolate those stations which were proposed for closure but were not closed prior to 1980. These 474 cases provide a point of comparison for our baseline estimates, since we would not expect to see comparable effects from cuts to stations that were not actually closed. Unfortunately, these proposed closures do not provide an ideal 'placebo' test, since there were usually specific reasons why these lines and stations were preserved meaning that parishes near proposed closures are not necessarily comparable to those where closures went ahead. Typically, lines and stations were spared because they were in some of the most remote rural areas with few roads where rail was deemed to be socially necessary, because they crossed electoral constituencies in which the incumbent party had a slender majority so wanted to avoid electoral damage, or because there was particularly powerful local lobbying. Some lines that were kept open experienced service reductions. Nevertheless, it would be worrying if we found effects from proposed closures of the same magnitude as those from the actual closures.

Table 6 compares the effects of proposed and actual closures using indicators of changes in distance to the nearest station (as in the top panel of Table 4). The first shows the association between proposed station closures and population change. The second row presents the effect of actual station closures. Evidently, there are population changes associated with the proposed closures, even if these were not enacted. However, these are substantially smaller than those linked to actual closures. If we look at the effect of changes in log station distance, the effects from proposed closures are just over half the magnitude of the effects from the actual closures. If we use a simple treatment indicator based on whether or not a parish was set to lose its nearest station, the effects from proposed closures are under one quarter the magnitude of the effects from actual closures. In both cases the difference between the effects from proposed and actual closures is statistically significant.

3.7 Global versus local centrality effects

As discussed in section 2.2, we can make an interesting and useful decomposition of the overall rail centrality index change in an area into components due to removal of local stations, holding the rest of the network constant, and changes to the network holding the set of local stations constant (a similar analysis is provided for airports in China in Gibbons and Wu 2017). This analysis helps us understand whether it is the additional journey times to the nearest local stations by road that matters, or whether it is changes in the centrality of preserved stations due to cutbacks elsewhere on the network. The results are shown in Table 7, where there are two centrality indices, one related to removal of stations, the other due to local changes in accessibility arising from global changes on the network (e.g. because some links to cities nearby have been removed). Both of these indices exhibit similar average reductions over the 1951-1981 period (around 18-19% - see Appendix Table 1) and the changes show comparable variation across space (the standard deviation of the change in local accessibility is 0.18 compared to 0.13 for the global index). The specifications in Table 7 are otherwise as for Table 1, column 8. The estimates show that both aspects matter, although the elasticity on the local changes is clearly much larger than that related to the global changes. Evidently, it is the costs associated with reaching a local station, rather than the loss in accessibility on the network once these stations are reached, that are largely responsible for the effects on local populations. This explains why the impacts of the Beeching era cuts are usually seen as a problem mainly for rural communities, where stations were closed, rather than in areas which retained their stations, but still experienced strong impacts from the removal of the rail network more widely.

3.8 Longer run and broader geographical population impacts

So far we have looked only at 1981 outcomes, and localised population redistribution at parish level. One might wonder whether these effects were only temporary. Perhaps the growth of car transportation meant that people gradually moved back to these areas that were disconnected from the rail network. A second question is how the population redistribution at parish level affected the more general pattern of populations across cities and regions: were the movements highly localised, or are there implications for broader geographical patterns of population.

Table 8 explores the first question by repeating the specification of Table 1, column 8 but with parish populations from the 1991 and 2001 censuses. Columns 1 and 3 clearly show that the effects were not temporary. The elasticity of 1991 and 2001 populations with respect to changes in centrality is much the same as for 1981 populations, implying that the effects of the rail cuts were permanent. In columns 2 and 4, we look at the effects conditional on previous census years. Controlling for 1981 populations in the 1991 population regression wipes out the effects of centrality: evidently the 1950-1980 rail cuts affected 1981 populations but had no additional impacts after that. The story for 2001 is slightly different. Now, conditional on 1981 and 1991 populations, we find that the 1950-1980 rail cuts had an additional impact on population growth up to 2001. The coefficient implies that a 10% cut in rail access in the 1950s, 60s or 70s led to further declines in population of around 0.6% after 1991. We have no data that can shed light on the reasons for this additional impact post-1991, but potential explanations are increased congestion on roads, or the shift from manufacturing to services in the UK economy, both of which may have favoured places that remained better connected by rail in recent years.

By construction, the patterns of redistribution of population at parish level mechanically follow the patterns of change in centrality shown in Figure 3. To investigate what these patterns imply for the city-size distribution, we first predicted the counterfactual 2001 population distribution across parishes, by subtracting the component attributable to the centrality cuts based on our estimates in Table 8. We then aggregated the actual and predicted parish populations to 2001 Travel to Work Area (TTWA) level (commuting areas). The results are mapped in Figure 6, which shows the difference in logs between the counterfactual and actual 2001 TTWA population distributions. The figures are adjusted such that the total population is the same under the actual and counterfactual scenarios and a negative number implies the TTWA population would have been higher without the rail cuts. The most obvious feature is that populations throughout London and the South East of Britain would have been at least 5% lower. The population of London itself comes out as 8.9% lower. Other major cities – Birmingham, Manchester, Glasgow – also show up as having lower counterfactual populations in the absence of the rail cuts.[5] Overall, without the cuts, population would have been more evenly distributed across TTWAs, as a result of shrinking the larger TTWAs: the standard deviation of populations in the actual distribution is 580,000 compared to 550,000 in the counterfactual. London's population shrinks from 8.2 million to 7.8 million in the absence of the rail cuts. In the Conclusion, we provide some remarks about what this might mean for productivity, given the well-established links between city size and productivity in the urban literature (Combes and Gobillion 2015).

3.9 Age, education and occupational structure

Turning to a wider range of socioeconomic outcomes, Table 9 presents results from regressions with a specification similar to Table 1, column 8, but with various different dependent variables relating to males' education (educated to age 20+), occupation-based social class (class 1 is professional, class 2 is intermediate, class 3 is skilled, class 4 is partly skilled, class 5 is unskilled) and population age structure. These regressions use census data at the Local Government District Level (LGD) covering England and Wales.

In column 1 we see that reductions in centrality reduced the proportions of high-qualified (defined as education to age 20+) in the district. Similarly, in columns 2 and 3, there are relative reductions in professional and managerial male workers, offset by a relative increase in workers in lower skill occupations in columns 4-6. Note these regressions are conditional on the log total numbers in all social class groups, so should be interpreted as changes in the share of one group holding the total constant. Looking at the age structure in columns 7-10 there is clear evidence of a negative association between centrality and the number of workers over 65 (i.e. a decline in centrality implies an older population) and a positive association with working age populations. These LGD results suggest that changes in rail centrality had non-negligible impacts on local

[5] There are also remote low population areas in Scotland that show up as having relative population losses in the absence of the cuts: this is because, as noted earlier, because their rail centrality change was small given that they were already poorly connected.

population composition. For example, places that were one standard deviation above the mean in the distribution of cuts (the standard deviation is around 0.27 in the LGD data) would have seen 4% less growth in the number of educated males in the population relative to the mean and 3% more growth in the number of males over retirement age (holding total population constant).

4. Conclusions

We studied the impact of a controversial rail disinvestment programme that occurred in Britain in mid-20th Century. While other work has begun to look at the spatial economic impacts of the growth of the rail network and other forms of transport, ours is the first of which we are aware to look at what happens when you remove transport infrastructure on a major scale. As well as providing general lessons regarding the role transport plays in shaping the spatial economy, our research answers a long running controversy over the impact of the 'Beeching Axe' in Britain. Did the cuts cause places to decline relative to other areas or were these places declining anyway?

