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Railroads of the Raj: Estimating the Impact of Transportation Infrastructure

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Abstract

How large are the benefits of transportation infrastructure projects, and what explains these benefits? To shed new light on these questions, I collect archival data from colonial India and use it to estimate the impact of India's vast railroad network. Guided by six predictions from a general equilibrium trade model, I find that railroads: (1) decreased trade costs and interregional price gaps; (2) increased interregional and international trade; (3) eliminated the responsiveness of local prices to local productivity shocks (but increased the transmission of these shocks between regions); (4) increased the level of real income (but harmed neighboring regions without railroad access); (5) decreased the volatility of real income; and (6), a sufficient statistic for the effect of railroads on welfare in the model accounts for virtually all of the observed reduced-form impact of railroads on real income. I find similar results from an instrumental variable specification, no spurious effects from over 40,000 km of lines that were approved but never built, and tight bounds on the estimated impact of railroads. These results suggest that transportation infrastructure projects can improve welfare significantly, and do so because they allow regions to exploit gains from trade.

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1 Introduction

In 2007, almost 20 percent of World Bank lending was allocated to transportation infrastructure projects, a larger share than that of education, health and social services combined (World Bank 2007). These projects aim to reduce trade costs. In prominent models of international and interregional trade, reductions in trade costs will increase the level of real income in trading regions.[1] A related body of theoretical work argues that trade cost reductions can change the volatility of real income. This is a second welfare effect that may be especially important in predominantly agricultural, low-income economies, but the theoretical predictions from this work are less clear-cut.[2] Unfortunately, despite an emphasis on reducing trade costs in both economic theory and contemporary aid efforts, we lack a rigorous empirical understanding of the extent to which transportation infrastructure projects actually reduce the costs of trading, and how the resulting trade cost reductions affect welfare.

In this paper I exploit one of history's great transportation infrastructure projects—the vast network of railroads built in colonial India (India, Pakistan and Bangladesh; henceforth, simply 'India')—to make three contributions to our understanding of transportation infrastructure improvements. In doing so I draw on a comprehensive new dataset on the Indian economy that I have constructed. First, I estimate the extent to which railroads improved India's trading environment (ie reduced trade costs, reduced interregional price gaps, increased trade flows, and promoted market integration). Second, I estimate the reduced-form welfare gains (higher real income levels and lower real income volatility) that the railroads brought about. Finally, I assess, in the context of a general equilibrium trade model, how much of these reduced-form welfare gains were newly exploited gains from trade.

The railroad network designed and built by the British government in India (then referred to as 'the Raj') brought dramatic change to the technology of trading there. Prior to the railroad age, bullocks carried most of India's commodity trade on their backs, traveling no more than 30 km per day along India's sparse network of dirt roads (Deloche 1994). By contrast, railroads could transport these same commodities 600 km in a day, and at much lower per unit distance freight rates. As the 67,247 km long railroad network expanded (from 1853 to 1930), it penetrated inland districts (local administrative regions), bringing them out of near-autarky and connecting them with the rest of India and the world. I use the arrival of the railroad network in each district to investigate the economic impact of this striking improvement in transportation infrastructure.

This setting is unique because the British government collected detailed records of economic ac-

[1]Workhorse trade models featuring trade costs include Dornbusch, Fischer, and Samuelson (1977), Krugman (1980), Eaton and Kortum (2002) and Melitz (2003). In all of these theories, two trading regions will both gain when the (iceberg) cost of trading goods between them falls symmetrically. However, there are theoretical settings in which symmetric trade cost reductions can harm one of two trading regions; for example, if increasing returns to scale production technologies mix with factor mobility, as in Krugman (1991), or traded intermediate goods, as in Krugman and Venables (1995), then one of two trading regions can experience a welfare loss.

[2]For example, Newbery and Stiglitz (1981) present models in which openness to trade can either increase or decrease real income volatility.

tivity throughout India in this time period—remarkably, however, these records have never been systematically digitized and organized by researchers. I use these records to construct a new dataset with almost seven million observations on district-level prices, output, daily rainfall and interregional and international trade in India, as well as a digital map of India's railroad network in which each 20 km segment is coded with its year of opening. This dataset allows me to track the evolution of India's district economies before, during and after the expansion of the railroad network. The records on *interregional* trade are particularly unique and important here. Information on trade flows within a country is rarely available to researchers, yet the response of these trade flows to a transportation infrastructure improvement says a great deal about the potential for gains from trade (as I describe explicitly below).

