Geographical Segregation, Missallocation and Productivity in Apartheid South Africa Manufacturing:

The Barrier-Breaking Iron Tracks of Growth

Timothy Ngalande

September 2, 2025

1 Introduction

The economic history of South Africa in the second half of the twentieth century presents a unique and profound paradox. On one hand, the Apartheid government was a developmental state, promoting economic welfare and advancement for the white minority. The government undertook ambitious and economically uplifting projects of modernisation and industrialisation; including investments in morden infrastructure and upgrading extensive railway network from steam to diesel and electric power (Lin and Si'ao, 2025). The economic objective was to drive economic prosperity through industrialisation and robust manufacturing for import substitution. The rise to dominance of manufacturing relative to other sectors of the economy in contributing to national output shows that these efforts were not futile (Feinstein, 2005).

On the other hand the apartheid machinery was designed unfavourably for non-white races, institutionalising racial segregation in geography, labour and education (Lin and Si'ao, 2025). One of the foundational policies for the architecture of institutionalised segregation was the Group Areas Act of 1950 which enforced residenstial segregation by race (Davies, 1981). In some scenarios non-whites were forcibly removed and resettled in what were called homelands (or Bantustans). These areas were often removed from modernisation and industrial activity. They were generally infertile and economically disadvantaged locations. Since the whites controlled most economic production and activity, inherent in the Group Areas Act was frictions in labour market and capital markets and consequently, distortions. One tool that helped grease the wheels of the apartheid segregative machinery was railroads. These aided inter- and intra-city mobility of labour and allowed the flow of labour from segregated locations to urban, industrial and white residential locations. In a way railroads helped recoup some of the losses of distortionary Apartheid policies.

In this paper, I explore the implications of Apartheid policies and infrastructure development on productivity in the manufacturing sector. I analyse the impact that railway upgrades had on aggregate productivity in South Africa's manufacturing during apartheid. In particular, I examine the relationship between geographical segregative policies by the apartheid government and distortions in the manufacturing sector and how rail upgrades during this period affected both segregation and consequently aggregate productivity.

I use maiden regional manufacturing data, digitised from manufacturing censuses to construct a manufacturing census data set for years 1970, 1980 and 1985. Following Hornbeck and Rotemberg (2024), I use this data to estimate district production functions for the respective census years and identify the existence of distortions in the market using input wedges. I find that the manufacturing sector had positive input wedges across the years, indicate the presence of a gap between marginal product and marginal cost and hence distortions in the market. I further estimate aggregate productivity and decompose it into Revenue Total Factor Productivity (TFPR) and Allocative Efficiency (AE). I also consult South Africa railways and harbours reports to digitise and geocode maps that detailed the progress of rail upgrades from steam to diesel and electric operated vehicle rail lines in the corresponding census years. I use the rail upgrades as the treatment variable in my analysis.

I estimate a Callaway and Sant'Anna (2021) (CS) staggered difference in difference (DiD) specification for the effect of the rail upgrades on aggregate in apartheid South Africa on aggregate productivity. I further decompose the effect to the TFPR and AE components to understand the source of growth in aggregate productivity. I find that that railroad upgrades increased the aggregate productivity of the connected districts. The decomposed effected shows that most of such growth in aggragate productivity was driven by the effect on Allocative efficiency relative to TFPR.

The analysis proceeds with examining the sources of growth in AE, to establish a mechanism for the growth in aggregate productivity. In this respect, I explore the effect of railroads and their upgrades on segregation during apartheid and the relationship between segregation and productivity. I use geographical location quotient as a measure of segregation in urban locations. I find that rail upgrades significantly reduced segregation using the CS DiD estimator. I also find that reduced segregation was associated with significant increases in AE but not TFPR. This identifies the channel of the effect of rail upgrades on aggregate productivity as re-allocation of inputs from the reduced segregation effect.

The rest of the paper proceeds with a discussion of the literature that I contribute to, followed by an elaborate discussion of the historical background of this study. Then I discuss the curation and construction of the data used in the paper and explore the theoretical underpinnings of the emperical estimations and tests that follow. I present the results and test the suggested mechanism of the analysis.

2 Contribution/Literature

This paper contributes to four main themes of economic literature. Firstly, it contributes to an emerging body of research on missallocation following seminal work by Restuccia and Rogerson (2008) and Hsieh and Klenow (2009) which suggests that the allocation of resources across heterogeneous firms or regions can significantly explain cross-country differences in aggregate Total Factor Productivity (TFP). The theory explains that in efficient markets, change in productivity of physical inputs (TFPR) should explain growth in aggregate productivity across all firms or regions but where distortions exists, it does not fully do so. It proposes a decomposition of aggregate productivity into TFPR and AE. Extensions to this seminal work including Restuccia and Rogerson (2013); Hornbeck and Rotemberg (2024); Baqaee and Farhi (2020); Liu et al. (2023) discuss how inefficiencies create heterogeneity and differences in productivity. I contribute to this body of literature by assessing how the re-allocation of resources improves efficiency and narrows the heterogeneity of production efficiency. I further unpack the "black box" of Allocative Efficiency and attempt to pin down factors driving growth in Allocative Efficiency.

Secondly, this paper examines the effect of policy on resource efficiency in line with literature that has focused on trade liberalisation, financial regulations, migration, capital and tax restrictions (Banerjee and Duflo, 2005; Khandelwal et al., 2013; Bai et al., 2024; Tombe and Zhu, 2019). I contribute to this theme of literature with an analysis of how a socio-economic policy such as geographical segregation can affect mobility or labour and hence efficiency. Similar literature relating spatial segregation and spatial misallocation by Hsieh and Moretti (2019); Liao et al. (2025) discus housing, income and education segregation which are not particularly policy imposed but self-selecting. This paper considers the possible effects of enforced racial segregation and how it affects productivity. This hence also links the paper to literature on the labour market frictions (Bilal et al., 2021, 2022; Elsby and Gottfries, 2022).

The paper also joins a growing literature on infrastructure development and its effects on growth and productivity. Fogel (1964); Donaldson and Hornbeck (2016); Atack et al. (2010); Atack and Margo (2011); Hornbeck and Rotemberg (2024); Baffi (2014); Hornung (2015) discuss extensively the role of railroads on growth in agriculture, manufacturing and overall economic output. Jedwab and Moradi (2016); Jedwab et al. (2017); Baum-Snow et al. (2017); Banerjee et al. (2020) also discuss the effect of infrastructure improvement such as highways in America, modern china and kenya on economic output. While also complementing earlier work on railroads and growth in current South Africa region by Fourie and Herranz-Loncán (2015), I contribute to the body of literature by analysing how improvements and investments in already existing infrastructure affects manufacturing output and productivity in South Africa. I further discuss the channel of the impact of the infrastructure improvements as a labour re-allocative dynamic.

Finally, This paper also contributes to a long-standing debate on the relationship between market forces and racial discrimination or segregation in this case. Becker (1971)'s seminal theory suggests that in a perfectly competitive market, segregation is costly for those who practice it. A firm that is inclined to segregate a group of potential workers by race must pay a premium for their preferred workers, thus reducing their profits relative to non-discriminating firms. In theory then, market competition is a powerful force that works to erode discrimination by rewarding firms that pursue profit maximization over prejudice. Parallel to this, the apartheid government institutionalised segregation of black labour while pursuing industrial and economic expansion. This scenario provides an environment to test Becker (1971)'s theory of discrimination in South Africa. I show how the apartheid machinery's preference for segregation is subverted by the very tools employed, in this case railroads. This aligns with similar tests in the literature by Yasuda (2023); Hirata and Soares (2016) and Charles and Guryan (2008).

3 Historical Background

The state-owned railway system played a critical and paradoxical role in the apartheid political economy. While seemingly designed to enforce spatial segregation, its economic characteristics, particularly cost-effectiveness over long distances, made it indispensable for integrating a low-wage Black labor force into the "white" economy's core. This process, propelled by 1970s and 1980s technological modernization, inadvertently fostered Black urbanization on a scale apartheid policy aimed to prevent. Consequently, it reduced de facto segregation even as it entrenched de jure segregation.

This section will first detail the political and legislative framework of apartheid labor policy. It will then explore the technological evolution of the South African Railways (SAR) and connect this infrastructure to the state's spatial engineering agenda. An economic analysis will compare rail and road transport to show the extent of negative externalities that were imposed on Black commuters and explain the state's reliance on rail. I will then discuss these elements to establish a clear rationale for examining the railway's dual function as a driver of both economic integration and social-economic segregation.

3.1 Political Economy of urban and segregation and effects on labour

The distinctive system of mass, long-distance commuting that characterized apartheid-era South Africa was not an organic development but a direct consequence of a carefully constructed political and economic plan. This framework was designed to achieve two conflicting objectives: to ensure a cheap mobile, and politically disenfranchised non-white labour force for the mines and growing industry, while at the same time enforcing racial and spatial segregation (Feinstein, 2005). The transport system that emerged, with railways at its core, can be understood as the state's solution to this fundamental contradiction.

The legislative structure for apartheid was erected long before the National Party's ascent to power in 1948. One of the foundational pieces of legislation for apartheid was the Natives Land Act, 1913. This act restricted African land ownership to designated reserves that initially constituted a mere 7.5% of the country's land, later expanded to 13% in 1936 (Ogura, 1996). This act served a crucial economic function beyond mere territorial segregation. It systematically undermined the capacity for subsistence agriculture within the Black rural population and created a powerful structural incentive for Africans to enter the cash-based wage economy. The recourse for most blacks was to supply cheap labour in white-owned farms and, the burgeoning mining industry and in manufacturing.

With the National Party's victory in 1948, the existing system of segregation was consolidated and intensified into the policy of "grand apartheid". A series of legislation formalised racial hierarchy in every aspect of life. Among these, the cornerstone of apartheid's spatial segregation was the Group Areas Act of 1950. This law mandated the strict residential and commercial segregation of urban areas by race. It empowered the state to forcibly remove non-white populations from established, often vibrant and racially mixed, communities like Sophiatown in Johannesburg and District Six in Cape Town These removals were conducted at a large scale; between 1960 and 1983, an estimated 3.5 million Black Africans were evicted from their homes and relocated to peripheral, racially homogenous townships (Feinstein, 2005). Aroud the same period, the Natives (Abolition of Passes and Co-ordination of Documents) Act, 1952, commonly known as the Pass Laws, centralized and tightened influx control, making it a criminal offence for a Black person to be in a "white" urban area for more than 72 hours without a permit proving they were employed there.

3.2 Labour Market segregation

The spatial and mobility controls were closely tied to the development of a highly segmented labor market. A series of laws, including the Mines and Works Act of 1911 and the Industrial Conciliation Acts of 1924, 1936, and 1956, established the "industrial color bar" (Hazlett, 1988). These laws effectively reserved skilled and semi-skilled jobs for white workers, allowing white trade unions to legally exclude Black workers from competition (Hazlett, 1988). This led to an artificial scarcity of skilled labor and a dual wage structure, maintaining the privileged status of white workers. The impact of this legislation is clearly reflected in mining employment statistics: the ratio of Black to white miners, which had reached a market-driven level of 11.4 to 1 after the suppression of the 1922 Rand Rebellion, was systematically reduced by regulation to an astonishing 6.4 to 1 by 1953, the peak of apartheid (Hazlett, 1988).

The combination of land and residential displacement, influx control, and job reservation led to a monopsonistic labor market, especially in the gold and diamond mining sectors. The Chamber of Mines, a powerful employers' association, acted as a buying cartel, keeping wages for Black workers artificially low. These policies created significant labor market frictions, depriving Black workers of geographic and occupational mobility, and hindering their ability to gain skills and negotiate for better wages (Hazlett, 1988). Despite its rigidity, this system was not immune to economic forces. By the late 1960s and early 1970s, the economic growth of previous decades resulted in a shortage of skilled white labor. In response, major industries like metal and engineering, motor manufacturing, and clothing began renegotiating agreements with white unions to allow certain semi-skilled jobs to be reclassified and opened to non-white workers. This shift, documented by Horrell (1969) and Lipton (1985), was driven by economic necessity rather than a change in racial ideology (Mariotti, 2012b). It showed that market pressures could start to undermine the structure of workplace apartheid from within, increasing the demand for a mobile, urbanizing Black workforce.

This historical context highlights the core dilemma faced by the apartheid state. Its political ideology insisted on complete spatial separation of races and confining the Black population to distant homelands (Lin and Si'ao, 2025). However, the state's economy which was driven by its mines, factories, and commercial farms relied heavily on a large, accessible pool of cheap Black labour (Ogura, 1996). The Group Areas Act was the state's effort to address this contradiction by establishing peripheral townships that were geographically separate yet economically linked to the white urban centers. Consequently, this policy of separation required a simultaneous policy of mass, controlled, daily integration. To operate effectively, the apartheid city needed a transport system that could move millions of workers over within and between cities efficiently and affordably. This necessity paved the way for the critical and unique role of the national rail system.

3.3 The Modernisation of the State's Railway System (1970-1985)

The transport infrastructure that enabled the apartheid state to manage its central contradiction was the national railway network. This system, consolidated under state control and subjected to a massive technological upgrade during the 1970s and 1980s, provided the physical capacity to enact the state's policy of medium-long distance, segregated commuting.

The origins of South Africa's railway network can be traced to the colonial needs of the late 19th century. The first rail lines were built mainly as "penetrating lines" to link coastal ports with inland areas rich in resources. This development sped up significantly after diamonds were discovered in Kimberley in 1870 and gold on the Witwatersrand in 1886 (Baffi, 2014). After the Union of South Africa was formed in 1910, the various colonial railways, which were often in competition, were consolidated into a single state-owned monopoly known as the South African Railways and Harbours (SARH) (Baffi, 2014). In 1981, SARH was restructured to operate more commercially and renamed the South African Transport Services (SATS), although it remained under state ownership (Stander and Pienaar, 2002). As a nationalised industry, the SARH played a crucial role in state policy, serving not only as a transport system but also as a means to advance Afrikaner nationalist goals.