The broad finding is that the cuts in rail infrastructure caused falls in population in affected areas relative to less affected areas, loss of educated and skilled workers, and an ageing population. A 10% reduction in rail access over the 1950-1980 period (measured by a network centrality index) was associated with a 3% fall in population by 1981 (relative to unaffected areas). Put another way, the 1 in 5 places in Britain that were most exposed to the rail network cuts saw 24 percentage points less growth in population than the 1 in 5 places that were least exposed. Populations did not recover in subsequent decades. A key lesson here is that rail infrastructure affects the spatial distribution of population – a relevant finding for those interested in the role of transport in land use and the spatial structure of the economy. A second key lesson is that some of the effects of rail infrastructure development on the population are impermanent, in the sense that population re-adjusts once the infrastructure is removed. To answer the question of how the decline in population when stations are closed compares to the growth when they are built requires estimates of the latter. The nearest point of comparison is from Bogart et al (2018) who looks at population and occupational change during the evolution of the railways in Britain during the 19th Century. The results in that paper suggest that parishes receiving a new station between 1831 and 1841 experienced a 30 percentage point increase in population on average compared to other parishes in the 30 years from 1831 to 1861. Our roughly-corresponding estimates are those in Table 4, which imply that the loss of population from parishes losing their closest station between 1951 and 1981 was about half that gained when the stations were opened (a 13 percentage point fall compared to other parishes). [6]

Although not the main focus of the study, an important additional finding is that growth in accessibility via the road network due to the construction of motorways also affected the distribution of population, and in ways that interacted with the changes in rail centrality. Places that experienced improvements in accessibility through the motorway network were less affected by the rail cuts. In general though, the places losing rail access were not those targeted by improvements in road access - the changes in rail and road centrality are uncorrelated - so the motorway network in Britain would have done little to compensate the places worst affected by loss of rail.

All these estimates relate to population movements and sorting and we do not have the data to directly answer the question of whether there were aggregate, national gains and losses in terms of productivity, employment and welfare. However, extrapolating from previous estimates of the relationship between access to economic mass and firm productivity or wages – 'agglomeration elasticities', which are typically 0.05 at most (Combes and Gobillon 2015) – suggests that the effects from cutting the railways were probably not that large. There are two channels through which aggregate productivity changes might emerge. Firstly, by cutting

[6] Unfortunately, their approach is not the same as ours. The nearest comparable figures are for 10 year population changes related to new stations in a parish, and appear in their Appendix Table 1.1. From these estimates, it looks like the population increase in a parish getting a new station between 1831 and 1841 was about 14 percentage points over a 10 year period. Their main results suggest growth of 15 percentage points over the subsequent 20 year period (their Figure 8) for parishes within 2km of a station in 1841, relative to those more than 70km away.

connectivity between places, the rail cuts had a direct effect on the centrality and access to economic mass (part of the so called 'wider benefits' of transport). The mean reduction in centrality in Britain was around 40%, implying a direct reduction in productivity of around 2%. Secondly, the concentration of population in cities – particularly London and the South East – as population moved from the areas experiencing the biggest cuts, may have boosted productivity by increasing city sizes. We can assess the scale of these effects by looking at what our estimates imply about the counterfactual distribution of population across cities, had the rail cuts not occurred. Our calculations from this exercise, suggest that the aggregate gains from population redistribution across cities were very small, at around 0.2%, leaving a net productivity loss from the rail cuts of around 1.8%. [7] [8]

[7] From these actual and predicted city size distributions described in Section 3.8, we can estimate the additional productivity attributable to agglomeration that was caused by the rail cuts. We follow previous literature in assuming a benchmark city-size productivity elasticity of 0.05 such that aggregate city productivity is proportional to population^1.05.

[8] This has echoes of Richard Fogel's claim (Fogel 1964) that the social savings from the railroad system in the US were less than 3% of GNP, although the social savings methodology is based on the value of time, rather than any productivity impacts.

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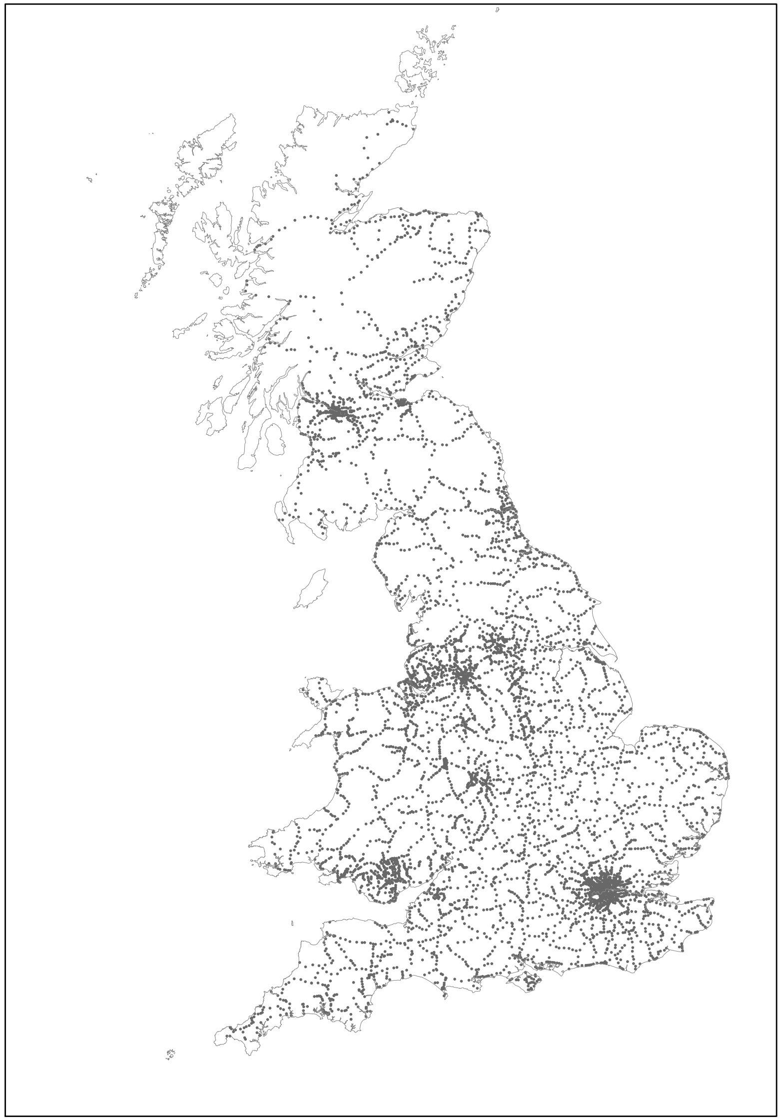
Figure 1: Rail network in Britain in 1950 and 1980

Figure 2: Rail stations in Britain in 1950 and 1980



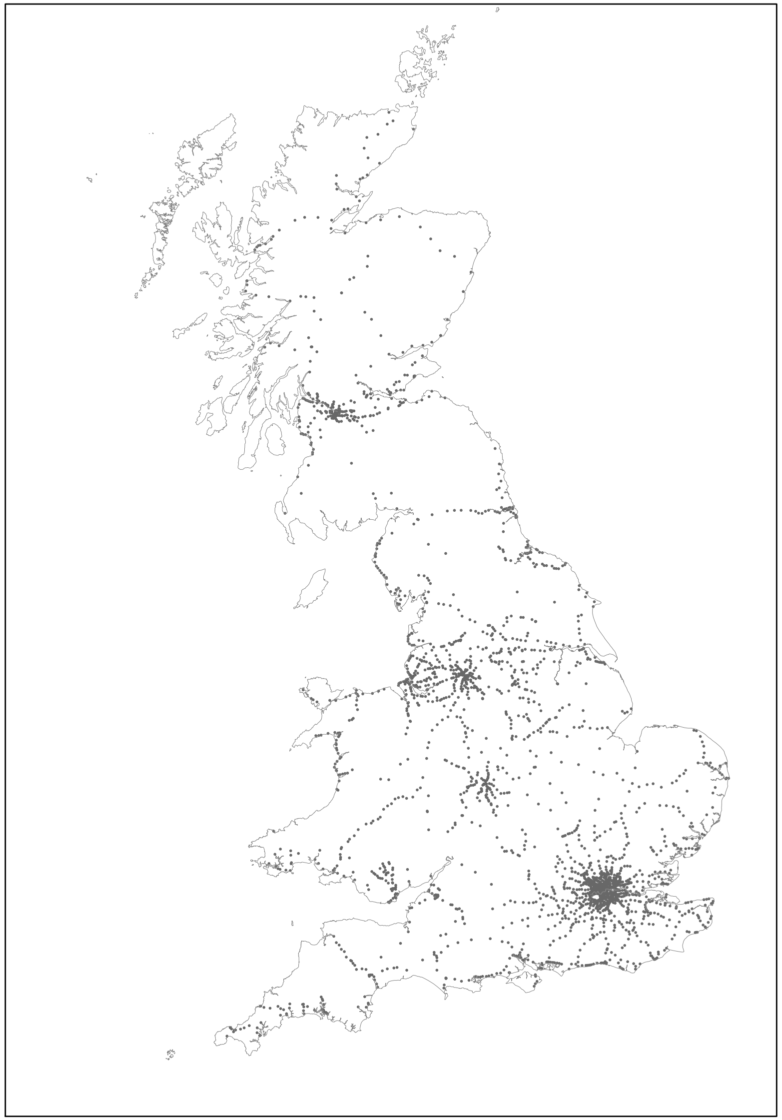


Figure 3: Rail lines cut 1950 to 1980 and changes in centrality/accessibility at parish level