To guide my empirical analysis I develop a multi-region, multi-commodity, Ricardian trade model, where trade occurs at a cost. Because of geographical heterogeneity, regions have differing productivity levels across commodities, which creates incentives to trade to exploit comparative advantage. A new railroad link between two districts lowers their bilateral trade cost, allowing consumers to buy goods from the cheapest district, and producers to sell more of what they are best at producing. There are thousands of interacting product and factor markets in the model. But the analysis of this complex general equilibrium problem is tractable if production heterogeneity takes a convenient but plausible functional form, as shown by Eaton and Kortum (2002).

I use this model to assess empirically the importance of one particular mechanism linking railroads to welfare improvements—that railroads reduce trade costs and thereby allow regions to gain from trade. The model makes six predictions that drive my six-step empirical analysis:

1. *Inter-district price differences are equal to trade costs (in special cases):* That is, if a commodity can be made in only one district (the 'origin') but is consumed in other districts ('destinations'), then that commodity's origin-destination price difference is equal to its origin-destination trade cost. I use this result to infer trade costs (which researchers never fully observe) by exploiting widely-traded commodities that could only be made in one district. Using inter-district price differentials, along with a graph theory algorithm embedded in a non-linear least squares routine, I estimate the trade cost parameters governing traders' endogenous route decisions on a network of roads, rivers, coasts and railroads. This is a novel method for inferring trade costs in networked settings. My resulting parameter estimates reveal that railroads significantly reduced the cost of trading in India.

2. *Bilateral trade flows take the 'gravity equation' form:* That is, holding constant exporter- and importer-specific effects, bilateral trade costs reduce bilateral trade flows. I find that railroad-driven reductions in trade costs (estimated in Step 1) increase bilateral trade flows, and show that the parameters estimated from the gravity equation identify my model.

3. *Railroads reduce the responsiveness of prices to local productivity shocks:* That is, a district's prices are less responsive to its own productivity shocks when it is connected to the railroad

network; however, a district's prices are more responsive to any other district's productivity shocks when these two districts are connected by a railroad line. I find empirical support for both of these predictions. Specifically, in a novel test for market integration, I find that railroads caused a dramatic reduction in the responsiveness of prices to local rainfall shocks, reducing responsiveness to almost zero (even when focusing purely on rainfall variation across crops, within a district and year). This implies that railroads brought India's district economies close to the small open economy limit where local conditions have no effect on local prices. I also find that a district's rainfall shocks affect prices in neighboring districts to which it is connected by the railroad network (to a weak but statistically significant extent).

4. *Railroads increase real income levels:* That is, when a district is connected to the railroad network its real income rises; however, improvements in the railroad network that by-pass a district reduce the district's real income (a negative spillover effect). Empirically, I find that own-railroad access raises real income by 18 percent, but a neighbor's access reduces real income by 4 percent. However, these are reduced-form estimates that could be due to a number of mechanisms. A key goal of Step 6 is to assess how much of the reduced-form effect of railroads can be attributed to gains from trade due to the trade cost reductions found in Step 1.

5. *Railroads decrease real income volatility:* When a district is connected to the railroad network, its real income is less responsive to stochastic productivity shocks in the district (which reduces volatility). Empirically, I find that railroads reduced the responsiveness of real agricultural income to local rainfall, which suggests a second welfare benefit of transportation infrastructure (in addition to that found in Step 4) that has not, to my knowledge, been demonstrated empirically before. However, as with the results in Step 4, a number of mechanisms could underpin this reduced-form result.

6. *There exists a sufficient statistic for the welfare gains from railroads:* That is, despite the complexity of the model's general equilibrium relationships, the impact of the railroad network on welfare in a district is captured by one variable: the share of that district's expenditure that it sources from itself. A prediction similar to this appears in a wide range of trade models but has not, to my knowledge, been tested before.[3] I test this prediction by regressing real income on this sufficient statistic (as calculated using the model estimated in Steps 1 and 2) alongside the regressors from Steps 4 and 5 (which capture the reduced-form impact of railroads).[4] When I do this, the reduced-form coefficients on railroad access estimated in Steps 4 and 5 fall to a level that is close to zero. This finding provides support for prediction 6 of the model and suggests that decreased trade costs account for virtually all of the real income impacts of the Indian railroad network.