3.3.1 The Technological Transition: Steam to Diesel and Electric

For much of its history, the SARH was know for its steam powered railway vehicles. As late as the early 1970s, vast portions of the network, including main lines in the Orange Free State and freight services in the Transvaal, were still worked entirely by steam locomotives

(Basu, 2006). However, by this time, the aging steam fleet was becoming increasingly inefficient and unable to cope with the rising traffic densities demanded by the growing economy and the mass movement of commuters. This prompted a period of intense technological modernization that transformed the face of South African transport.

The 1970s and early 1980s saw a decisive and large-scale shift away from steam traction towards diesel and electric power. The dieselisation programme, which had begun in the late 1950s with the importation of locomotives, was greatly expanded. By 1973, for instance, steam had been almost entirely eliminated from the busy main line south of Bloemfontein, replaced by more efficient and less labour-intensive diesel-electrics[1]. Simultaneously, the state embarked on an extensive electrification programme. While the first lines had been electrified in the 1920s, the 1973 oil crisis provided a powerful impetus to accelerate this process. During the 1980s, higher-voltage systems were introduced for the country's heavy-haul freight corridors, which moved strategic commodities like export coal and iron ore (Arup, 2012). This investment in modern traction was not limited to freight; it was fundamental to increasing the capacity and reliability of the commuter rail network. The entire system was also computerized from 1980, further enhancing operational control and efficiency. Although a brief but technologically significant experiment in "modern steam" was conducted in 1981, this did not alter the overarching strategic commitment to phasing out steam[2]. The state's long-term policy was clear: to build a modern, high-capacity railway system based on diesel and electric power. link text

The scale of this state-led investment, particularly in electric traction, was immense. It led to a 400% growth in electric locomotives from approximately 600 in 1969 to 2400 in 1989 (Arup, 2012). This technological transformation was not merely a technical upgrade; it was a strategic necessity. It equipped the state with an infrastructure capable of handling the unprecedented passenger volumes generated by its own policies of spatial engineering.

3.4 Mass rail commuting and Its economic advantage over road transport

The apartheid state's reliance on railways was not a matter of convenience but an economic necessity. Given the spatial layout and labour market it engineered, only rail could move

[1] *see*: An economic and environmental alternative to diesel traction

[2] *see:* Modern steam : an economic and environmental alternative to diesel traction

enough workers over long distances at a price the low-wage economy and the state budget could afford.

The main economic difference between rail and road transport lies in their cost structures. Rail has very high fixed costs—investment in track, signals, stations, and specialized rolling stock, but relatively low variable costs per passenger-kilometre once traffic volumes are high enough (Pienaar et al., 2012). This leads to strong economies of distance and density: as trips get longer and passenger volumes grow, fixed costs are spread over more users, and the average cost per passenger falls (Pienaar et al., 2012).

Road transport—buses and minibus taxis—shows the opposite pattern: lower fixed costs but higher variable costs, especially for fuel and labour per passenger. While more flexible, it is less efficient for moving large, concentrated flows of people on fixed, high-density corridors. On the long-distance commuter routes created by apartheid, rail was therefore the more cost-efficient option. State policy reflected this. From the Motor Carrier Transportation Act of 1930 until deregulation in the late 1970s and 1980s, road transport was tightly regulated to protect the state railway's monopoly on profitable routes (Pienaar, 2012). Even commissions that favoured market principles, such as the Welgemoed Commission of 1982, recommended rationalizing overlapping bus and rail services to eliminate uneconomic competition, implicitly recognizing rail's advantage on the high-density corridors it was designed to serve.

The spatial legacy of apartheid imposed what can be conceptualized as a heavy "transport tax" on the Black workforce, paid in time and money. Long travel times and high fares eroded already low wages. Because the apartheid economy depended on keeping Black wages low, workers could not absorb the full cost of these forced, lengthy commutes. The state therefore stepped in with large subsidies for bus and rail services to keep the workforce mobile and to ensure that commuting did not make employment uneconomic for workers (Baffi, 2014). On the other hand, the access to motorcars by whites saw their use of the railroads decline in intra-city commute and slow down in inter-city travel. Figure 1 shows these trends in the evolution of the use of trains by first class and second class passengers (whites) as well as third class passengers (blacks).

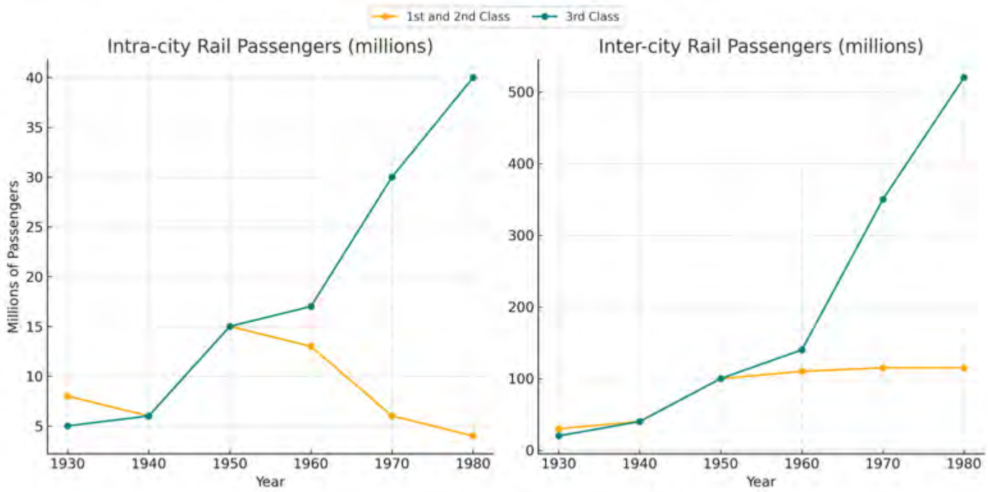


Figure 1: Evolution of train use by Commuters

Note: This figure shows the evolution of rail commuters in South Africa for 1st class, 2nd class and 3rd class users. The first plot shows the evolution for intra-city commuters while the second plot shows the evolution of inter-city commuters Source: SARH

Rail, with its economies of scale, was the cheapest mode for the state to support. Heavy public investment in railway electrification and dieselisation in the 1970s and 1980s aimed to expand capacity and efficiency so the system could move labor at the lowest cost to the treasury. Although the minibus taxi sector grew into a flexible part of the transport network,it received little subsidy and could not match the prices of heavily subsidized rail and bus services on the main long-distance commuter routes. Most of its growth took place after deregulation began in 1987 which is beyond the scope of this paper.

4 Data

4.1 Manufacturing Data

I use data from the Republic of South Africa's censuses of manufacturing for years 1970, 1980 and 1985. The series manufacturing census data is also available for years prior to this period but the 1970 census was the first to report regional statistics in manufacturing[3]. The censuses record gross revenue values, values of machinery, land, and vehicles as well as cost of materials and wages paid to different types of labour in the respective calendar years. These are presented as magisterial district aggregates as well as industry level aggregates for census

[3]Chapter 2 of my dissertation covers manufacturing censuses from 1911 to 1990 in analysing manufacturing productivity in the 20th Century.

defined regions.

I digitise tables for the regional principal statistics in the census for manufacturing in South Africa covering 1970, 1980 and 1985. This supplements previously digitised manufacturing census data by Mariotti (2012a) with district and/or region by industry level statistics necessary for the insights drawn in this paper. The regional data consists of district level aggregates the principal statistics by district and by industry. Industries enter and exit the census panel across the three years of focus, as such the base analysis is at a more stable and consistent 1970 district level. The classification of industries in South Africa changed in 1975 to a more expanded and disaggregated definition of industries. I re-aggregate the industry classifications in 1980 and 1985 records to match the 1970 classification for a more uniform record of industrial statistics across the period of focus.

Table B.1 in the appendix shows the list of industries available in the data for the 1970, 1980 and 1985 and how I aggregate the 1980 and 1985 records to match the 1970 classification. Unlike Hornbeck and Rotemberg (2024) who aggregate the industries to five major classifications for consistency, I maintain the eighteen major groups defined in the 1970 census throughout the years for a similar reason. At this level of aggregation, industries that exit or enter the census in subsequent years are tracked and treated accordingly in the analysis. To avoid inconsistencies in industry level data for respective districts, I estimate production functions using industries that are recorded in 1970 and do not exit the district until 1985.

The 1985 census and later censuses also record detailed industry categories at regional level which effectively allow for estimation of industry level production functions. However, since the 1970 and 1980 censuses are lacking in this level of detail, the analysis in this paper is limited to the major industry groups and does not therefore attempt to estimate industry level production functions. Instead, the industry major groups provide enough within district variation in the data to allow for estimation of production functions at the district level.

For geopolitical reasons there are some regions of the current South Africa that are not included in the manufacturing census during these Apartheid years in focus. These include areas designated by the South African Apartheid government as homeland areas for the homogenous residence and occupation of black/bantu South Africans in the Bantu Homelands Citizenship Act of 1970. Four homeland territories of Transkei, Bophuthatswana, Venda and Ciskei were declared and regarded as independent, self-governing territories. Consequently, the manufacturing censuses of 1980 and 1985 do not cover these areas and therefore not included in the analysis. Other homeland territories such as Gazankulu, KwaZulu, KaNgwane, Kwandebele Lebowa, Qwaqwa were included in the post 1970 censuses. Figure 2 presents a map of the homeland areas that are not covered on the manufacturing censuses of 1980 and 1985.

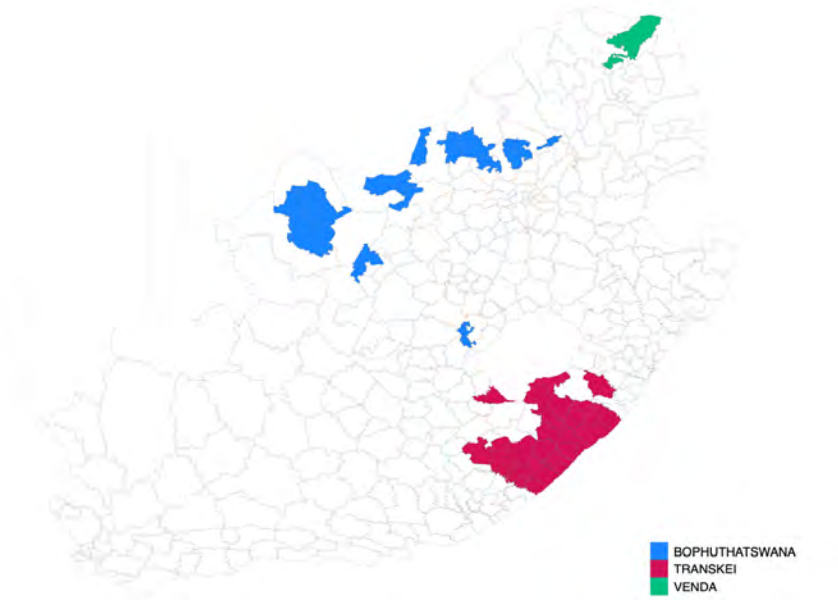


Figure 2: Native homeland areas in 1980

Note: The highlighted areas indicate the location ot the Native homeland areas also known as the Bantoustans. From 1979 these were the designated locations for native occupation. They were regarded as independent and by implication, were not included in the 1980 and 1985 manufacturing censuses. These areas are hence not part of the analysis in this paper.

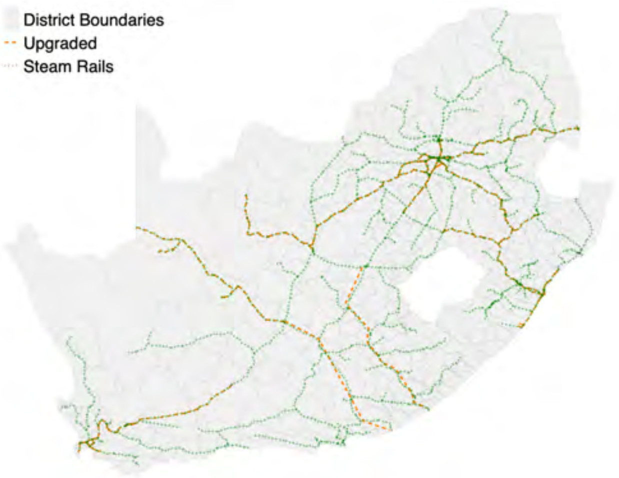
The designation of homelands after 1970 consequently redefined some district boundaries especially in areas where there was an overlap between homeland territories and non-homeland territories such as Natal and KwaZulu. Some districts in the manufacturing censuses of 1980 and 1985 carry the same name for KwaZulu and Natal according as they were split into either regional definition. To harmonise the spatial unit for these districts and every other district whose boundaries are re-defined after 1970, I aggregate the statistics by district for KwaZulu and Natal and use area crosswalks to rebase the principal statistics to 1970. Hornbeck (2010); Eckert et al. (2020) and Ferrara et al. (2024) discuss and use a similar approach where the proportion of the overlap area between a redefined spatial unit (i.e. 1980) and the purported base spatial unit (i.e.1970) is used as a weight for the statistics of the redefined spatial unit to be rebased. I digitised the 1980 and 1985 shapefiles at magisterial district level and thus computed these weights that I subsequently used to rebase the 1980 and 1985 censuses of manufacturing.

For each district-industry-year I observe gross revenue in manufacturing as the total value of manufacturing output (Y_{dit}). I use the total year end value of fixed assets in land, machinery and vehicles to measure capital expenditure. I multiply the total value of capital with the central bank discount rate for the corresponding census years to measure capital expenditure (K_{dit}). The value of in-kind payments and total wages paid to labour is used as a measure of labour expenditure (L_{dit}) while the cost of intermediate materials as the measure of expenditure on materials (M_{dit}).