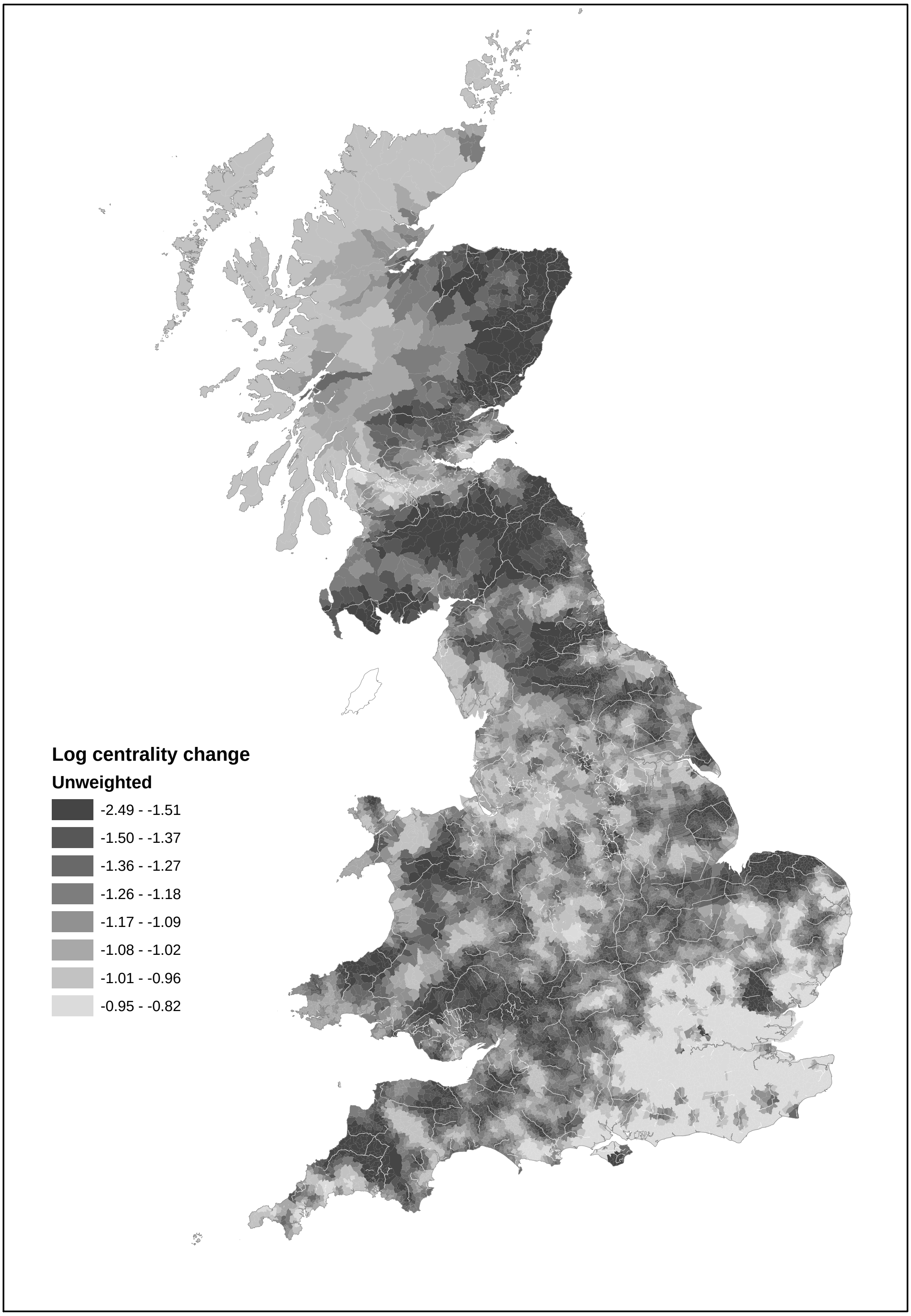


Figure 4: Trends in log population, by depth of rail cuts 1950-1980

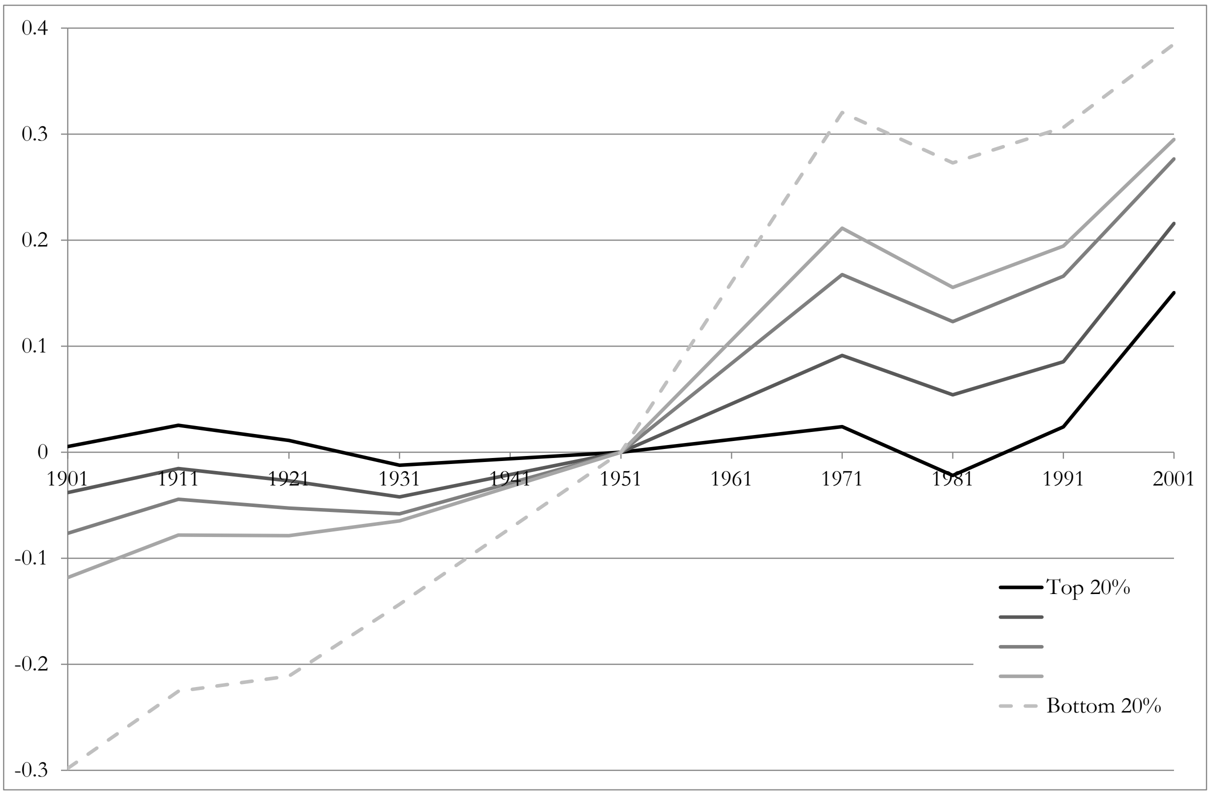
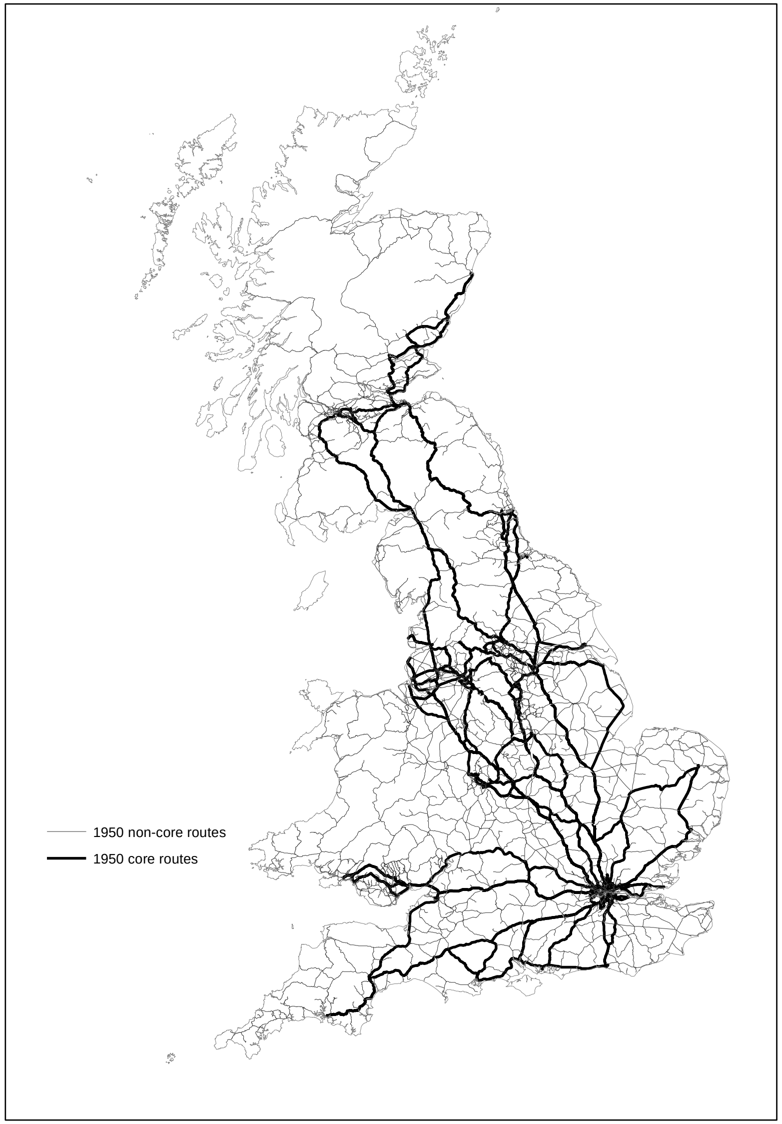