[3]Arkolakis, Klenow, Demidova, and Rodriguez-Clare (2008) show that this prediction applies to the Krugman (1980), Eaton and Kortum (2002), Melitz (2003), and Chaney (2008) models of trade, but these authors do not test this prediction in their empirical application.

[4]This procedure is similar in spirit to the "sufficient statistic approach" proposed by Chetty (2008) as a compromise between reduced-form and structural methods of welfare analysis.

These six results demonstrate that India's railroad network improved the trading environment (Steps 1, 2 and 3), generated welfare gains (Steps 4 and 5), and that these welfare gains arose predominantly because railroads allowed regions to exploit gains from trade (Step 6).

Because railroads were not randomly assigned to districts, I pursue three strategies to mitigate concerns of bias due to a potential correlation between railroad placement and unobserved changes in the local economic environment. First, I estimate *four placebo specifications* using over 40,000 km of railroad lines that reached advanced stages of costly surveying but were never actually built, but find no spurious effects from these unbuilt lines. Second, I estimate *instrumental variable* specifications in which I instrument for railroad construction post-1884 with rainfall shortages in the 1876-78 agricultural years (because the 1880 Indian Famine Commission recommended that railroad lines be built in regions that experienced drought in the 1876-78 famine), and find IV results that are very close to my OLS results. Finally, in a *bounds check*, I find similar results among railroad lines whose estimates are likely to be biased upwards and lines whose estimates are likely to be biased downwards.

This paper contributes to a growing literature on estimating the economic effects of large infrastructure projects,[5] as well as a literature on estimating the 'social savings' of railroad projects.[6] A distinguishing feature of my approach is that, in addition to estimating reduced-form relationships between infrastructure and welfare as in the existing literature, I fully specify and estimate a general equilibrium model of how railroads affect welfare. The model makes auxiliary predictions and suggests a sufficient statistic for the role played by railroads in raising welfare—all of which shed light on the economic mechanisms that could explain my reduced-form estimates. Using a model also improves the external validity of my estimates because the primitive in my model—the cost of trading—is specified explicitly, and is portable to a range of settings in which the welfare benefits of trade cost-reducing polices might be sought.[7] By contrast, my reduced-form estimates are more likely to be specific to the context of railroads in colonial India. Finally, the model suggests a general equilibrium treatment externality of railroads that, if ignored, would bias estimates of the effects of this infrastructure project by almost 20 percent.[8] This point has not, to my knowledge, been incorporated before in the infrastructure literature, or in the literature estimating the welfare

[5]For example, Dinkelman (2007) estimates the effect of electrification on labor force participation in South Africa, Duflo and Pande (2007) estimate the effect of dam construction in India on agriculture, Jensen (2007) evaluates how the construction of cellular phone towers in South India improved efficiency in the fish market, and Michaels (2008) estimates the effect of the US Interstate Highway system on the skilled wage premium. An older literature, beginning with Aschauer (1989), pioneered the use of econometric methods in estimating the benefits of infrastructure projects.

[6]Fogel (1964) first applied the social savings methodology to railroads in the United States, and Hurd (1983) performed a similar exercise for India. In section 7.7 I compare my estimates to those from using a social savings approach.

[7]For example, Raballand and Macchi (2008) find in surveys of African trucking firms that transportation costs are relatively high in Africa because of a number of policy-relevant features (e.g. poor roads, expensive inputs, and underutilized payload capacity). Similarly, Djankov, Freund, and Pham (2006) survey freight forwarding firms in 126 countries to measure wider, policy-relevant costs of trading (e.g. inspections, technical clearance, mandatory storage, port handling, and customs clearance).

[8]Most of the policy evaluation literature assumes that policy treatments received by one unit of observation do not affect outcomes for any other units (the "stable unit treatment value assumption," in the language of Rubin (1978).) Heckman and Abbring (2007) survey the recent literature on general equilibrium policy evaluation.

effects of openness to trade.[9]

The next section describes the historical setting in which the Indian railroad network was constructed and the new data that I have collected from that setting. In section 3, I outline a model of trade in colonial India and the model's six predictions. Sections 4 through 9 present six empirical steps that test the model's six predictions qualitatively and quantitatively. Section 10 concludes.