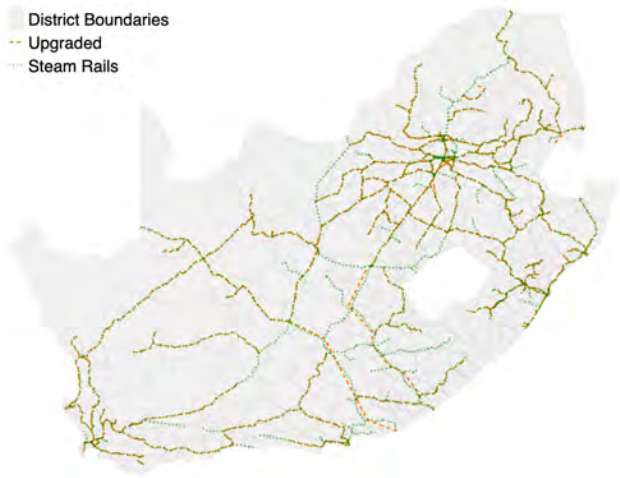
4.2 Railroad data

To analyse the effect of railroad infrastructural improvements on subsequent manufacturing productivity, I digitise railroad maps published in the annual reports by the "Department of Transport and National Transport Commission" of South Africa. These maps record the status and progress of transport infrastructure construction, extensions, and improvements across South Africa. I use archive maps indicating the progressive improvements of the railroads up to 1970, 1980 and 1985 respectively as in figure A.1. The maps show the railroads that had been upgraded from steam to diesel or electric operated vehicles by the respective years or were still under development. While most of the improvements were from steam carriers to either diesel of electric, it can be noticed in panels (b) and (c) of figure A.1 that some diesel carriers eventually upgraded to electric carriers. These are regarded as diesel carriers in the years that they are noted as under development.

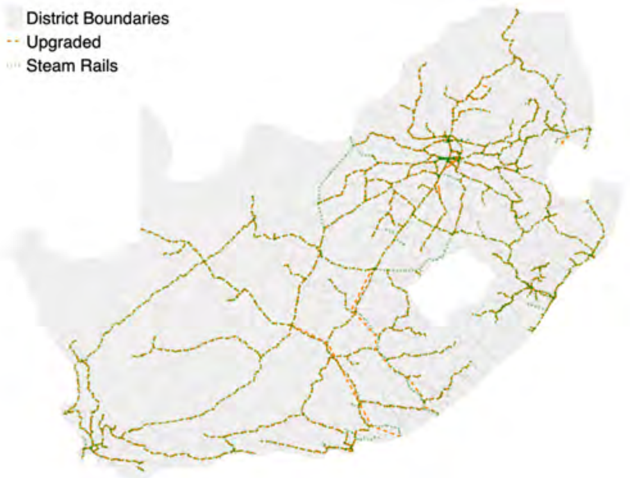
I geocoded these to South Africa's spatial representation in QGIS and overlayed a South Africa National Geo-spatial Information (2016) railroad shapefile with precise geo-locations of the railroads. I encoded the overlayed shapefile with the railroad improvement status for each of the census years. Figures 3, A.3 and A.2 in the appendix show the digitised maps and the respective treated districts over the three census years. The adoption of the treatment shows clear expansionary progression from 1970 to 1985. A combination of diesel and electric vehicle upgrades shows that by 1985 a majority of the railroad network had been upgraded to either diesel or electric or both.



(a) Map of rail upgrades up to 1970



(b) Map of rail upgrades up to 1980



(c) Map of rail upgrades up to 1985

Figure 3: Geocoded and digitised state of rail improvements

Note: The figure presents a plot of the state of the railroads in the manufacturing census years of 1970, 1980 and 1985. This figure depicts the progression of the improvement of the railroad network from steam as at these census years. The blue lines represent the lines that were fully upgraded to diesel and electric carriers by the respective year while the green lines represent steam rail carriers.

Figure A.4 shows the treatment adoption across the years. This gives the indication that for most districts, their railroad connection was improved in the 1970-1980 period. By 1970 only 30 of the 250 districts had an improved railroad. Most of the improvement involved an upgrade to diesel powered rail vehicles relative to electric powered vehicles.

4.3 Population census

The manufacturing census years coincide with South Africa's population census years. I use the population censuses to construct variables that I use in this paper as controls as well as tests for mechanisms of the effect of upgrading railroads on productivity. The 1970 census is the least detailed among the three censuses. It has fewer variables recorded uniformly across all the ethnic groups. These include the education levels, urban status and literacy levels. It also has a 5% count of the African population relative to the other population groups with full counts. I therefore weigh the population of blacks in each district in 1975 by this proportional representation in the census. All the counts from 1980 and 1985 censuses are re-based to 1970 census boundaries using area cross-walks.

5 Theoretical Framework: Influx control, Labour Misallocation and productivity in Apartheid South Africa

The Apartheid regime in South Africa implemented a comprehensive system of laws and policies that effectively enforced racial segregation and sustained the economic and political dominance of the white population. Among these laws; influx control measures focused on urban racial segregation of the population and consequently defined the geospatial landscape of the nation. Influx control, dictated where South Africans could reside and work based on their race, curtailing the mobility and employment opportunities especially for non-white populations. The infamous Pass Laws, mandated non-whites to carry documents authorising their presence in restricted areas. They served as an instrument of control and led to more than 17 million arrests over their duration (Feinstein, 2005)

In this section I aim to capture the dynamics of the historic influx control measures in an economic theoretic canvas, relating urban segregation to labour market frictions, Misallocation and the consequent effect on aggregate productivity. I build a theoretical framework that links labour frictions from segregation to input ”wedges” and their subsequent effect on productivity. The model shows how a soft relaxation of segregation parameters, for example, as a consequence of improved transport infrastructure affects productivity through allocative efficiency and depicts the economic gains or losses.

5.1 Labour frictions, wedges and missallocation/distortions

In the Apartheid period, the different regulations imposed by government had a collective potential to distort the labour market. Assuming all other regulations remain unchanged and imposing an influx control measure for non-white populations also has a distortionary effect on the market. Restricting the flow of labour into urban manufacturing areas affects the supply of labour and thus its cost. The cost of labour is consequently higher under such conditions, which leads to production inefficiency that drives a wedge between firm marginal product and marginal costs. A positive wedge suggests that there is inefficient use of inputs in production such that increasing the use of an inefficiently utilised input increases output, efficiency, and profitability (Hornbeck and Rotemberg, 2024).

The existence of positive wedges can be deduced from figure A.5 which shows the distribution of the costs of inputs in production as a share of total revenue. Panel (a) plots the revenue share for each input across all the three census years in the data while panel (b) plots the revenue share of the total cost of inputs for the respective years. The input revenue share averages at about 0.8 for all the census years, indicating positive wedges and the existence of distortions and inefficiencies in the market. The revenue share is slight lower in than the overall average in 1985. Panel (a) of figure A.5 shows that most of the input expenditure goes to materials while labour and capital expenditure average around 0.13. Notably the distribution of expenditure shares for labour and materials are identically bimodal. This reflects the disparity in wages and respectively efficiency in production for white and black workers in production. Figure A.6 further shows the evolution of the bimodality of the labour and materials expenditure shares across the three census years in the data.

5.1.1 Wedges

The positive wedges suggested by the distribution of input expenditure shares can be estimated using production function elasticities. The data does not report these elasticities or the district production functions directly and hence they need to be estimated. Such estimations are confronted with the classic issues of simultaneity as discussed and resolved in the literature by Olley and Pakes (1996); Levinsohn and Petrin (2003) and Hsieh and Klenow (2009).

I follow Hsieh and Klenow (2009)'s estimation which exploits properties of the cobb douglas production function to overcome simultaneity concerns. Assuming a Cobb-Douglas production function with constant returns to scale[4], the average share of costs for each input, reflects their elasticity in production irrespective of price and productivity shocks. As implemented by Hornbeck and Rotemberg (2024), I henceforth estimate the wedges and infer distortions using the input-expenditure share of total costs and of revenue from the data.

For industry production functions, I estimate the elasticities using national input cost shares for the respective inputs and industries from the data as follows:

$$\alpha_{it}^{\nu} = \frac{\sum_d \Xi_{dit}^{\nu}}{\sum_{d\nu} \Xi_{dit}^{\nu}} \tag{1}$$

Where α_{it}^{ν} is the elasticity for input ν in industry i and year t. Ξ_{dit}^{ν} is the total expenditure on input ν in district d, industry i and year t.

Similarly, for the district production function, I use the average cost shares of the respective inputs with respect to the industries in the district across the three census years, weighted by the revenue share of the respective district:

$$\alpha_{d}^{\nu} = \frac{1}{3} \sum_{it} \left[\frac{\mathcal{R}_{dit}}{\sum_i \mathcal{R}_{dit}} \right] \left(\frac{\sum_d \Xi_{dit}^{\nu}}{\sum_{d\nu} \Xi_{dit}^{\nu}} \right) \tag{2}$$

Where $\left(\frac{\sum_d \Xi_{dit}^{\nu}}{\sum_{d\nu} \Xi_{dit}^{\nu}} \right) = \alpha_{it}^{\nu}$ is the industry elasticity in equation 1 weighted by the revenue share of each district $\left[\frac{\mathcal{R}_{dit}}{\sum_i \mathcal{R}_{dit}} \right]$; where $\mathcal{R}_{dit}$ is the revenue of district d, industry i and year t. Table 1 reports the estimated census average elasticities across industries districts for the inputs. In all the years, materials were the most important input on average with a 0.6 elasticity followed by labour with a 0.14 elasticity and capital at 0.02. While materials were most important in 1980 with an elasticity of 0.622, of the three census year, capital and labour were most important in 1985 with elasticities of 0.029 and 0.147 respectively. This suggests that the processing of materials to final output was moving to more efficient capital and labour application.

[4]Hornbeck and Rotemberg (2024) has shown that the varying the returns to scale of the Cobb-Douglas production function does not affect the subsequent interpretation of the estimated production functions and elasticities

Table 1: Input elasticities

	1970	1980	1985	Average
Capital	0.015	0.015	0.029	0.020
	(0.003)	(0.002)	(0.005)	(0.007)
Materials	0.566	0.622	0.602	0.597
	(0.067)	(0.048)	(0.062)	(0.064)
Labour	0.141	0.134	0.147	0.141
	(0.037)	(0.032)	(0.033)	(0.035)

Notes: This table presents average input elasticities for each of the years and their standard deviations as estimated with the manufacturing census data

Given these elasticities, I follow Hsieh and Klenow (2009) in calculating the wedges as

$$\omega_d^{\nu} = \frac{\alpha_d^{\nu} - \mathcal{s}_d^{\nu}}{\mathcal{s}_d^{\nu}} \tag{3}$$

Where ω_d^{ν} is the wedge for input ν in district d and $\mathcal{s}$ is the average share input ν's share of the district revenue;across the three census years

$$\mathcal{s}_d^{\nu} = \frac{1}{3} \sum_t \left[\frac{\sum_i \Xi_{dit}^{\nu}}{\sum_i \mathcal{R}_{dit}} \right] \tag{4}$$

Positive input wedges suggest the presence of distortions in the market and therefore inefficiencies in production. Thus, the manufacturers are using proportionally too few inputs in production, raising their cost of production and affecting aggregate productivity. In this case a wedge on materials, the most important input in the census years in my data, will impact aggregate productivity more than a relatively similar wedge on labour or capital. Table 2 shows that the average cross-country input wedges for each year are all positive and hence indicative of distortions and inefficiencies in the market. The Materials input wedges are slightly lower than both capital and labour inputs.

Table 2: Input wedges

	1970	1980	1985	Average
Capital	0.938	1.059	1.335	1.111
	(0.485)	(0.486)	(4.003)	(2.350)
Materials	0.846	0.952	0.957	0.918
	(0.193)	(0.105)	(0.105)	(0.149)
Labour	0.965	1.054	1.025	1.014
	(0.290)	(0.199)	(0.266)	(0.257)

Notes: This table presents average census input wedges and their standard deviations as estimated with the manufacturing data

All the wedges progressively increase in average over the census years, particularly the capital wedge whose average increased by almost 0.5 over the period relative to labour and materials that each increase by less than 0.1. Since capital has the lowest elasticity, the effect of such change in wedges on aggregate productivity is weighed down relative to materials and labour. The distribution of input wedges shown in figure 4 and A.7 shows the distinction in the variation of capital, labour and material wedges. Capital has the widest distribution across the country which is indicative of wide gaps in access to capital and its respective constraints in the Apartheid economy. Labour had a slightly wider but bimodal wedge distribution and Materials have the smallest variation of the three wedges. The distribution of the wedges in figure A.7 also shows the relative narrowing of the variation of input wedges of the period for all the inputs.

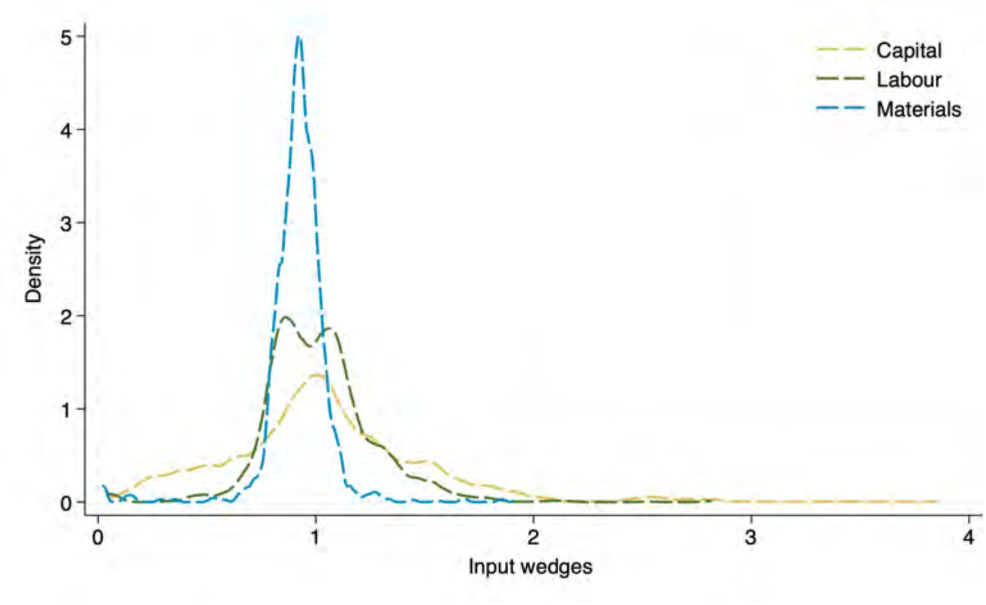


Figure 4: Distribution of input wedges

Note: This figure present the distribution of input wedges for all inputs across all district years and for the respective inputs in the respective census years. Industry wedges in each district-year are estimated from revenues and costs of inputs in the manufacturing census data for 1970, 1980 and 1985

The market distortions reflected by theses positive wedges could include markups, capital and/or credit constraints or labour frictions. In the Apartheid case, restrictions on the movement and settlement of labour created frictions that significantly contribute to these market distortions.