Figure 5: Instruments: a)Trunk/non-trunk routes based on network analysis; b) E-W lines



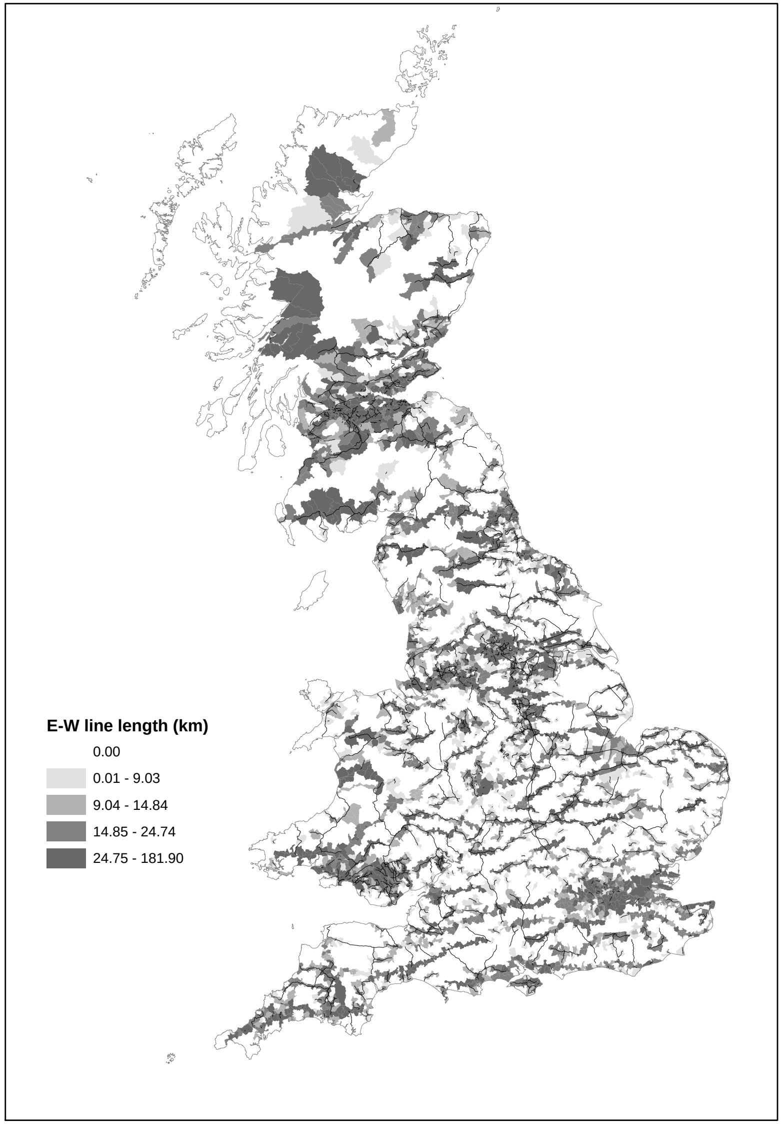


Figure 6: Predicted counterfactual log population changes, without rail cuts, at Travel to Work Area level, 2001