2 Historical Background and Data

In this section I discuss some essential features of the economy in colonial India and the data that I have collected in order to analyze how this economy changed with the advent of railroad travel. I go on to describe the transportation system in India before and after the railroad era, and the institutional details that determined when and where railroads were built.

2.1 New Data on the Indian Economy, 1861-1930

In order to evaluate the impact of the railroad network on economic welfare in colonial India I have constructed a new panel dataset on 239 Indian districts. The dataset tracks these districts annually from 1861-1930, a period during which 98 percent of British India's current railroad lines were opened. Table 1 contains descriptive statistics for the variables that I use in this paper and describe throughout this section. Appendix A contains more detail on the construction of these variables.

During the colonial period, India's economy was predominantly agricultural, with agriculture constituting an estimated 66 percent of GDP in 1900 (Heston 1983).[10] For this reason, district-level output data was only collected systematically in the agricultural sector. Data on agricultural output was recorded for each of 17 principal crops (which comprise 93 percent of the cropped area of India in 1900). Retail prices for these 17 crops were also recorded at the district-level. I use these price figures to construct a nominal agricultural GDP series for each district and year and then a real agricultural income per acre figure by dividing by a consumer price index and district land area.[11] The resulting real agricultural income per acre variable provides the best available measure of district-level economic welfare in this time period.

Real incomes were low during my sample period, but there was 22 percent growth between 1870 and 1930.[12] Real incomes were low because crop yields were low, both by contemporaneous interna-

[9]Frankel and Romer (1999), Rodriguez and Rodrik (2001), Irwin and Tervio (2002), and Alcala and Ciccone (2004) are leading contributions to this literature. But the empirical approach used in these papers assumes that one country's openness does not affect welfare in any other country.

[10]Factory-based industry—which Chandler (1977) and Atack, Haines, and Margo (2008) argue benefited from access to railroads in the United States—contributed only 1.6 percent of India's GDP in 1900.

[11]The use of real income, rather than real GDP, in open-economy settings is advocated by Diewert and Morrison (1986), Feenstra (2003) and Kehoe and Ruhl (2008). As the latter authors argue, real income captures the gains from trade in a wide range of trade models, but real GDP does not.

[12]For comparison, Heston (1983) estimates that in 1869, on the basis of purchasing power exchange rates, per capita income in the United States was four times that in India. This income disparity rises to ten if market exchange rates are used instead of PPP rates.

tional standards and by Indian standards today.[13] One explanation for low yields, which featured heavily in Indian agricultural textbooks of the day (such as Leake (1923), Mollison (1901) and Wallace (1892)), was inadequate water supply. Only 12 percent of cultivated land was irrigated in 1885; while this figure had risen to 19 percent in 1930, the vast majority of agriculture maintained its dependence on rainfall.[14]

Because rainfall was important for agricultural production, 3614 meteorological stations (plotted in Figure 1) were built throughout the country to record the amount of rainfall at each station on every day of the year. Daily rainfall data was recorded and published because the distribution of rainfall throughout the year was far more important to farmers and traders than total annual or monthly amounts. In particular, the intra-annual distribution of rainfall governed how different crops (which were grown in distinct stretches of the year) were affected by a given year's rainfall. In sections 5 through 9, I use daily rainfall data from each of India's 3614 meteorological stations to construct crop-specific measures of rainfall, in order to provide exogenous variation in crop-specific productivity.

Rainfall was extremely volatile from year-to-year, giving rise to the common description of colonial Indian agriculture as "a gamble in monsoons."[15] Like rainfall, prices, nominal agricultural incomes, and real agricultural incomes were also volatile over time within districts. The clearest manifestation of this volatility appeared in India's 11 official famines between 1860 and 1930, in which at least 15 million people died.[16] Even beneath these extreme events laid significant real income volatility. I investigate the role that railroads played in reducing this volatility in section 8.

2.2 Transportation in Colonial India

Prior to the railroad era, goods transport within India took place on roads, rivers, and coastal shipping routes. The bulk of inland travel was carried by bullocks, along the road network.[17] Bullocks were employed either as 'pack bullocks' (which carried goods strapped to their backs and usually traveled directly over pasture land), or 'cart bullocks' (which pulled a cart containing goods and traveled along improved roads). On the best road surfaces and during optimal weather conditions, cart bullocks could cover 20-30 km per day. However, high-quality roads were extremely sparse and

[13] For example, the yield of wheat in India's 'breadbasket', the province of Punjab, was 748 lbs/acre in 1896. By contrast, for similar types of wheat, yields in Nevada (the highest state yields in the United States) in 1900 were almost twice as high (see plate 15 of United States Census Office (1902)) and yields in (Indian) Punjab in 2005 were over five times higher than those in 1896 (as calculated from the *Indian District-wise Crop Production Statistics Portal*, `http://dacnet.nic.in/apy/cps.aspx`).