5.1.2 Distortions and Aggregate productivity

The production function for each district in given by a Cobb-Douglas function of capital, labour and materials

$$Y_{dt} = \prod_{\nu} \mathcal{A}_{dt} \mathcal{I}_{\nu dt}^{\alpha_{\nu d}} \tag{5}$$

Where Y_{dt} is manufacturing output for district d in year t, $\mathcal{A}_{dt}$ is the technical progress for the respective distict-year and $\mathcal{I}_{\nu dt}^{\alpha_{\nu d}}$ are the inputs in production with their respective shares in production. Different districts can thus have different shares of the inputs in production as well as different production technology.

With the three factors of production in this function, I can define distortions that affect their respective marginal products as τ_{ν}. These can account for credit or capital restrictions, mobility constraints or transportation costs, subsidies and access to markets. Following

Hornbeck and Rotemberg (2024), a district's aggregate productivity is defined from total revenue, net of input costs

$$\mathscr{Pr}_d = \mathscr{R}_d - \sum_{\nu}(1-\tau_{d\nu})\Xi_d^{\nu} \tag{6}$$

Where the presence of input specific distortions in the respective districts has a negative effect on its aggregate productivity $\mathscr{Pr}_d$. I can henceforth assess how upgrades to the rail infrastructure affects aggregate productivity. Consider log of productivity in equation 6. The marginal effect of rail upgrades on productivity $\left(\frac{\partial \ln \mathscr{Pr}_d}{\partial \mathscr{U}_d}\right)$ in district d is expressed as a function of the log of revenue and input expenditures:

$$\begin{aligned}
\frac{\partial \ln \mathscr{Pr}_d}{\partial \mathscr{U}_d} &= \frac{\mathscr{R}_d}{\mathscr{Pr}_d}\left[\frac{\partial \ln \mathscr{R}_d}{\partial \mathscr{U}_d} - \sum_{\nu}\frac{\Xi_d^{\nu}}{\mathscr{R}_d}\frac{(1-\tau_{d\nu})\partial \ln \Xi_d^{\nu} - \tau'_{d\nu}}{\partial \mathscr{U}_d}\right] \\
&= \phi_d\left[\frac{\partial \ln \mathscr{R}_d}{\partial \mathscr{U}_d} - \sum_{\nu}\mathscr{s}_d^{\nu}\frac{(1-\tau_{d\nu})\partial \ln \Xi_d^{\nu} - \tau'_{d\nu}}{\partial \mathscr{U}_d}\right] && (7) \\
&= \phi_d\left[\frac{\partial \ln \mathscr{R}_d}{\partial \mathscr{U}_d} - \sum_{\nu}\alpha_d^{\nu}\frac{\partial \ln \Xi_d^{\nu}}{\partial \mathscr{U}_d}\right] && \text{TFPR} \\
&\quad + \phi_d\left[\sum_{\nu}(\alpha_d^{\nu} - \mathscr{s}_d^{\nu})\frac{\partial \ln \Xi_d^{\nu}}{\partial \mathscr{U}_d} - \sum_{\nu}\mathscr{s}_d^{\nu}\frac{\tau_{d\nu}\partial \ln \Xi_d^{\nu} + \tau'_{d\nu}}{\partial \mathscr{U}_d}\right] && \text{AE} \qquad (8)
\end{aligned}$$

Where $\phi_d = \frac{\mathscr{R}_d}{\mathscr{Pr}_d}$ is the ratio of district revenue to its productivity, which gives in this case scales growth in revenue into growth in productivity. $\mathscr{s}_d^{\nu} = \frac{\Xi_d^{\nu}}{\mathscr{R}_d}$ is the revenue share of the respective inputs in every district.

Equation 7 shows the expected change in aggregate productivity with respect to rail upgrades. A positive change reflects growth in aggregate productivity. However, in the presence of market distortions, this does not indicate the source of the growth in aggregate productivity. Aggregate productivity growth could either be a consequence of the change in input efficiency following the rail upgrade or it could be a consequence of re-allocation of miss-allocated inputs (Baqaee and Farhi, 2020).

To ascertain the source of change in aggregate productivity, Equation 8 shows decomposition of the impact of rail upgrades on aggregate productivity into impacts on Total Revenue Factor productivity (TFPR) and Allocative efficiency (AE). Appendix C.1 shows the details of how this decomposition is derived. As in Petrin and Levinsohn (2012) I derive meaning from production function elasticities for the decomposition; adding and subtracting the term $\sum_{\nu} \alpha_d^{\nu} \frac{(1-\tau_{d\nu})\partial \ln \Xi_d^{\nu} - \tau'_{d\nu}}{\partial \mathcal{U}_d}$ and rearranging. The resulting equation 8 shows marginal change in aggregate productivity from marginal changes in inputs due to rail upgrades in one part and from gains in marginal products from re-allocation.

The first part of the decomposition explains productivity in an ideal economy without distortions. Given that all input markets are perfect then revenue total factor productivity (TFPR) equals Total factor productivity (TFP; $\mathcal{A}_d$). The AE term in equation 8 would disappear since $\tau_{d\nu}$ would be zero and from neoclassical economic theory, input share of revenue would be equal to output elasticity ($\alpha_d^{\nu} = \mathscr{s}_d^{\nu}$). However, with distortions present in the market, AE presents the marginal impact of rail upgrade on aggregate productivity from re-allocation of inputs in the distorted economy. A positive distortion $\tau_{d\nu}$ reduces aggregate productivity with miss-allocation of inputs. I assume in this paper that $\tau_{d\nu}$ is a function of rail upgrades and therefore has a marginal change with respect to change in the state of the rail. Equation C.1 shows that a negative marginal change in the distortion will effectively contribute to growth in aggregate productivity by improving allocative efficiency.

I use the manufacturing census data to estimate the parameters in equation 8 and ascertain the source of productivity growth. I estimate the impact of raill upgrages on output, and the inputs as well as its impact on TFPR and allocative efficiency.

6 Estimation

To examine the effect of railway upgrades on productivity, I use a Callaway and Sant'Anna (2021) (CS) Difference in difference (DiD) estimation with the following specification: $\mathbb{1}$

$$y_d t = \theta_{dt} + \beta_G \mathcal{X} + \sum_{G}^{G-1} \gamma_t \mathcal{U} \mathbb{1}(G = t) + \sum_{G=0}^{G+1} \delta_G \mathcal{U} \mathbb{1}(G = t) + \epsilon_{dt} \tag{9}$$

y_{dt} is the outcome for district d in year t, which is expressed as a function of district by year fixed effects (θ_{dt}), district level controls ($\mathcal{X}_{\mathscr{d}}$) and the treatment ($\mathcal{U}$). The district level controls include, population density, urban status, distance to coast and distance to mines. δ_G is the coefficient of interest, measuring the treatment effect from period ($G = 0$) of treatment which in this case is 1980 up to 1985 ($G = 1$). γ_G is the treatment effect for the lead period which in this case is 1970 ($G = -1$). The estimation is done using districts that were previously already connected to the rail and subsequently received upgrades on a rolling basis.

A few data generation considerations informed this empirical strategy. Firstly. As shown in figures 3 and figures A.3 and A.2 in the appendix, the upgrade of the rails was a progressive roll out over the three census years. Thus the adoption of the treatment is staggered over time and space; once a district is connected to an upgraded rail they remain connected for the rest of the census period. The effect of a first connection if present, therefore changes in subsequent years and does not remain static. The districts that connect to the upgraded rails are also fundamentally heterogenous and the effect of connecting to an upgrade is likewise heterogenous across districts and time. These properties raise concerns of bias when using a two-way fixed effects estimator (TWFE) which is mainly suited for static and homogenous effects. The CS estimator, computes the average treatement effect of each treated cohort, with reference to either the not yet treated groups or the never treated. The overall ATT is estimated as an average of the group-time treatment effects.

7 Estimation Results

Table 3 and figure A.8 present the results from a CS estimation of equation 9 with manufacturing revenue and the respective input expenditures as outcomes. Table 3 shows the Average treatment effects of rail upgrade on these outcomes across the three cohorts. Similarly, figure A.8 shows the event study plot for the group time coefficients of the same outcomes with 95% confidence bands. The result shows that the districts that got connected to an upgraded railroad had their manufacturing revenue more than trippled over the three cohort years.

Table 3: Impact of Rail upgrades on output and inputs

	(1) Output	(2) Capital	(3) Materials	(4) Labour
ATT	3.85**	3.99**	3.93**	4.04**
	(1.38)	(1.36)	(1.39)	(1.37)
H0: Parallel trends				
Chi-square	0.1372	0.0277	0.0010	0.0128
P-Value	0.7110	0.8679	0.9750	0.9100

Notes: This table presents average treatment effects of rail upgrades on South Africa's manufacturing output and input expenditures over the period 1970-1985. The coefficients were estimated using the Callaway and Sant'Anna (2021) estimator with inverse probability weighting and "not yet" treated as the control group. There are three treated cohorts (1970, 1980 and 1985). Of these three, 1970 is always treated and therefore not included. Only districts that were previously connected to the rail network are included in the estimation. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, Standard errors in parentheses.

Figure 5 presents the same estimation for productivity. The figure presents a plot of event study coefficients for the impact of rail upgrades on productivity. The estimation ensures conditional parallel trends by controlling for population density, distance to coast, distance to mines and urban status. The test for parallel trends as shown in table B.2, does not reject the null hypothesis of parallel trends in all the outcomes presented in the figure. There are three treated cohorts in the data, of which 1970 is always treated and therefore excluded from the estimation. The treatment effects for the connected districts are relative to not yet treated districts.

The results in figure 5 and table B.2 present a decomposition of the impact of rail upgrades on aggregate productivity into impact on TFPR and allocative efficiency. As shown in the figure and table, the estimated impact on aggregate productivity is mostly driven by the impact of the upgrades on allocative efficiency and much less by TFPR. The marginal change in Allocative efficiency contributes 78% of the change in aggregate productivity while change in technical efficiency contributes 22%. This suggests that connecting to upgrade railroads had a re-allocative effect on the prevailing distortions which drove aggregate productivity growth.

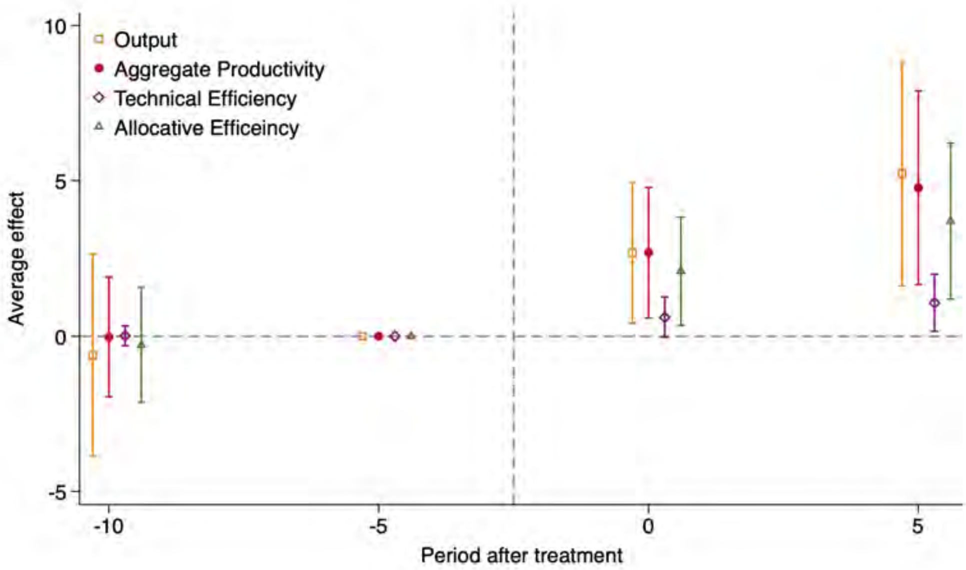


Figure 5: Impact of Rail upgrades on productivity

*Note:*This figure presents an event study plot of coefficients for the effect of rail upgrades on productivity. The coefficients were estimated using the Callaway and Sant'Anna (2021) estimator with inverse probability weighting and "not yet" treated as the control group. Controls included for conditional parallel trends include population density, urban status, distance to coast and distance to mines. There are three treated cohorts (1970, 1980 and 1985). Of these three, 1970 is always treated and therefore not included. Only districts that were previously connected to the rail network are included in the estimation. The figure shows a decomposition of the effect on aggregate productivity into impact on TFPR and on AE. The bars represent a 95% confidence interval around the coefficients. P-values for pretrend tests are (0.711, 0.9783, 0.9240, 0.7614) respectively

8 Mechanism

In this section, I explore the pathway of the effect of rail upgrades on aggregate productivity, mainly through changes in allocative efficiency. I examine the role of influx control during this period, acknowledging its segregative objective and explore how railroads that were serving to facilitate the segregation relaxed the policy's distortionary effects. Pirie (1993) and Baffi (2014) discuss how railraods during the apartheid era played an important role for both inter- and intra-urban segregation of non-white workers. It was a tool that facilitated segregation. The growing industrial and white surburb areas were restricted for non-whites; they however needed a supply of labour into these locations. At the intra-city level, townships were established in areas that had a rail connection to facilitate the movement of black labour to industry (Baffi, 2014). Thus railways aided in enforcing segregation and expansion of urban areas at the same time. At the inter-city level for example, some workers were segregated either in dormitories at industrial locations or in their homelands. Periodic commutes by train were arranged to allow movement of labour into compounds (Pirie, 1993).