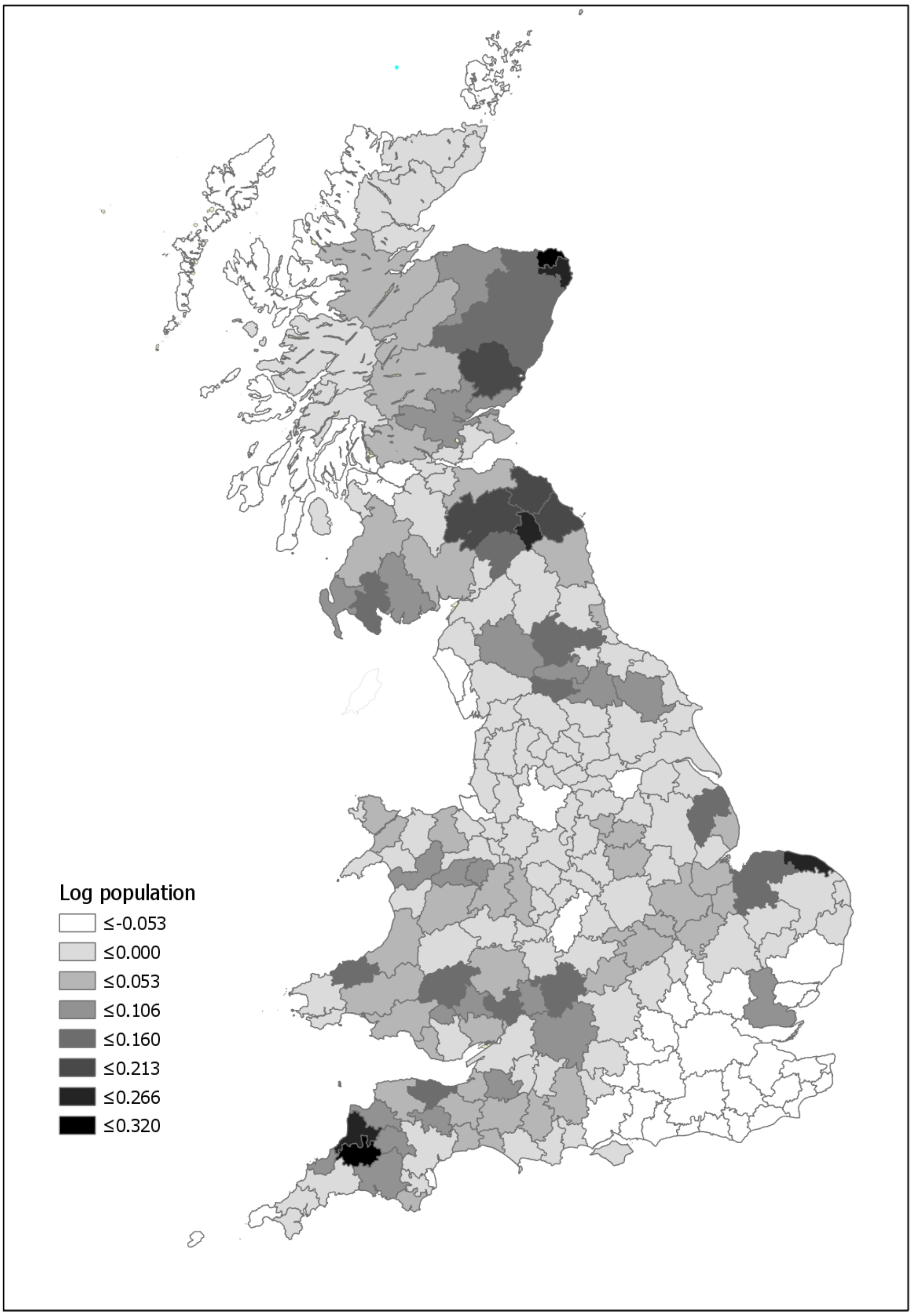


Table 1: Changes in rail network centrality and 1981 populations in parishes, Great Britain

	(1) OLS no pre trend	(2) OLS lagged pop	(3) OLS pre trend all	(4) Pairwise diff 01	(5) Pairwise diff 11	(6) Pairwise diff 21	(7) Pairwise diff 31	(8) Pairwise diff matched
Change in log centrality 51-81	0.373***	0.323***	0.323***	0.296***	0.302***	0.312***	0.294***	0.318***
	(0.023)	(0.022)	(0.022)	(0.021)	(0.021)	(0.020)	(0.020)	(0.021)
Observations	13,254	13,254	13,254	13,249	13,250	13,245	13,247	13,253
R-squared	0.040	0.899	0.899	0.853	0.854	0.863	0.872	0.691

Robust standard errors in parentheses, *** p<0.001, ** p<0.01, * p<0.05.
Dependent variable if parish population in 1981 (based on 1951 parish geographical definitions).
All regressions include log centrality in 1951, mean distance to stations 1951 and parish land area. All regressions except column 1 include log population in 1951.
Column 1 has no other controls; Column 2 includes log population in 1931, 1921, 1911, 1901; Column 3 includes dummies for 5 percentile bins in distribution of changes in log population between 1901-1951, 1911-1951, 1911-1951; 1931-1951. Columns 4-7 estimated on pairwise differences between observations ranked on changes in log population between given year and 1951; Column 9 estimated on pairwise differences between matched observations ranked on linear predictions from regression of 1951-1981 change in centrality on quadratic in log population in 1901 and quadratics in change in log population 1901-1951, 1911-1951, 1911-1951; 1931-1951.
Sample size in columns 4-7 depends on having population variables in both 1951 and respective base year (1901, 1911, 1921, 1931).
Sample size in column 8 drops one observation relative to 1-3 due to differencing in ranked sample.

Table 2: Controlling for geographical time trends and shocks

	(1) 100km grid cells	(2) 50km grid cells	(3) 20km grid cells	(4) LGD demographics
Change in log centrality 51-81	0.315***	0.297***	0.306***	0.284***
	(0.023)	(0.030)	(0.031)	(0.024)
Observations	13,253	13,253	13,253	11,589
R-squared	0.718	0.700	0.694	0.692

Robust standard errors in parentheses, *** p<0.001, ** p<0.01, * p<0.05.
Dependent variable if parish population in 1981 (based on 1951 parish geographical definitions).
All regressions include log centrality in 1951, log population in 1951.
Estimated on pairwise differences between matched observations ranked on linear predictions from regression of 1951-1981 change in centrality on quadratic in log population in 1901 and quadratics in change in log population 1901-1951, 1911-1951, 1911-1951; 1931-1951 (as Table 1 column 8).
Column 4 controls for LGD demographics, age 0-14, age 15-64, age 65+, educated to 20+, social class 1, 2, 3, 4, England and Wales sample only.

Table 3: Effects on 1981 population of changes in rail centrality, by motorway access and initial rail centrality

	(1) Above median 1951 rail centrality	(2) Indicator that parish >10km from stations, 1981 and 1951	(3) Above median spatial centrality 1951	(4) Above median distance to LGDs population 80k plus	(5) Indicator of New Towns	(6) 1951-1981 motorway centrality change (pop weighted)	(7) 1915-1981 motorway centrality change (pop weighted)
Change in log rail centrality 51-81	0.293***	0.329***	0.357***	0.295***	0.312***	0.316***	0.604***
	(0.026)	(0.022)	(0.039)	(0.034)	(0.020)	(0.022)	(0.140)
x Column heading variable	0.071	0.130	-0.053	-0.053	0.954*	-	-0.420*
	(0.041)	(0.069)	(0.045)	(0.043)	(0.405)		(0.202)
Column heading variable	0.200***	-0.063	-0.062	-0.210***	2.248***	0.262***	0.097
	(0.053)	(0.084)	(0.056)	(0.054)	(0.469)	(0.062)	(0.101)
Observations	13,253	13,253	13,253	13,253	13,253	13,245	13,245
R-squared	0.693	0.695	0.691	0.695	0.698	0.678	0.674

HAC robust standard errors in parentheses *** p<0.001, ** p<0.01, * p<0.05.
parish level regressions based on matched pairwise differences, as in Table 1, column 8.
First row shows baseline effect of change in centrality in parishes in low access group. Second row shows interaction with high access indicator. High/Low access defined in column headings.
Change in road centrality 51-81 is the change in a population weighed centrality index due to construction of the motorways and general road speed increases, 1951-1981.
Sample smaller in columns 6 and 7 due to missing motorway centrality values for islands.

Table 4: Alternative treatment definitions. Effects of rail access changes on 1981 log population.

	(1) Change in log station distance	(2) Lost nearest station	(3) Nearest station twice as far
Change in rail access	-0.168***	-0.130***	-0.149***
	(0.011)	(0.015)	(0.012)

	(4) Population weighted	(5) Centrality 1 station	(6) Centrality 4 stations
Change in rail access	0.311***	0.092***	0.362***
	(0.022)	(0.009)	(0.022)

	(7) Centrality 3 stations	(8) Centrality 1 station	(9) Centrality 4 stations
Top quintile cuts	-0.272***	-0.299***	-0.274***
	(0.018)	(0.018)	(0.018)
4th quintile cuts	-0.182***	-0.211***	-0.148***
	(0.018)	(0.018)	(0.018)
3rd quintile cuts	-0.100***	-0.094***	-0.091***
	(0.018)	(0.018)	(0.018)
2nd quintile cuts	-0.064***	-0.045*	-0.058**
	(0.018)	(0.018)	(0.018)

HAC robust Standard errors in parentheses *** p<0.001, ** p<0.01, * p<0.05.
parish level regressions based on matched pairwise differences, as in Table 1, column 8.