[14] These figures encompass a wide definition of irrigation, including the use of tanks, cisterns, and reservoirs as well as canals. See the *Agricultural Statistics of India*, described in Appendix A. 1885 is the first year in which comprehensive irrigation statistics were collected.

[15] See, for example, Gadgil, Rajeevan, and Francis (2007). The phrase is still used to refer to agriculture today—for example, in the state of Orissa's 2005 *Economic Survey*, a state in which only 56 percent of cultivated land is irrigated.

[16] I calculate this figure from Appendix Table 5.2 of Visaria and Visaria (1983). Davis (2001) argues that this is a gross underestimate and suggests an upper estimate of 34 million deaths. In particular, Visaria and Visaria (1983) do not include any deaths from the severe famine of 1899-1900, for want of data.

[17] Camels were also used in sandy areas. Horses, ponies, donkeys, mules and elephants were less common forms of animal-powered transportation.

the roads that did exists were virtually impassable in the monsoon season (Deloche 1994). Pack bullocks were more versatile than cart bullocks, but their freight rates were three times higher per unit distance and weight (Derbyshire 1985).

Water transport was far superior to road transport, but it was only feasible on the Brahmaputra, Ganges and Indus river systems.[18] In optimal conditions, downstream river traffic (with additional oar power[19]) could cover 65 km per day; upstream traffic needed to be towed from the banks and struggled to cover 15 km per day. Extensive river travel was impossible in the rainy monsoon months, or the dry summer months, and piracy was a serious hazard (Deloche 1995). Coastal shipping, however, was perennially available along India's long coastline. This form of shipping was increasingly steam-powered post-1840. Steamships were fast, covering over 100 km per day, but they could only service major ports. The bulk of this trade, both before and after the railroads, therefore consisted of shipments between the major ports (Naidu 1936).

Against this backdrop of costly and slow internal transportation, the appealing prospect of railroad transportation in India was discussed as early as 1832 (Sanyal 1930)—though it was not until 1853 that the first track was actually laid. From the outset, railroad transport proved to be far superior to road, river or coastal transport (Banerjee 1966). Railroads were capable of traveling up to 600 km per day and they offered this superior speed on predictable timetables, throughout all months of the year, without any risk of piracy (Johnson 1963). Railroad freight rates were also considerably cheaper: 4-5, 2-4, and 1.5-3 times cheaper than road, river and coastal travel, respectively (Deloche 1994, Deloche 1995, Derbyshire 1985, Hurd 1975).

2.3 Railroad Line Placement Decisions

Throughout the history of India's railroads, all railroad line placement decisions were made by the Government of India. It is widely accepted that the Government had three motives for building railroads: military, commercial, and humanitarian—in that order of priority (Thorner 1950, Macpherson 1955, Headrick 1988). In 1853, Lord Dalhousie (head of the Government of India) wrote an internal document to the East India Company's Court of Directors that sketched railroad policy in India for decades to come. Military motivations for railroad-building appeared on virtually every page of this document,[20] and these motivations gained new momentum when the 1857 'mutiny' highlighted the importance of military communications (Headrick 1988). Dalhousie's minute described five 'trunk lines' that would connect India's five major provincial capitals along direct routes and maximize the "political advantages" of a railroad network.

[18]Navigable canals either ran parallel to sections of these three rivers or were extremely localized in a small number of coastal deltas (Stone 1984, Whitcombe 1983).

[19]Steamboats had periods of success in the colonial era, but were severely limited in scope by India's seasonal and shifting rivers (Derbyshire 1985).

[20]For example, from the introduction: "A single glance...will suffice to show how immeasurable are the political advantages to be derived from the system of internal communication, which would admit of full intelligence of every event being transmitted to the Government...and would enable the Government to bring the main bulk of its military strength to bear upon any given point in as many days as it would now require months, and to an extent which at present is physically impossible." (House of Commons Papers 1853).