Trains during Apartheid became a mode of transport for segregated communities. After democratisation of motorcars in South Africa, access to motorcars became part of the white culture and consequently the use of trains by first class passengers declined overtime while the 3rd class passenger use of trains grew (see figure 1). This suggests that the reduced cost and increased speed of upgraded railways during apartheid, benefited the segregated communities in accessing industrial jobs while at the same time allowing for segregation in expanding urban areas. Effectively the marginal representation of black workers in industrial and urban locations increased and essentially affected the costs of production, allocation of inputs and productivity.

To assess this causal channel for rail upgrades on productivity, I compute a location quotient $\mathscr{L}\mathscr{Q}$ statistic for each district to estimate the level of geographic representation of a race group in that district. LQ is expressed as:

$$\mathscr{L}\mathscr{Q}_{dr} = \frac{\sum_d \mathscr{P}_d}{\mathscr{P}_d}\left[\frac{\mathscr{P}_{dr}}{\sum_r \mathscr{P}_r}\right] \tag{10}$$

Where $\mathscr{L}\mathscr{Q}_{dr}$ is the location quotient for race r in district or region d which is given by the proportion of that race group in the district weighted by the inverse fraction of the district population in the country. Thus $\mathscr{P}_{dr}$ is the population of race r in district d, while $\mathscr{P}_d$ population of a district d and $\mathscr{P}_r$ the population of a race group nationwide. If $\mathscr{L}\mathscr{Q}_{\mathscr{dr}} > 1$ for blacks in district d then they are over-represented in that district or region and if $\mathscr{L}\mathscr{Q}_{\mathscr{dr}} > 1$ for blacks then they are under-represented. For a more intuitive interpretation of the location quotient, I focus on urban statistic for each district which gives an indication of the level of representation of blacks in the urban and industrial areas. I use $\mathscr{L}\mathscr{Q}$ to test if the rail upgrades had an effect in the dynamics of labour. I also check if there is a rail upgrade effect, net of the effect on $\mathscr{L}\mathscr{Q}$ as well as asses the relationship between $\mathscr{L}\mathscr{Q}$ and productivity.

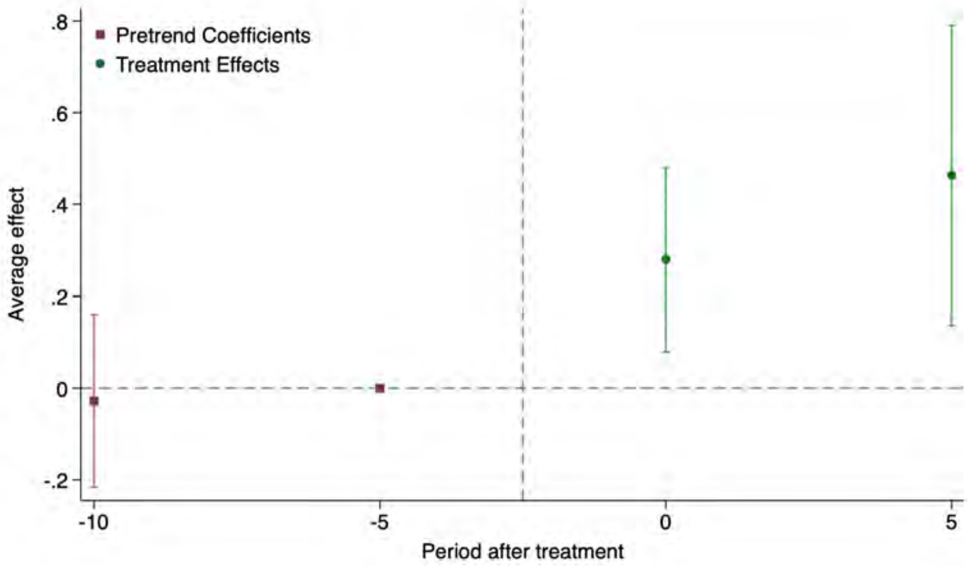


Figure 6: Impact of Rail upgrades on productivity

*Note:*This figure presents an event study plot of coefficients for the effect of rail upgrades on Location quotient. The coefficients were estimated using the Callaway and Sant'Anna (2021) estimator with inverse probability weighting and "not yet" treated as the control group. Controls included for conditional parallel trends include population density, urban status, distance to coast and distance to mines. There are three treated cohorts (1970, 1980 and 1985). Of these three, 1970 is always treated and therefore not included. Only districts that were previously connected to the rail network are included in the estimation. The bars represent a 95% confidence interval around the coefficients. P-values for pre-trend tests are (0.711) respectively

Figure 6 show the event plot of coefficients for the effect of railroad upgrade on $\mathscr{L}\mathscr{Q}$ for blacks in urban locations across the country. These are results from a similar DID estimation in equation 9 with the Callaway and Sant'Anna (2021) estimator. The results show that that the representativeness of the black population in urban locations was positively affected in districts that connected to an upgraded rail. Table 4 further shows results a fixed effects estimation of the relationship between $\mathscr{L}\mathscr{Q}$ and productivity as well as input wedges in production. This is to examine if $\mathscr{L}\mathscr{Q}$ has a significant effect on productivity and its components as well as its systematic effect on the inputs in production.

Table 4: Effect of segregation on productivity and input distortions

	(1)	(2)	(3)	(4)	(5)
	AE	TFPR	Capital Wedges	Labour Wedges	Materials Wedges
$\mathscr{LQ}_{db}$	1.172**	0.066	-0.262	-0.081*	-0.057**
	(0.348)	(0.140)	(0.639)	(0.042)	(0.027)
district FE	Y	Y	Y	Y	Y
year FE	Y	Y	Y	Y	Y
Controls	Y	Y	Y	Y	Y

Notes: This table presents results of a Fixed Effects regression of the productivity components (TFPR and AE) and input wedges on the segregation statistic ($\mathscr{LQ}_d^b$). Both year and district fixed effects are controlled for including controls for population density, urban status, distance to coast and distance to the nearest mine. Columns 1 and 2 present the marginal change in Allocative Efficiency and TFPR respectively, given a change in Location Quotient. Columns 2, 3 and 4 present the same effect for capital, labour and materials wedges. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.05$, Standard errors in parentheses.

The result in table 4 shows that an increase in $\mathscr{LQ}$ can be associated with a significant change in allocative efficiency but not as significant a relationship with technical efficiency. Given that levels of segregation are a causal pathway of the effect of rail upgrades on aggregate productivity, this result gives an indication of why the effect of upgrades on TFPR from the results in 5 is less, relative to its effect on AE. Figure 7 also shows the effect of rail upgrades on TFPR and AE (solid lines) in comparison to the same effect, net of the effect of the segregation measure ($\mathscr{LQ}$) (dotted lines). The figure indicates how TFPR is relatively less affected by the marginal change in $\mathscr{LQ}$ in response to rail upgrades as much as magnitude of the effect on AE. The significant effect on AE is accounted for by $\mathscr{LQ}$ while that is not the case with TFPR.

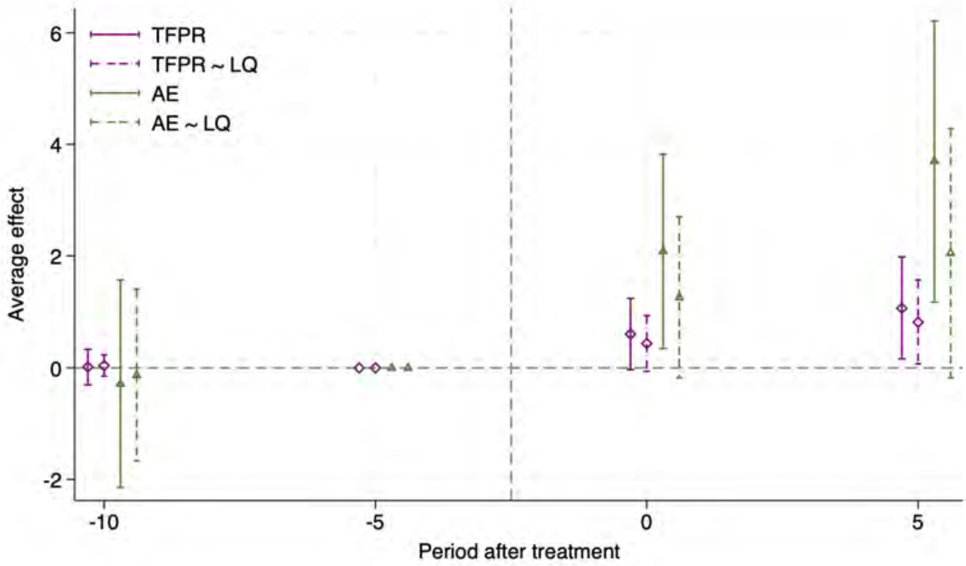


Figure 7: Impact of Rail upgrades on productivity

Note: This figure presents an event study plot of coefficients for the effect of rail upgrades on TFPR and AE, net of the effect on segregation (LQ). The coefficients were estimated using the Callaway and Sant'Anna (2021) estimator with inverse probability weighting and "not yet" treated as the control group. Controls included for conditional parallel trends include population density, urban status, distance to coast and distance to mines. There are three treated cohorts (1970, 1980 and 1985). Of these three, 1970 is always treated and therefore not included. Only districts that were previously connected to the rail network are included in the estimation. The figure shows the effect of railroad upgrades on TFPR and AE (solid lines) and the same effect net the effect on segregation measure (LQ) (dotted lines). The bars represent a 95% confidence interval around the coefficients. P-values for pretrend tests are (0.711) respectively

This suggests that the rail upgrades affected the growth in aggregate productivity through its effect on the dynamics of segregation which in turn forced a reallocation of resources to increase productivity. Columns 1-3 in table 4 show the relationship between the segregation measure and input wedges. A marginal increase in $\mathscr{LQ}$ is associated with a small significant reduction in labour and materials wedges. There is no significant reduction in the capital wedges. This further underscores the importance of labour market distortions in explaining productivity during Apartheid.

9 Conclusion

The paper explores the implications of Apartheid policy and infrastructure development on productivity in the manufacturing sector. I analyse the impact that railway upgrades had on aggregate productivity in South Africa's manufacturing during apartheid. In particular, I examine the relationship between geographical segregative policies by the apartheid government and distortions in the manufacturing sector and how rail upgrades during this period affected both segregation and consequently aggregate productivity.

I use maiden regional manufacturing data, digitised from manufacturing censuses to construct a manufacturing census data set for years 1970, 1980 and 1985. I use this data to estimate district production functions for the respective census years and identify the existence of distortions in the market. I also construct I also consult South Africa railways and harbours reports digitise and geocode maps that detailed the progress of rail upgrades from steam to diesel and electric operated vehicle rail lines in the corresponding census years. I use the rail upgrades as the treatment variable.

I estimate a staggered difference in difference model for the effect of the rail upgrades on aggregate in apartheid South Africa on aggregate productivity. I find significant effect of rail upgrades on aggregate productivity. Districts the connected to upgraded rails were more productive. The sources of the productivity growth has been shown to be allocative efficiency gains from re-allocation of labour due to low cost rail transport.

References

Arup (2012). Report on the relative comparison of the technical and operational efficiencies between electric and diesel-electric traction, *Queensland Rail National Network* .

Atack, J., Bateman, F., Haines, M. and Margo, R. A. (2010). Did Railroads Induce or Follow Economic Growth?: Urbanization and Population Growth in the American Midwest, 1850–1860, *Social Science History* **34**(2): 171–197.

Atack, J. and Margo, R. A. (2011). The Impact of Access to Rail Transportation on Agricultural Improvement: The American Midwest as a Test Case, 1850-1860, *Journal of Transport and Land Use* **4**(2).

Baffi, S. (2014). Railroads to civilization:The railroad in South Africa's territorial policies, *L'Espace géographique* **43**(4): 338–355.

Bai, Y., Jin, K. and Lu, D. (2024). Misallocation under Trade Liberalization, *American Economic Review* **114**(7): 1949–1985.

Banerjee, A., Duflo, E. and Qian, N. (2020). On the road: Access to transportation infrastructure and economic growth in China, *Journal of Development Economics* **145**(C).

Banerjee, A. V. and Duflo, E. (2005). Chapter 7 Growth Theory through the Lens of Development Economics, *in* P. Aghion and S. N. Durlauf (eds), *Handbook of Economic Growth*, Vol. 1, Elsevier, pp. 473–552.

Baqaee, D. R. and Farhi, E. (2020). Productivity and Misallocation in General Equilibrium, *The Quarterly Journal of Economics* **135**(1): 105–163.

Basu, P. (2006). Understanding Labour Market Frictions: A Tobin's Q Approach, *CDMA Conference Paper Series* (0601).

Baum-Snow, N., Brandt, L., Henderson, J. V., Turner, M. A. and Zhang, Q. (2017). Roads, Railroads, and Decentralization of Chinese Cities, *The Review of Economics and Statistics* **99**(3): 435–448.

Becker, G. S. (1971). *The Economics of Discrimination*, Economic Research Studies, University of Chicago Press, Chicago, IL.

Bilal, A., Engbom, N., Mongey, S. and Violante, G. L. (2021). Labor Market Dynamics When Ideas are Harder to Find.