Table 5: IV estimates based on line orientation and non-core routes

	(1) Distance to imputed non-trunk routes	(2) Distance to imputed non-trunk routes, dropping cities	(3) Length of E-W running lines	(4) Both instruments
Change in log centrality 51-81	0.822*	0.920*	0.455*	0.791**
	(0.402)	(0.395)	(0.217)	(0.243)
Distance to non-core routes*100	0.001	0.001	-	0.001
	(0.000)	(0.000)		(0.000)
E-W line length*10	-	-	-0.021	-0.016
			(0.003)	(0.002)
First stage F	10.96	10.78	59.44	24.10
p-value	0.001	0.001	0.0000	0.000
Hansen-Sargan J	-	-	-	0.012
p-value				0.913
Observations	13,213	10,971	13,213	13,213

Robust standard errors in parentheses *** p<0.001, ** p<0.01, * p<0.05.
Instrument in column 1 is distance to non-core route on 1950 network, where non-core routes are defined as those not on the least-length network path between London and Local Government Districts with populations 80k plus, nor on the least-length route required to traverse all the Local Government Districts with populations greater than 80k plus.
Column 2 restricts sample to parishes at least 40km from London and 10km from other major urban areas (>80,000 population).
Instrument in column 3 is length of lines in a parish (km) orientated in E-W direction (<10km N-S gap between end nodes).
Regressions include controls for log population in 1901-1951, log centrality in 1951, parish land area and distance to 1950 rail network.
Sample excludes outlying islands in Scotland to avoid outlying values in distance to imputed non-trunk routes.

Table 6: 'Placebo' test – proposed but unclosed stations

	(1) Change in log station distance	(2) Lost nearest station
Station proposed not closed	-0.086***	-0.030*
	(0.018)	(0.012)
Station closed	-0.149***	-0.136***
	(0.010)	(0.015)
Test for equality p-value	0.0009	0.0000
Observations	13,253	13,253
R-squared	0.686	0.688

HAC Standard errors in parentheses *** p<0.001, ** p<0.01, * p<0.05.
Parish level regressions based on matched pairwise differences, as in Table 1, column 8.

Table 7: Local versus global centrality changes

	(1)
Change in log centrality 51-81 due to removal of local stations	0.423***
	(0.029)
Change in log centrality 51-81 due to global network changes	0.144***
	(0.041)
Observations	13,253
R-squared	0.691

HAC Standard errors in parentheses *** p<0.001, ** p<0.01, * p<0.05.
Parish level regressions based on matched pairwise differences, as in Table 1, column 8.

Table 8: Long run effects on parish populations in 1991 and 2001

	(1) 1991	(2) 1991, conditional on 1981	(3) 2001	(4) 2001, conditional on 1991 and 1981
Change in log centrality 51-81	0.296***	-0.003	0.299***	0.047***
	(0.024)	(0.014)	(0.021)	(0.013)
Observations	13,249	13,249	13,253	13,249
R-squared	0.635	0.872	0.643	0.871

HAC Standard errors in parentheses *** p<0.001, ** p<0.01, * p<0.05.
Parish level regressions based on matched pairwise differences, as in Table 1, column 8.
Sample smaller in columns 1, 2 and 4 due to missing 1991 and 1981 population data.

Table 9: Changes in rail network centrality and 1981 outcomes in Local Government Districts in England and Wales

	(1) Education Pairwise diff matched	(2) Soc 1 Pairwise diff matched	(3) Soc 2 Pairwise diff matched	(4) Soc 3 Pairwise diff matched	(5) Soc 4 Pairwise diff matched	(6) Soc 5 Pairwise diff matched	(7) Age 0-15 Pairwise diff matched	(8) Age 15-64 Pairwise diff matched	(19) Age 65+ Pairwise diff matched
Change in log centrality 51-81	0.132***	0.175**	0.102***	-0.037*	-0.107***	-0.015	-0.008	0.021***	-0.102***
	(0.037)	(0.059)	(0.029)	(0.018)	(0.031)	(0.085)	(0.012)	(0.005)	(0.018)
Observations	1,465	1,465	1,465	1,465	1,465	1,465	1,465	1,465	1,465
R-squared	0.782	0.659	0.849	0.920	0.795	0.401	0.958	0.992	0.880

Robust standard errors in parentheses *** p<0.001, ** p<0.01, * p<0.05
Dependent variables are: (1) log higher educated males; (2)-(6) log males in social class 1-5, (7)-(10) population in age groups. Class 1 is professional, class 2 is intermediate, class 3 is skilled, class 4 is partly skilled, class 5 is unskilled.
All regressions include log centrality in 1951, log population in 1951, log denominator for dependent variable in 1981 and 1951, log dependent variable in 1951
Estimated on pairwise differences between matched observations ranked on linear predictions from regression of 1951-1981 change in parish centrality on quadratic in parish log population in 1901 and quadratics in change in log population 1901-1951, 1911-1951, 1911-1951; 1931-1951 (as Table 1 column 8)

6. Appendix tables

Table 10: Descriptive statistics

Variable	N	Mean	SD	Min	Max
Parishes					
Population 1951	3678.901	22169.95	2	1.11E+06	13254
Population 1931	3372.066	22120.22	2	1.01E+06	13254
Population 1921	3217.843	21219.18	3	9.24E+05	13254
Population 1911	3065.404	20184.82	2	8.25E+05	13254
Population 1901	2777.213	18757.45	2	7.49E+05	13254
Change in ln pop 81-51	0.121	0.6	-5.796	5.536	13254
Change in ln centrality 81-51 (3 stations)	-1.223	0.277	-2.493	-0.823	13254
Change in local ln centrality 81-51	-0.238	0.204	-0.799	0	13254
Change in global ln centrality 81-51	-0.985	0.143	-2.072	-0.823	13254
Change in ln pop weighted centrality 81-51	-0.39	0.263	-1.681	-0.096	13254
Change in log station distance actual closures	0.699	0.56	-0.163	3.661	13254
Change in ln station distance proposed	0.173	0.316	0	2.61	13254
Lost nearest station proposed	0.357	0.479	0	1	13254
Lost nearest station	0.821	0.383	0	1	13254
Change in log pop weighted m'way centrality	0.698	0.096	0.026	0.951	13245
Length of W-E running lines km	6.98	13.142	0	181.895	13213
Distance to non-trunk routes km	1.517	3.126	0	77.833	13213
Distance to stations 1951 km (nearest 3)	7.66	12.217	0.468	404.777	13254
Parish area (km squared)	17.522	41.667	0.027	1106.58	13254
Local Government Districts					
Educated 20 years up 1981	238.139	317.597	2.033	4122.911	1465
Social class 1 1981	523.558	727.939	0	8946.313	1465
Social class 2 1981	2067.721	2488.785	10.076	33083.55	1465
Social class 3 1981	4377.846	6287.431	27.066	1.06E+05	1465
Social class 4 1981	1527.589	2462.769	9.517	50516.73	1465
Social class 5 1981	564.318	1048.782	0	17238.08	1465
Age 0 1981	6795.945	9522.312	59.831	1.78E+05	1465
Age 15 1981	21332.53	30001.71	226.569	5.21E+05	1465
Age 65 1981	4960.488	7208.362	42.524	1.20E+05	1465
Educated 20 years up 1951	205.685	411.882	3	6795	1465
Social class 1 1951	348.121	647.69	6	8425	1465
Social class 2 1951	1529.92	2599.052	44	44647	1465
Social class 3 1951	5564.779	11373.21	86	2.28E+05	1465
Social class 4 1951	1697.926	2762.212	14	55134	1465
Social class 5 1951	1379.66	3301.046	12	62752	1465
Age 0 1951	6609.07	13409.39	77	2.64E+05	1465
Age 15 1951	19939.14	39133.6	374	7.45E+05	1465
Age 65 1951	3289.779	5899.905	101	1.03E+05	1465

Table 11: 'First stage' regression of log rail centrality change 1981-1951 on lagged population growth trends

Log population 1901	-0.003
	(0.008)
Log population 1901 squared	0.002**
	(0.001)
Log pop 1911- log pop 1901	0.110***
	(0.017)
Log pop 1911- log pop 1901 squared	-0.045**
	(0.017)
Log pop 1921- log pop 1911	0.063***
	(0.011)
Log pop 1921- log pop 1911 squared	0.006
	(0.006)
Log pop 1931- log pop 1921	0.123***
	(0.011)
Log pop 1931- log pop 1921 squared	0.000
	(0.011)
Log pop 1951- log pop 1931	0.056***
	(0.006)
Log pop 19511- log pop 19311 squared	0.009*
	(0.004)
Observations	13,254
R-squared	0.042