Between 1853 and 1869, all of Dalhousie's trunk lines were built—but not without significant debate over how best to connect the provincial capitals. Dalhousie and Major Kennedy, India's Chief Engineer, spent over a decade discussing and surveying (at great cost) their competing, but very different, proposals for a pan-Indian network (Davidson 1868, Settar 1999). This debate indicates the vicissitudes of railroad planning in India and it was repeated many times by different actors in Indian railroad history. I have collected planning documents from a number of railroad expansion proposals that, like Kennedy's proposal, were debated and surveyed at length, but were never actually built. As discussed in section 7.4, I use these plans in a placebo strategy to check that unbuilt lines display no spurious 'impact' on the district economies in which they were nearly built.

By 1876, railroad expansion had slowed significantly in India. But railroads benefited from new enthusiasm in the wake of the 1880 Famine Commission, which recommended railroads as a means for future famine prevention. The Commission's recommendations for specific railroad lines formed the bedrock on which more detailed plans over the ensuing 15 years were built. In section 7.5 I describe how this motivates an instrumental variable for railroad construction. A second consequence of the 1880 Famine Commission report, from the perspective of my identification strategy in section 7.6, is that all railroad proposals from 1883 to 1904 were required to be designated according to their intended purpose. I use this feature to motivate a set of bounds on my estimates of the average effect of railroads.

As is clear from Figure 2, the railroad network in place in 1930 (by and large, the same network that is open today) had completely transformed the transportation system in India. 67,247 km of track were open for traffic, constituting the fourth-largest network in the world. From their inception in 1853 to their zenith in 1930, railroads were the dominant form of public investment in British India.[21] But influential observers were highly critical of this public investment priority—the Nationalist historian, Romesh Dutt, argued that they did little to promote agricultural development,[22] and Mahatma Gandhi argued simply that "there can be little doubt that they [railroads] promote evil."[23] In the remainder of this paper I use new data to assess quantitatively the effect of railroads on India's trading environment and agricultural economy.

[21] Kumar (1983) summarizes government revenues and expenditure in India. Public investment (which included railroads, roads, irrigation, buildings, health and education) accounted for around 20 percent of total expenditure (the largest category behind defense) and railroads accounted for over 40 percent of this category.

[22] For example, on page 174 of his textbook on Indian economic history: "Railways...did not add to the produce of the land." (Dutt 1904)

[23] From Chapter IX of the 1938 English translation of Gandhi's 1909 *Hind Swaraj* [Indian Home Rule], his influential newspaper columns. Other passages are equally polemic: "...but for the railways, the English could not have such a hold on India as they have. The railways, too, have spread the bubonic plague...Railways have also increased the frequency of famines, because, owing to facility of means of locomotion, people sell out their grain, and it is sent to the dearest markets....They [railways] accentuate the evil nature of man. Bad men fulfil their evil designs with greater rapidity." (Gandhi 1938)

3 A Model of Railroads and Trade in Colonial India

In this section I develop a general equilibrium model of trade among many regions in the presence of trade costs. The model is based on Eaton and Kortum (2002), extended to a setting with more than one commodity; this extension allows me to generate cross-commodity predictions that exploit the full richness of my commodity-level data.[24] The model serves two purposes. First, it delivers six predictions about the response of observables to trade cost reductions. Second, I estimate the model and use it to assess whether the observed reduction in trade costs due to the railroads can account, via the mechanism stressed in this model, for the observed increase in welfare due to railroads. Both of these features inform our understanding of *how* transportation infrastructure projects can raise welfare.

3.1 Model Environment

The economy consists of D regions (indexed by either o or d). There are K commodities (indexed by k), each available in a continuum (with mass normalized to one) of horizontally differentiated varieties (indexed by j). In my empirical application I work with data on prices, output and trade flows that refer to commodities, not individual varieties. While my empirical setting will consider 70 years of annual observations, for simplicity the model is static; I therefore suppress time subscripts until they are necessary.