Bilal, A., Engbom, N., Mongey, S. and Violante, G. L. (2022). Firm and Worker Dynamics in a Frictional Labor Market, *Econometrica* **90**(4): 1425–1462.

Callaway, B. and Sant'Anna, P. H. C. (2021). Difference-in-Differences with multiple time periods, *Journal of Econometrics* **225**(2): 200–230.

Charles, K. K. and Guryan, J. (2008). Prejudice and Wages: An Empirical Assessment of Becker's The Economics of Discrimination, *Journal of Political Economy* **116**(5): 773–809.

Davies, R. (1981). The Spatial Formation of the South African City, *GeoJournal* pp. 59–72.

Donaldson, D. and Hornbeck, R. (2016). Railroads and American Economic Growth: A "Market Access" Approach *, *The Quarterly Journal of Economics* **131**(2): 799–858.

Eckert, F., Gvirtz, A., Liang, J. and Peters, M. (2020). A Method to Construct Geographical Crosswalks with an Application to US Counties since 1790.

Elsby, M. W. L. and Gottfries, A. (2022). Firm Dynamics, On-the-Job Search, and Labor Market Fluctuations, *The Review of Economic Studies* **89**(3): 1370–1419.

Feinstein, C. H. (2005). *An Economic History of South Africa: Conquest, Discrimination, and Development*, Cambridge University Press, Cambridge.

Ferrara, A., , Patrick A., T. and and Zhou, L. (2024). New area- and population-based geographic crosswalks for U.S. counties and congressional districts, 1790–2020, *Historical Methods: A Journal of Quantitative and Interdisciplinary History* **57**(2): 67–79.

Fogel, R. W. (1964). *Railroads and American Economic Growth: Essays in Econometric History*, Johns Hopkins Press.

Fourie, J. and Herranz-Loncán, A. (2015). Growth (and Segregation) by Rail: How the Railways Shaped Colonial South Africa, *Research Papers in Economics* .

Hazlett, T. W. (1988). ECONOMIC ORIGINS OF APARTHEID, *Contemporary Economic Policy* **6**(4): 85–104.

Hirata, G. and Soares, R. R. (2016). Competition and the Racial Wage Gap: Testing Becker's Model of Employer Discrimination, *Working Paper 9764*, IZA Discussion Papers.

Hornbeck, R. (2010). Barbed Wire: Property Rights and Agricultural Development, *The Quarterly Journal of Economics* **125**(2): 767–810.

Hornbeck, R. and Rotemberg, M. (2024). Growth Off the Rails: Aggregate Productivity Growth in Distorted Economies, *Journal of Political Economy* .

Hornung, E. (2015). Railroads and Growth in Prussia, *Journal of the European Economic Association* **13**(4): 699–736.

Horrell, M. (1969). *South Africa's Workers: Their Organizations and the Patterns of Employment*, South African Institute of Race Relations, Johannesburg.

Hsieh, C.-T. and Klenow, P. J. (2009). Misallocation and Manufacturing TFP in China and India, *The Quarterly Journal of Economics* **124**(4): 1403–1448.

Hsieh, C.-T. and Moretti, E. (2019). Housing Constraints and Spatial Misallocation, *American Economic Journal: Macroeconomics* **11**(2): 1–39.

Jedwab, R., Kerby, E. and Moradi, A. (2017). History, Path Dependence and Development: Evidence from Colonial Railways, Settlers and Cities in Kenya, *The Economic Journal* **127**(603): 1467–1494.

Jedwab, R. and Moradi, A. (2016). The Permanent Effects of Transportation Revolutions in Poor Countries: Evidence from Africa, *The Review of Economics and Statistics* **98**(2): 268–284.

Khandelwal, A. K., Schott, P. K. and Wei, S.-J. (2013). Trade Liberalization and Embedded Institutional Reform: Evidence from Chinese Exporters, *American Economic Review* **103**(6): 2169–2195.

Levinsohn, J. and Petrin, A. (2003). Estimating Production Functions Using Inputs to Control for Unobservables, *The Review of Economic Studies* **70**(2): 317–341.

Liao, Y., Gil, J., Yeh, S., Pereira, R. H. M. and Alessandretti, L. (2025). Socio-spatial segregation and human mobility: A review of empirical evidence, *Computers, Environment and Urban Systems* **117**: 102250.

Lin, W. and Si'ao, L. (2025). Economic Growth in South Africa under Apartheid: Drivers and Consequences of Institutionalized Inequality, *Open Access Library Journal* **12**(3): 1–10.

Lipton, M. (1985). *Capitalism and Apartheid: South Africa, 1910-1985*, Gower, Aldershot.

Liu, S., Ma, S., Yin, L. and Zhu, J. (2023). Land titling, human capital misallocation, and agricultural productivity in China, *Journal of Development Economics* **165**: 103165.

Mariotti, M. (2012a). Estimating the Substitutability of African and White Workers in South African Manufacturing, 1950–1985, *Economic History of Developing Regions* **27**(2): 47–60.

Mariotti, M. (2012b). Labour markets during apartheid in South Africa, *The Economic History Review* **65**(3): 1100–1122.

Ogura, M. (1996). Urbanization and apartheid in South Africa: Influx controls and their abolition, *The Developing Economies* **34**(4): 402–423.

Olley, G. S. and Pakes, A. (1996). The Dynamics of Productivity in the Telecommunications Equipment Industry, *Econometrica* **64**(6): 1263–1297.

Petrin, A. and Levinsohn, J. (2012). Measuring aggregate productivity growth using plant-level data, *The RAND Journal of Economics* **43**(4): 705–725.

Pienaar, W., de Bod, A. and Havenga, J. H. (2012). Economies of density in rail freight transport: Potential for utilisation in Southern Africa, *Journal of Governance and Regulation* .

Pienaar, W. J. (2012). The innovative use of the corridor concept to enhance the performance of transport operations, *Journal of Transport and Supply Chain Management* **6**(1): 1–12.

Pirie, G. H. (1993). Railway Ganging in Southern Africa, c. 1900–37, *The Journal of Transport History* **14**(1): 64–76.

Restuccia, D. and Rogerson, R. (2008). Policy distortions and aggregate productivity with heterogeneous establishments, *Review of Economic Dynamics* **11**(4): 707–720.

Restuccia, D. and Rogerson, R. (2013). Misallocation and productivity, *Review of Economic Dynamics* **16**(1): 1–10.

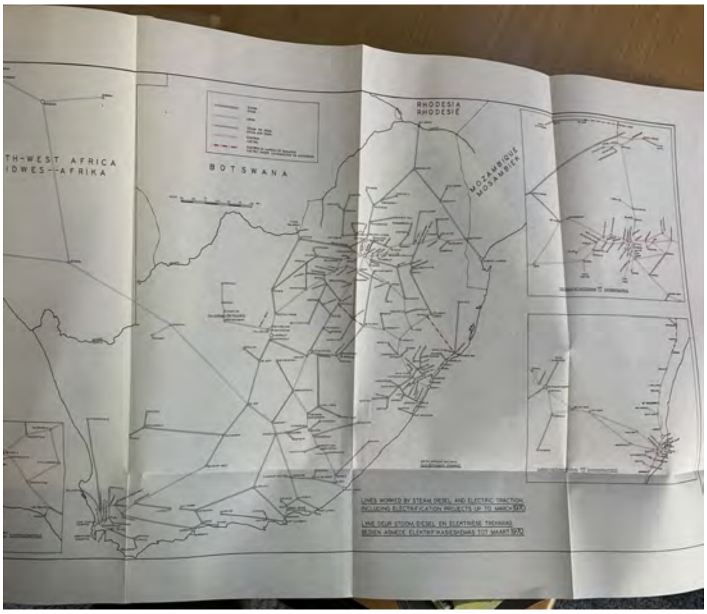
South Africa National Geo-spatial Information (2016). Railroads, South Africa.

Stander, H. J. and Pienaar, W. J. (2002). Perspectives on freight movement by road and rail in South Africa, *SATC 2002* .

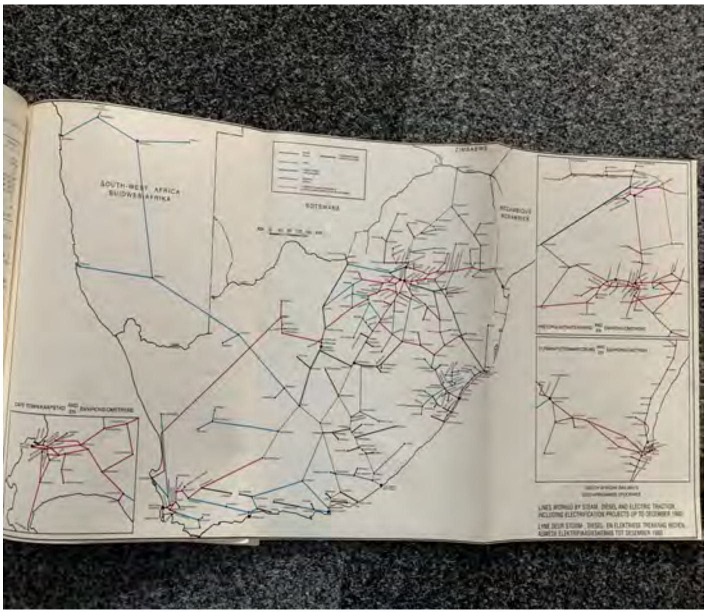
Tombe, T. and Zhu, X. (2019). Trade, Migration, and Productivity: A Quantitative Analysis of China, *American Economic Review* **109**(5): 1843–1872.

Yasuda, H. (2023). Employers' stereotypes and taste-based discrimination, *Journal of the Japanese and International Economies* **67**: 101240.

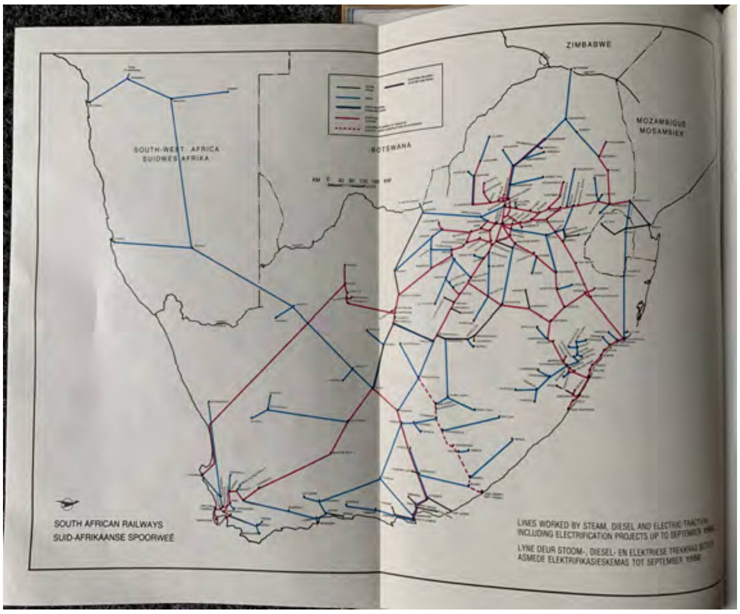
A Figures



(a) Map of rail upgrades up to 1970



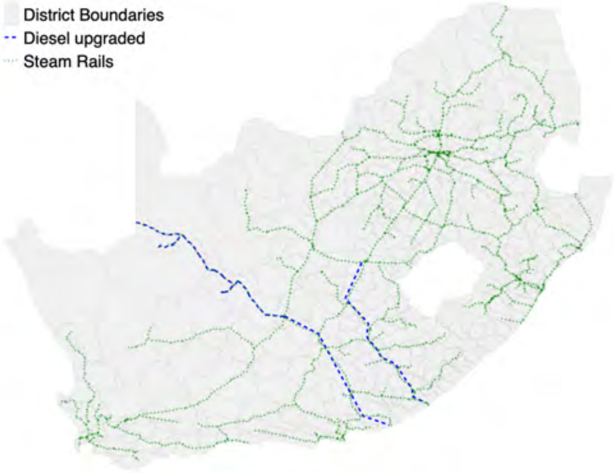
(b) Map of rail upgrades up to 1980



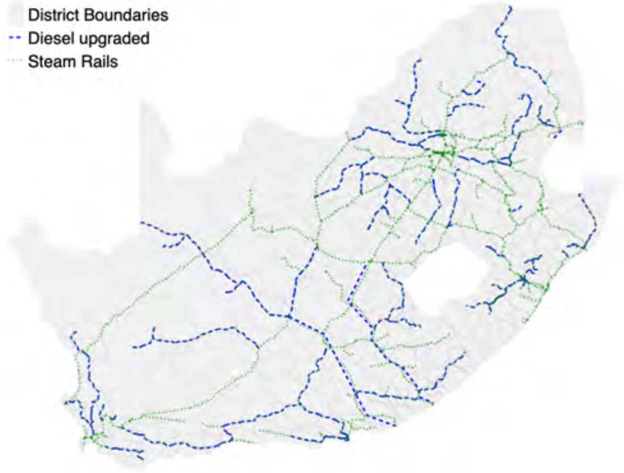
(c) Map of rail upgrades up to 1985

Figure A.1: Archive records of rail improvements during apartheid South Africa (Referred on page 13)

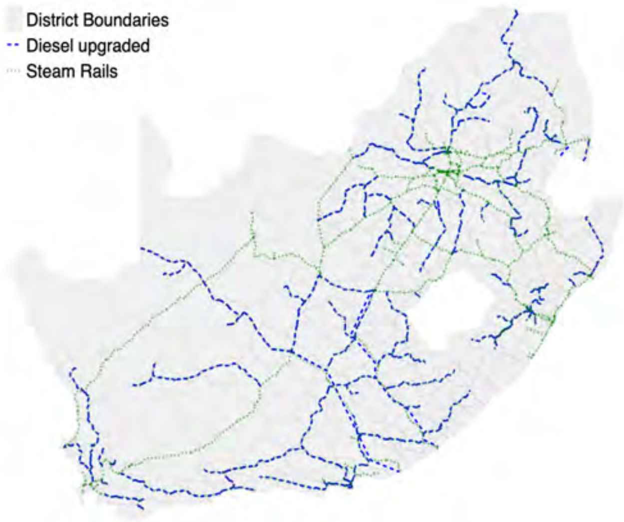
Note: Figures (a) to (c) present archival pictures showing the state of improvement of the rail lines up to the year of the manufacturing censuses consulted in this paper. The figures depict which rail lines had been fully upgraded to carry diesel or electric vehicles as well as the ones under development. While most of the improvements were from Steam carriers to either diesel of electric, it can be noticed in panels (b) and (c) that some diesel carriers eventually upgraded to electric carriers. The red lines indicate rail lines that were upgraded to electric carriers, the blue lines denoting diesel upgrade while doted lines indicated that upgrade was underway.