Table 12: Population pre-trend test

	(1) Pre-trends log pop 51 | log pop 21	(2) Pre-trends Log pop 31 | log pop 01	(3) Pre-levels Log pop 1951
Change in log centrality 51-81	0.001	0.003	-0.013
	(0.008)	(0.008)	(0.031)
Observations	13,253	13,253	13,253

7. Appendix figures:

Figure 7: parishes 10km from rail stations 1950 and 1980

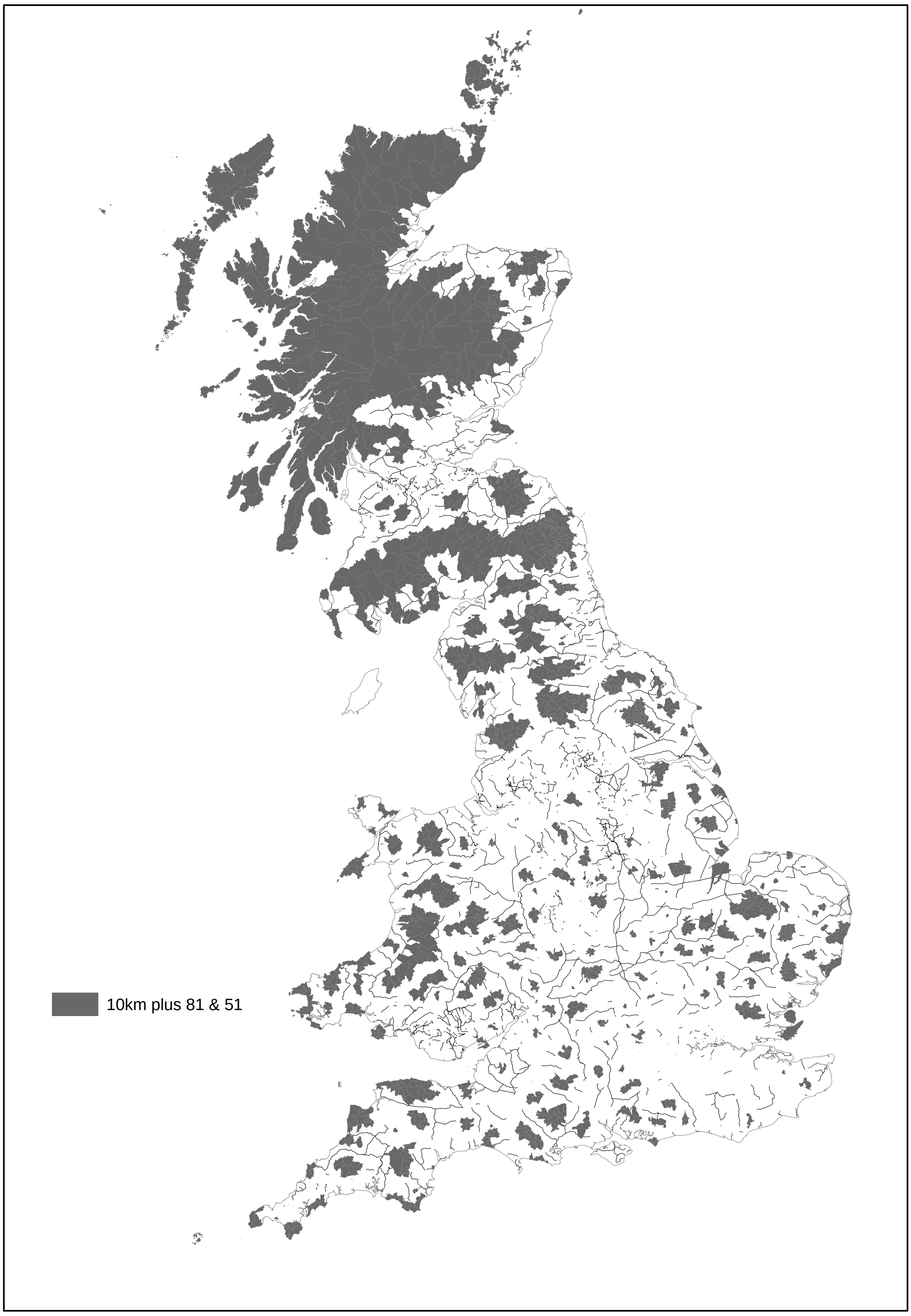


Figure 8: Motorway centrality index change, 1950-1980

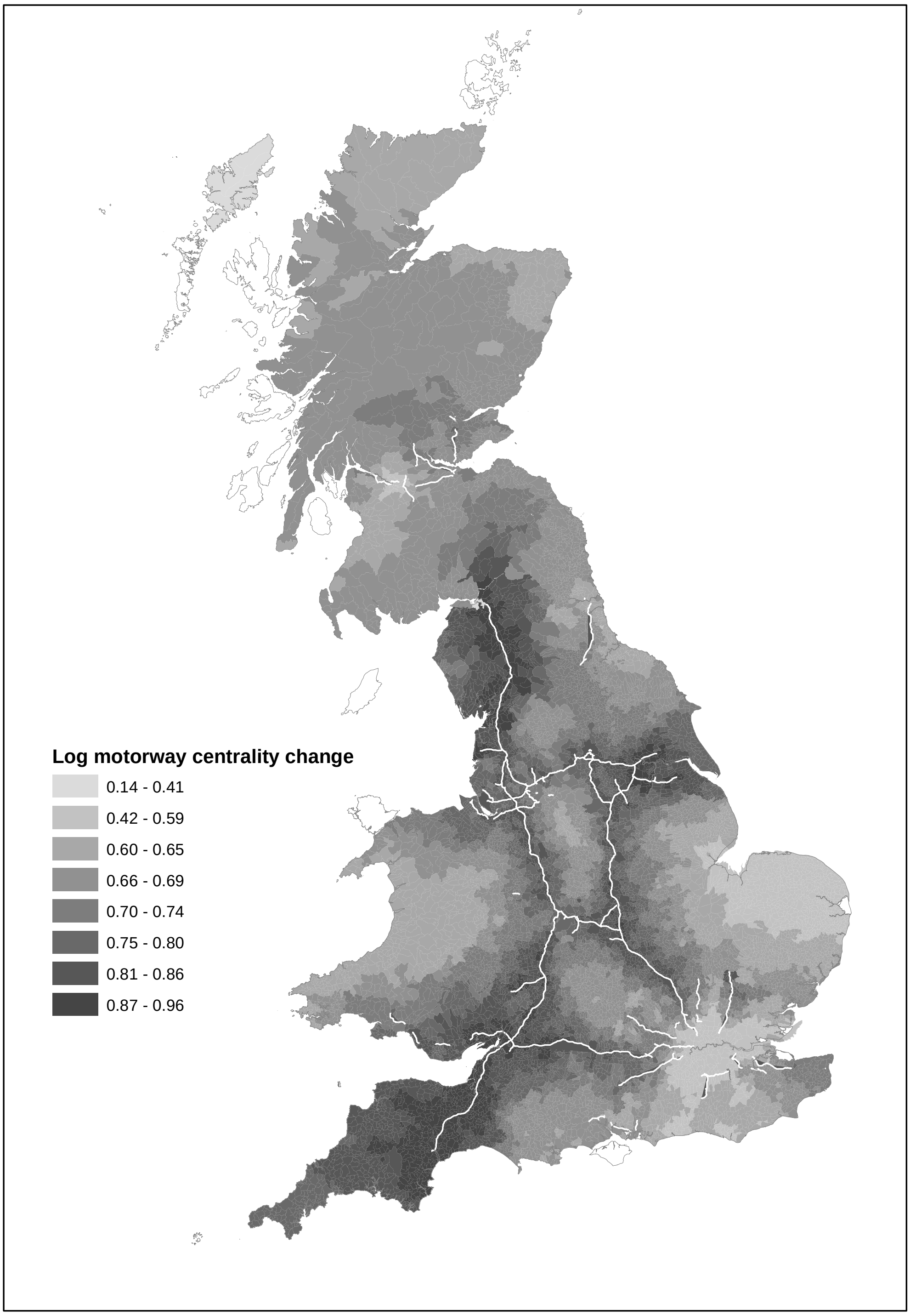


Figure 9: Trunk routes proposed for development in British Railways Board (1965)