<u>Consumer Preferences:</u>

Each region o is home to a mass (normalized to one) of identical agents, each of whom owns L_o units of land. Land is geographically immobile and supplied inelastically. Agents have Cobb-Douglas preferences over commodities (k) and constant elasticity of substitution preferences over varieties (j) within each commodity; that is, their (log) utility function is

$$\ln U_o = \sum_{k=1}^{K} \left(\frac{\mu_k}{\varepsilon_k}\right) \ln \int_0^1 (C_o^k(j))^{\varepsilon_k} dj, \tag{1}$$

where $C_o^k(j)$ is consumption, $\varepsilon_k = \frac{\sigma_k - 1}{\sigma_k}$ (where σ_k is the (constant) elasticity of substitution), and $\sum_k \mu_k = 1$. Agents rent out their land at the rate of r_o per unit and use their income $r_o L_o$ to maximize utility from consumption.

<u>Production and Market Structure:</u>

Each variety j of the commodity k can be produced using a constant returns to scale production technology in which land is the only factor of production.[25] Let $z_o^k(j)$ denote the amount variety j

[24]While Eaton and Kortum (2002) use a continuum of varieties (j in the notation I use below), these are all varieties from one commodity (k in the notation I use below). The main predictions of their model, and the model that I present here, are at the level of commodities rather than varieties.

[25]It is straightforward to extend this setting to an arbitrary number of immobile factors (provided that the stochastic productivity term remains Hicks-neutral) by replacing the land rental rate r_o with a general unit cost function $c^k(\mathbf{w}_o)$, where $\mathbf{w}_o$ is the vector of factor payments in region o.

of commodity k that can be produced with one unit of land in region o. I follow Eaton and Kortum (2002) in modeling $z_o^k(j)$ as the realization of a stochastic variable Z_o^k drawn from a Type-II extreme value distribution whose parameters vary across regions and commodities; that is,

$$F_o^k(z) \doteq \Pr(Z_o^k \leq z) = \exp(-A_o^k z^{-\theta_k}) \tag{2}$$

where $A_o^k \geq 0$ and $\theta_k > 0$. These random variables are drawn independently for each variety, commodity and region.[26] The exogenous parameter A_o^k increases the probability of high productivity draws and the exogenous parameter θ_k captures (inversely) how variable the productivity of commodity k in any region is around its average.

There are many competitive firms in region o with access to the above technology; consequently, firms make zero profits.[27] These firms will therefore charge a pre-trade costs price of $p_{oo}^k(j) = r_o/z_o^k(j)$, where r_o is the land rental rate in region o.

Opportunities to Trade:

Without opportunities to trade, consumers in region d must consume even their region's worst draws from the productivity distribution in equation (2). The ability to trade breaks this production-consumption link. This allows consumers to import varieties from other regions in order to take advantage of the favorable productivity draws available there, and allows producers to produce more of the varieties for which they received the best productivity draws. These two mechanisms constitute the gains from trade in this model.

However, there is a limit to trade because the movement of goods is subject to trade costs (which include transport costs and other barriers to trade). These trade costs take the convenient and commonly used Samuelson (1954) 'iceberg' form. That is, in order for one unit of commodity k to arrive in region d, $T_{od}^k \geq 1$ units of the commodity must be produced and shipped in region o; trade is free when $T_{od}^k = 1$. (Throughout this paper I refer to trade flows between an *origin* region o and a *destination* region d; all bilateral variables, such as T_{od}^k, refer to quantities *from o to d*.)

[26] The assumption of within-sector heterogeneity characterized by a continuous stochastic distribution of productivities is a standard feature in the literature on trade with heterogeneous firms (eg Melitz (2003)). It is common in that literature to assume that the productivity distribution is Pareto (to which the upper tail of a Type-II extreme value distribution converges) and that productivities are drawn independently across varieties (firms), commodities, and countries (eg Melitz and Ottaviano (2007), Chaney (2008) and Helpman, Melitz, and Rubinstein (2008).) An attraction of the Type-II extreme value distribution is its plausible micro-foundations: Kortum (1997) applies the extremal types theorem to show that the distribution of productivities among producers who use only the highest draws from any iid process of 'ideas' will converge to an extreme value distributional form. Nevertheless, Costinot and Komunjer (2008) show that the key features of the Eaton and Kortum (2002) model hold locally around a symmetric distribution of exogenous productivity terms A_o^k for *any* continuous productivity distribution.