(a) 1970



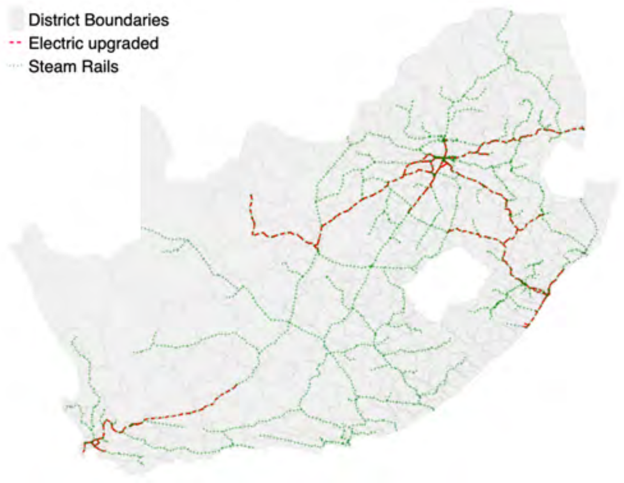
(b) 1980



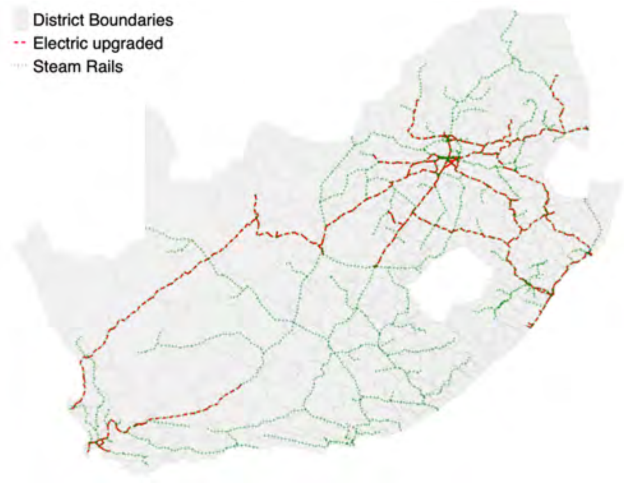
(c) 1985

Figure A.2: Geocoded and digitised state of rail improvements for diesel carriers (Referred on page 13)

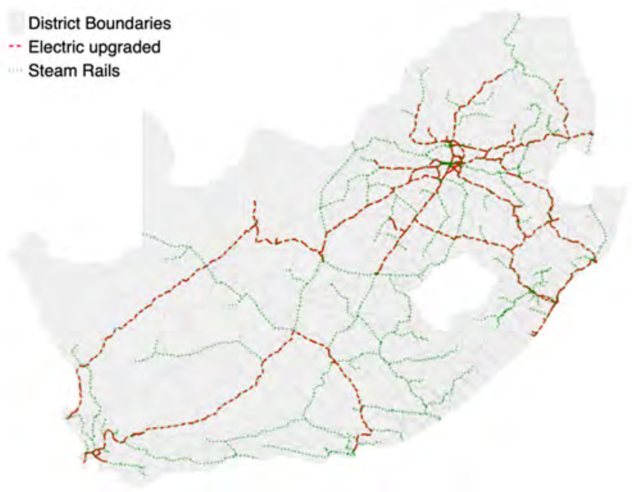
Note: The figure presents a plot of the state of the railroads in the manufacturing census years of 1970, 1980 and 1985. This figure depicts the progression of the improvement of the railroad network from steam to diesel as at these census years. The blue lines represent the lines that were fully upgraded to diesel carriers by the respective year while the green lines represent steam rail carriers.



(a) Map of electric upgrades up to 1970



(b) Map of electric upgrades up to 1980



(c) Map of electric upgrades up to 1985

Figure A.3: Geocoded and digitised state of rail improvements for electric carriers (Referred on page 13)

Note: The figure presents a plot of the state of the railroads in the manufacturing census years of 1970, 1980 and 1985. This figure depicts the progression of the improvement of the railroad network from steam to electric as at these census years. The red lines represent the lines that were fully upgraded to electric carriers by the respective year while the green lines represent steam rail carriers.

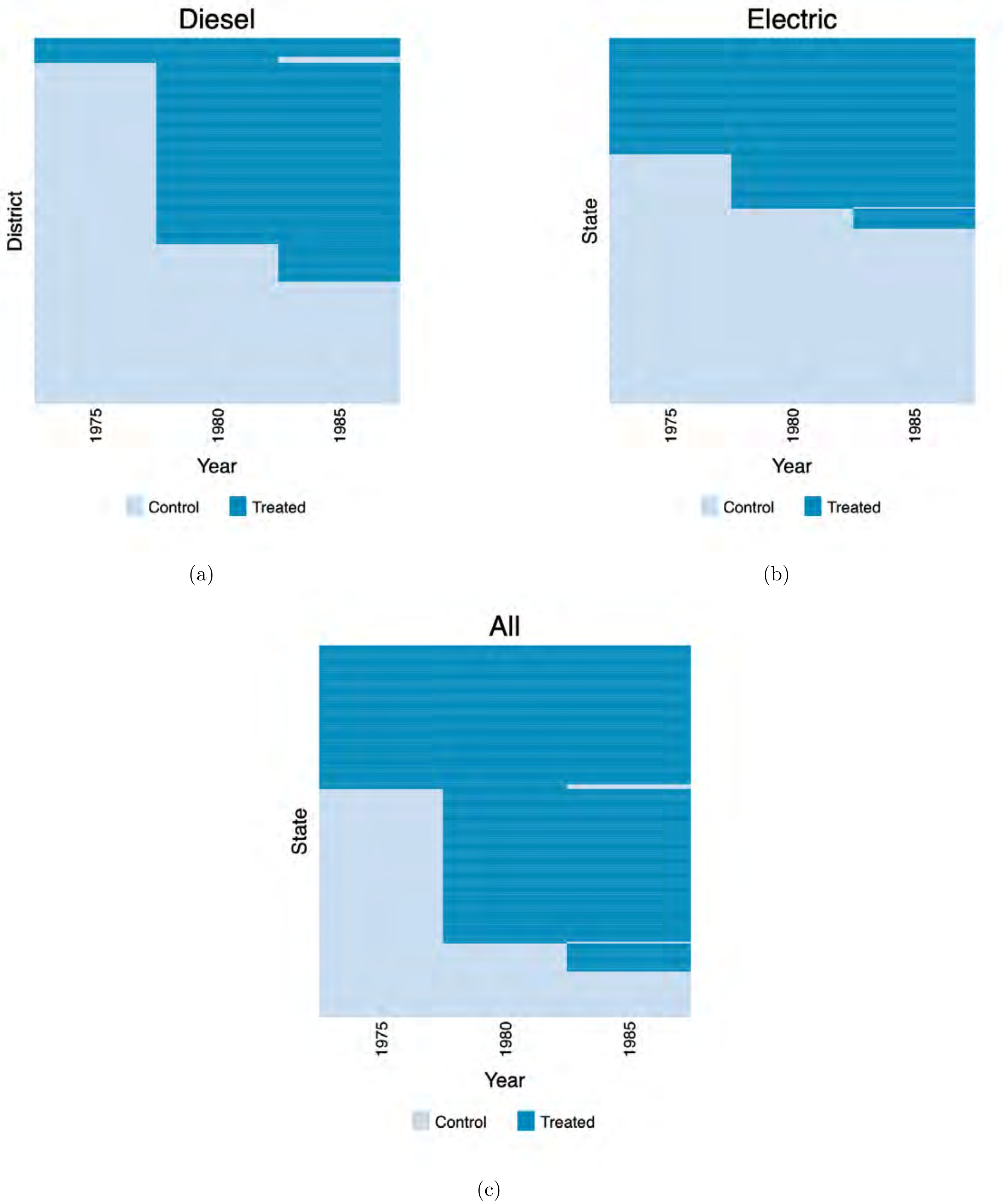
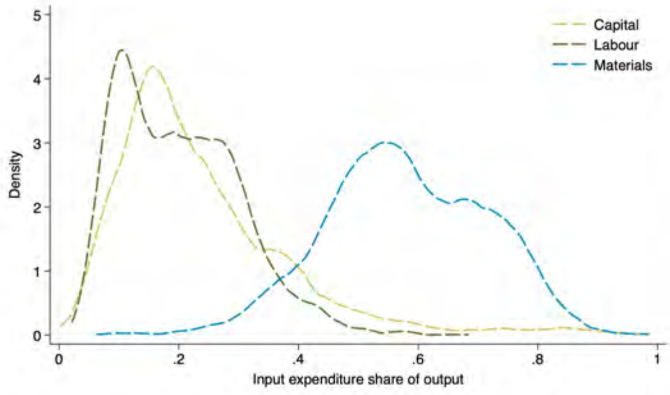
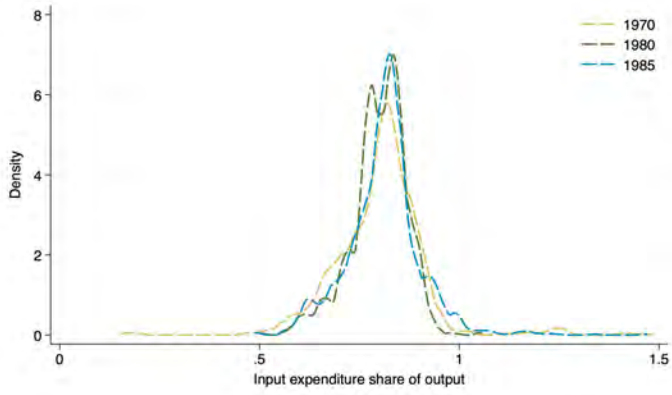


Figure A.4: Adoption of treatment by the districts over the census years (Ref: page 13)

Note: The three panels depict the districts connected to the upgraded rails. Panel (a) shows the progression of diesel rail upgrades, panel (b) for electric and panel (c) for both. Earlier upgrades were mostly electric and most upgrades in the second period were diesel.



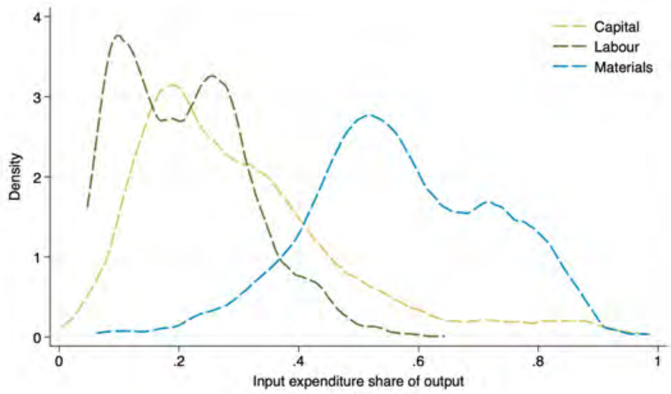
(a)



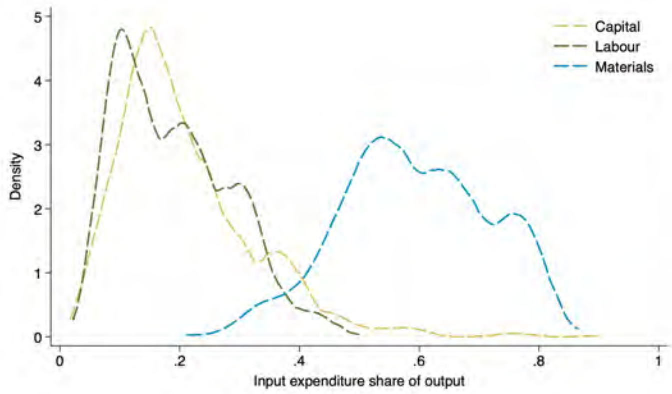
(b)

Figure A.5: Distribution of input expenditure share of revenue (Ref: page 16)

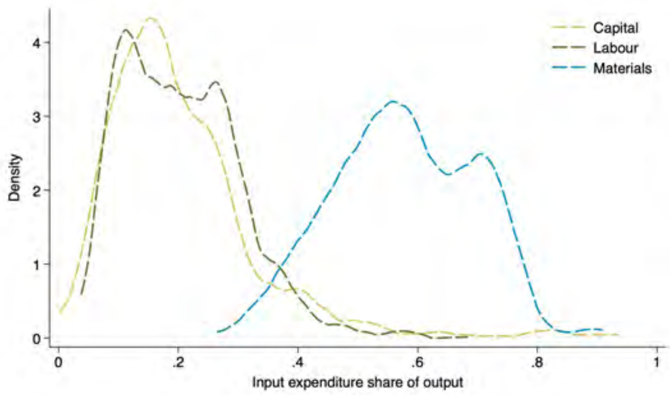
Note: This figure plots the costs of inputs in production as a share of total revenue. Panel (a) plots the revenue share for each input across all the three census years in the data while panel (b) plots the revenue share of the total cost of inputs for the respective years.