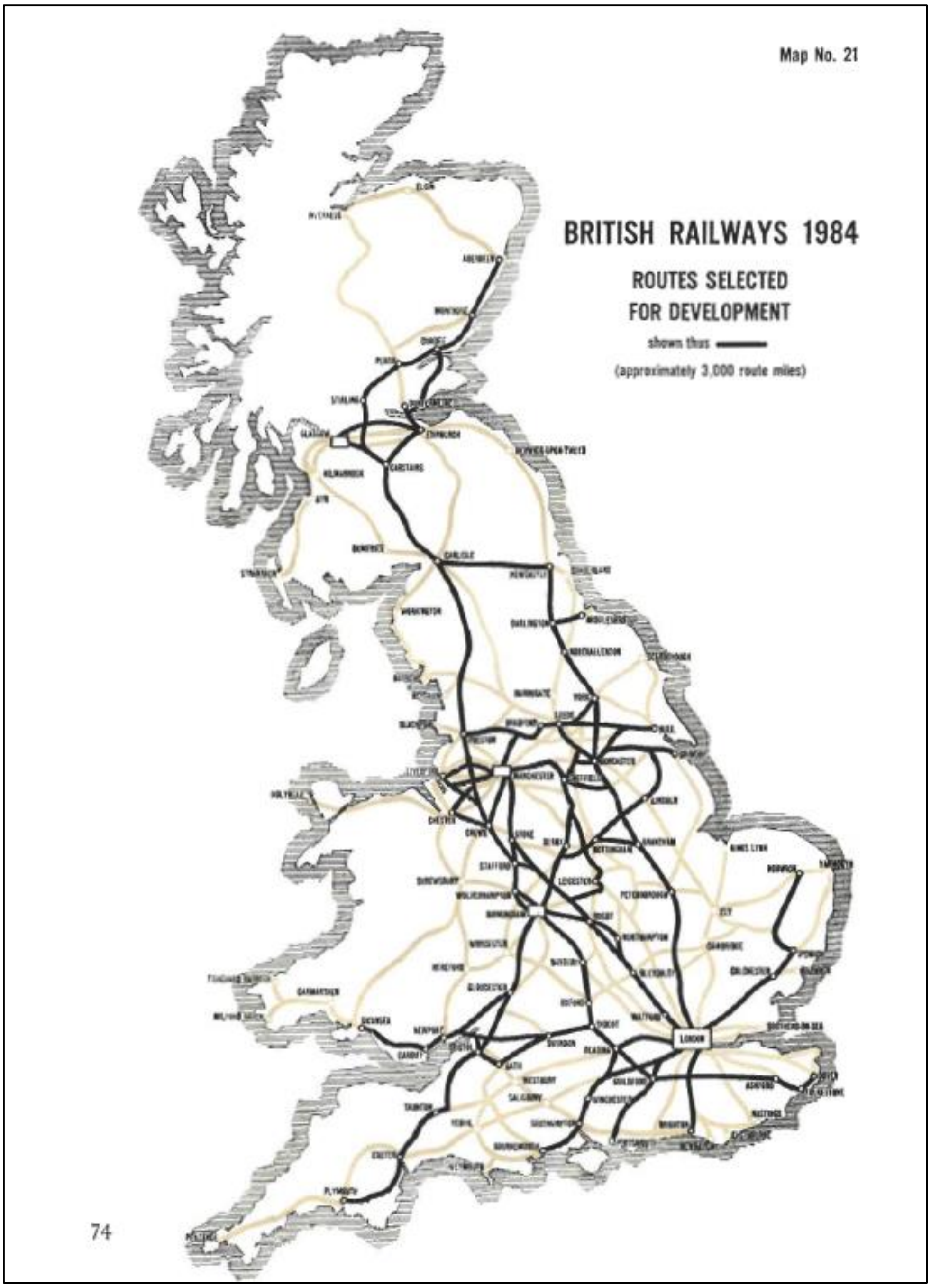
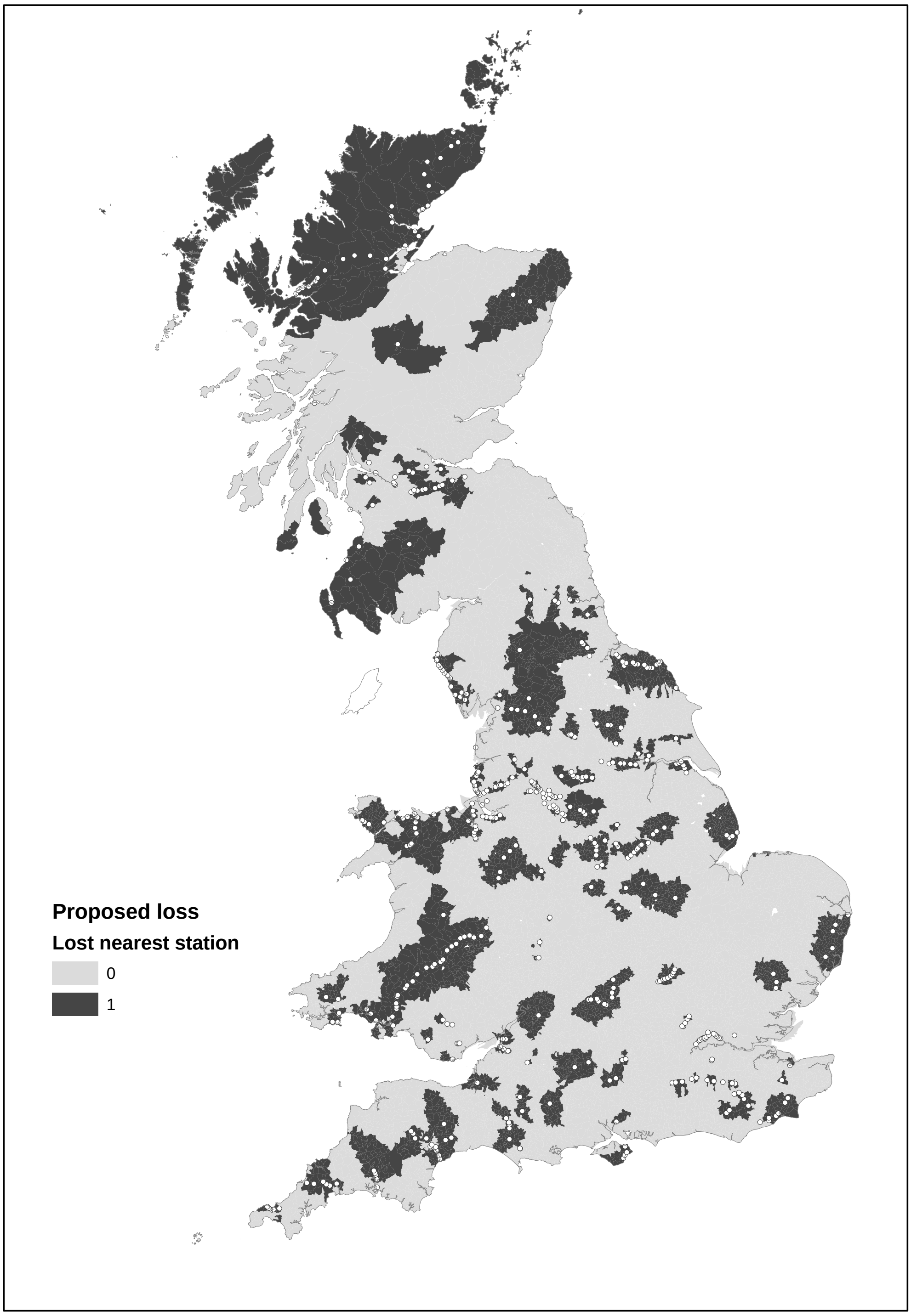


Figure 10: Proposed but not closed stations



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