(a) 1970



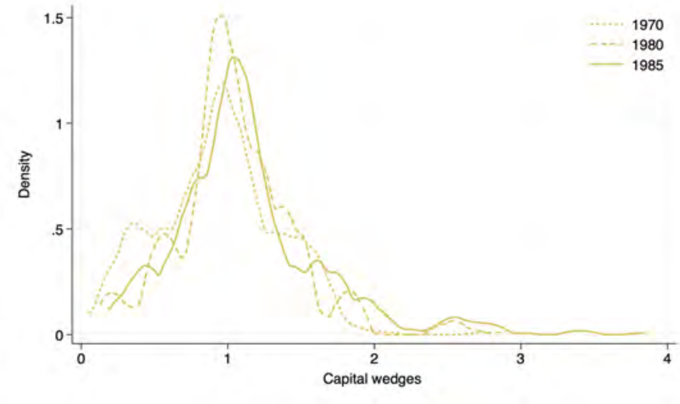
(b) 1980



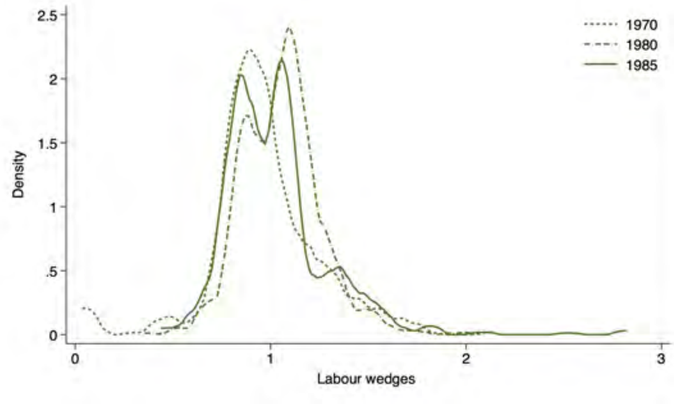
(c) 1985

Figure A.6: Distribution of input expenditure share of revenue (Ref: page 16)

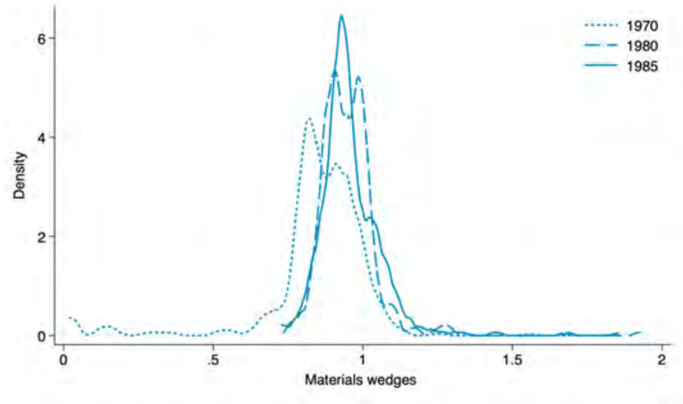
Note: This figure plots the costs of inputs in production as a share of total revenue. The respective panels plot the subject revenue share of the total cost of inputs for the respective subject years to shoe the changes in the distributions across the years.



(a) Capital



(b) Labour



(c) Materials

Figure A.7: Distribution of input wedges

*Note:*This figure present the distribution of input wedges for all inputs across all district years and for the respective inputs in the respective census years

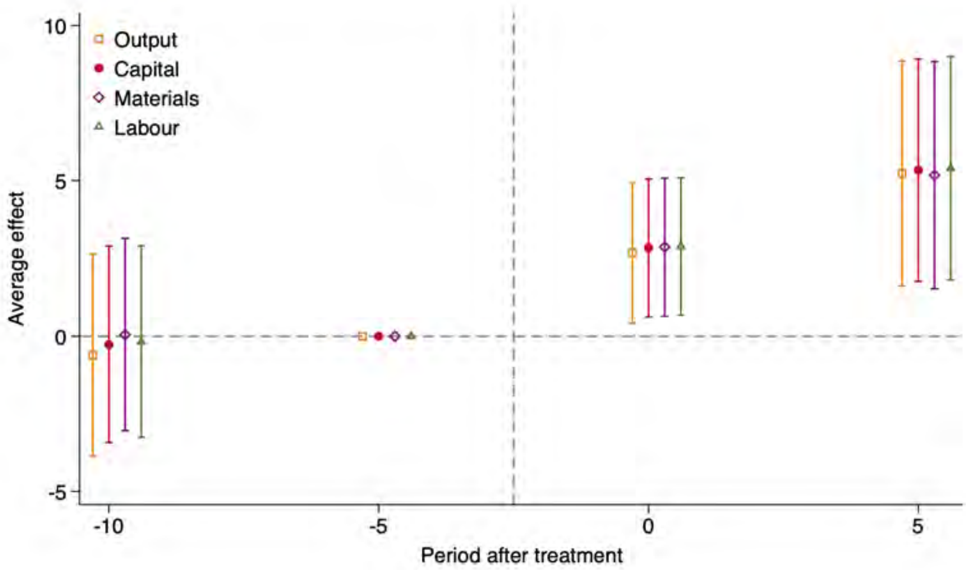


Figure A.8: Impact of Rail upgrades on output and inputs

Note: This figure presents an event study plot of coefficients for the effect of rail upgrades on Output and input expenditures. The coefficients were estimated using the Callaway and Sant'Anna (2021) estimator with inverse probability weighting and not yet treated as the control group. There are three treated cohorts (1970, 1980 and 1985). Of these three, 1970 is always treated and therefore not included. The bars show 95% confidence interval

B Tables

Table B.1: Industry classifications (as referred to in section 4.1)

1970	**1980 and 1985**
Major Group 1 - Food, excluding beverages	*Major Group* 1 - Food, excluding beverages
Major Group 2 - Beverage industries	*Major Group* 2 - Beverage industries
Major Group 3 - Tobacco	*Major Group* 3 - Tobacco
Major Group 4 - Textiles	*Major Group* 4 - Textiles
Major Group 5 - Clothing, footwear and made-up textile goods	*Major Group* 5 - Wearing apparel, except footwear
	Major Group 7 - Footwear
Major Group 6 - Wood and cork products, excluding furniture	*Major Group* 8 - Wood and cork products, excluding furniture
Major Group 7 - Furniture and fixtures	*Major Group* 9 - Furniture and fixtures, except primarily of metal
Major Group 8 - Paper and paper products	*Major Group* 10 - Paper and paper products
Major Group 9 - Printing, publishing and allied industries	*Major Group* 11 - Printing, publishing and allied industries
Major Group 10 - Leather and leather products	*Major Group* 6 - Leather and leather products excluding footwear and wearing apparel
Major Group 11 - Rubber products	*Major Group* 14 - Rubber products
Major Group 12 - Chemicals and chemical products	*Major Group* 12 - Industrial Chemicals
	Major Group 13 - Other chemical products
Major Group 13 - Non-metallic mineral products, excluding products of petroleum and coal	*Major Group* 18 - Other non-metallic mineral products
Major Group 14 - Basic metal industries	*Major Group* 19 - Iron and steel basic industries
	Major Group 20 - Non-Ferrous Metal Basic Industries
Major Group 15 - Metal products, excluding machinery and transport equipment	*Major Group* 21 - Fabricated Metal Products, except machinery and equipment
Major Group 16 - Machinery, excluding electrical machinery	*Major Group* 22 - Machinery except electrical
Major Group 17 - Electrical machinery, etc.	*Major Group* 23 - Electrical Machinery, apparatus, appliances and supplies
Major Group 18 - Transport equipment	*Major Group* 24 - Motor Vehicles, Parts and accessories
	Major Group 25 - Transport Equipment not elsewhere classified
Major Group 19 - Miscellaneous Industries	*Major Group* 15 - Plastic Products
	Major Group 16 - Pottery, China and earthenware
	Major Group 17- Glass and glass products
	Major Group 26- Professional and scientific and measuring and controlling equipment, and photographic and optical equipment
	Major Group 27- Other manufacturing industries

Notes: This table shows my mapping of industry classifications for the 1980 and 1985 manufacturing census data to 1970 the census industry classifications.

Table B.2: Impact of Rail upgrades on productivity

	(1) Output	(2) Aggregate	(3) TFPR	(4) AE
ATT	3.85^{**}	3.64^{**}	0.82^{*}	2.83^{**}
	(1.38)	(1.26)	(0.38)	(1.00)
H0: Parallel trends				
Chi-square	0.1372	0.0007	0.0091	0.0922
p-value	0.7110	0.9783	0.9240	0.7614

Notes: This table presents average treatment effects of rail upgrades on South Africa's manufacturing output and productivity over the period 1970-1985. The coefficients were estimated using the Callaway and Sant'Anna (2021) estimator with inverse probability weighting and "not yet" treated as the control group. Controls included for conditional parallel trends include population density, urban status, distance to coast and distance to mines. There are three treated cohorts (1970, 1980 and 1985). Of these three, 1970 is always treated and therefore not included. Only districts that were previously connected to the rail network are included in the estimation. The figure shows a decomposition of the effect on aggregate productivity into impact on TFPR and on AE. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, Standard errors in parentheses.

C Theory

C.1 Aggregate productivity decomposition

In this section, I describe the decomposition of aggregate productivity as presented by equation 8 in detail. This expresses the effect of rail upgrades on aggregate productivity as a sum of total revenue factor productivity and allocative efficiency. I basically log the aggregate productivity in equation 6 and express it as a partial derivative with respect to upgrade of the rail in district d.

$$\frac{\partial \ln \mathscr{P}r_d}{\partial \mathcal{U}_d} = \frac{\partial \ln(\mathscr{R}_d - \sum_\nu (1-\tau_{d\nu})\Xi_d^\nu)}{\partial \mathcal{U}_d} \tag{C.1}$$

$$\textit{Since } \frac{\partial \ln \mathscr{P}r_d}{\partial \mathcal{U}_d} = \frac{\partial \mathscr{P}r_d}{\mathscr{P}r_d} \textit{ then the above can be expressed as}$$

$$= \frac{1}{\mathscr{P}r_d}\left[\frac{\partial \mathscr{R}_d}{\partial \mathcal{U}_d} - \sum_\nu \frac{\partial(1-\tau_{d\nu})\Xi_d^\nu}{\partial \mathcal{U}_d}\right] \tag{C.2}$$

In equation C.2, it is clear that $\left(\partial \ln \mathscr{R}_d = \frac{\partial \mathscr{R}_d}{\mathscr{R}_d}\right)$ for the first term in [] brackets. I also assume for the summation term, that the distortion $\tau_{d\nu}$ is a function of the rail upgrade in district d. Therefore, $\partial(1-\tau_{d\nu})\Xi_d^\nu$ is differentiated using product rule and thus express line C.2 as:

$$\frac{\partial \ln \mathscr{P}r_d}{\partial \mathcal{U}_d} = \frac{1}{\mathscr{P}r_d}\left[\mathscr{R}_d \frac{\partial \ln \mathscr{R}_d}{\partial \mathcal{U}_d} - \sum_\nu \Xi_d^\nu \frac{(1-\tau_{d\nu})\partial \ln \Xi_d^\nu - \tau'_{d\nu}}{\partial \mathcal{U}_d}\right] \tag{C.3}$$

$$= \frac{\mathscr{R}_d}{\mathscr{P}r_d}\left[\frac{\partial \ln \mathscr{R}_d}{\partial \mathcal{U}_d} - \sum_\nu \frac{\Xi_d^\nu}{\mathscr{R}_d} \frac{(1-\tau_{d\nu})\partial \ln \Xi_d^\nu - \tau'_{d\nu}}{\partial \mathcal{U}_d}\right] \tag{C.4}$$

$$= \phi_d\left[\frac{\partial \ln \mathscr{R}_d}{\partial \mathcal{U}_d} - \sum_\nu s_d^\nu \frac{(1-\tau_{d\nu})\partial \ln \Xi_d^\nu - \tau'_{d\nu}}{\partial \mathcal{U}_d}\right] \tag{C.5}$$

Where $\phi_d = \frac{\mathscr{R}_d}{\mathscr{P}r_d}$ and $s_d^\nu = \frac{\Xi_d^\nu}{\mathscr{R}_d}$

Adding and subtracting the term $\sum_\nu \alpha_d^\nu \frac{(1-\tau_{d\nu})\partial \ln \Xi_d^\nu - \tau'_{d\nu}}{\partial \mathcal{U}_d}$

$$
\begin{aligned}
\frac{\partial \ln \mathscr{P}\mathfrak{r}_d}{\partial \mathcal{U}_d} &= \phi_d \left[\frac{\partial \ln \mathcal{R}_d}{\partial \mathcal{U}_d} - \sum_\nu \alpha_d^\nu \frac{(1-\tau_{d\nu})\partial \ln \Xi_d^\nu - \tau'_{d\nu}}{\partial \mathcal{U}_d} \right] \\
&\quad + \phi_d \left[\sum_\nu (\alpha_d^\nu - \mathcal{s}_d^\nu) \frac{(1-\tau_{d\nu})\partial \ln \Xi_d^\nu - \tau'_{d\nu}}{\partial \mathcal{U}_d} \right]
\end{aligned}
$$

Re-arranging ...

$$
\begin{aligned}
&= \phi_d \left[\frac{\partial \ln \mathcal{R}_d}{\partial \mathcal{U}_d} - \sum_\nu \alpha_d^\nu \frac{\partial \ln \Xi_d^\nu}{\partial \mathcal{U}_d} \right] && \text{TFPR} \\
&\quad + \phi_d \left[\sum_\nu (\alpha_d^\nu - \mathcal{s}_d^\nu) \frac{\partial \ln \Xi_d^\nu}{\partial \mathcal{U}_d} - \sum_\nu \mathcal{s}_d^\nu \frac{\tau_{d\nu}\partial \ln \Xi_d^\nu + \tau'_{d\nu}}{\partial \mathcal{U}_d} \right] && \text{AE} \qquad \text{(C.6)}
\end{aligned}
$$