[27] My empirical application is primarily to the agricultural sector. This sector was characterized by millions of smallholding farmers who were likely to be price-taking producers of undifferentiated products (varieties j in my model). For example, in the 1901 census in the province of Madras, workers in the agricultural sector (67.9 percent of the almost 20 million strong workforce) were separately enumerated by their ownership status, and 35.7 percent of these workers were owner-cultivators (extremely small-scale farms) (Risley and Gait 1903). Nevertheless, Bernard, Eaton, Jensen, and Kortum (2003) and Eaton, Kortum, and Kramarz (2005) extend the Eaton and Kortum (2002) framework to allow for Bertrand and monopolistic competition, respectively. While in principle it is possible to estimate these alternative models, the most natural way to do so uses firm-level trade data, which is unavailable in my setting.

Trade costs are assumed to satisfy the property that it is always (weakly) cheaper to ship directly from region o to region d, rather than via some third region m: that is, $T_{od}^k \leq T_{om}^k T_{md}^k$. Finally, I normalize $T_{oo}^k = 1$. In my empirical setting I proxy for T_{od}^k with measures calculated from the observed transportation network, which incorporates all possible modes of transport between region o and region d. Railroads enter this transportation network gradually over time, reducing T_{od}^k and creating more gains from trade.

Trade costs drive a wedge between the price of an identical variety in two different regions. Let $p_{od}^k(j)$ denote the price of variety j of commodity k produced in region o, but shipped to region d for consumption there. The iceberg formulation of trade costs implies that any variety in region d will cost T_{od}^k times more than in region o; that is, $p_{od}^k(j) = T_{od}^k\, p_{oo}^k(j) = r_o\, T_{od}^k / z_o^k(j)$.

Equilibrium Prices and Allocations:

Consumers have preferences for all varieties j along the continuum of varieties of commodity k. But they are are indifferent about where a given variety is made—they simply buy from the region that can provide the variety at the lowest cost. I therefore solve for the equilibrium prices that consumers in a region d actually face, given that they will only buy a given variety from the cheapest source region (including their own).

The price of a variety sent from region o to region d, denoted by $p_{od}^k(j)$, is stochastic because it depends on the stochastic variable $z_o^k(j)$. Since $z_o^k(j)$ is drawn from the CDF in equation (2), $p_{od}^k(j)$ is the realization of a random variable P_{od}^k drawn from the CDF

$$G_{od}^k(p) \doteq \Pr(P_{od}^k \leq p) = 1 - \exp[-A_o^k (r_o T_{od}^k)^{-\theta_k} p^{\theta_k}]. \tag{3}$$

This is the price distribution for varieties (of commodity k) made in region o that could *potentially* be bought in region d. The price distribution for the varieties that consumers in d will *actually* consume (whose CDF is denoted by $G_d^k(p)$) is the distribution of prices that are the lowest among all D regions of the world:

$$\begin{aligned} G_d^k(p) &= 1 - \prod_{o=1}^{D} [1 - G_{od}^k(p)], \\ &= 1 - \exp\left(- \left[\sum_{o=1}^{D} A_o^k (r_o T_{od}^k)^{-\theta_k} \right] p^{\theta_k} \right). \end{aligned}$$

Given this distribution of the actual prices paid by consumers in region d, it is straightforward to calculate any moment of the prices of interest. The price moment that is important for my empirical analysis is the expected value of the equilibrium price of any variety j of commodity k found in region d, which is given by

$$E[p_d^k(j)] \doteq p_d^k = \lambda_1^k \left[\sum_{o=1}^{D} A_o^k (r_o T_{od}^k)^{-\theta_k} \right]^{-1/\theta_k}, \tag{4}$$

where $\lambda_1^k \doteq \Gamma(1+\frac{1}{\theta_k})$.[28] In section 6 I treat these expected prices as equal to the observed prices collected by statistical agencies.[29]

Given the price distribution in equation (3), Eaton and Kortum (2002) derive two important properties of the trading equilibrium that carry over to the model here. First, the price distribution of the varieties that any given origin actually sends to destination d (ie the distribution of prices for which this origin is region d's cheapest supplier) is the same for all origin regions. This implies that the share of expenditure that consumers in region d allocate to varieties from region o must be equal to the probability that region o supplies a variety to region d (because the price per variety, conditional on the variety being supplied to d, does not depend on the origin). That is $X_{od}^k/X_d^k = \pi_{od}^k$, where X_{od}^k is total expenditure in region d on commodities of type k from region o, $X_d^k \doteq \sum_o X_{od}^k$ is total expenditure in region d on commodities of type k, and π_{od}^k is the probability that region d sources any variety of commodity k from region o. Second, this probability π_{od}^k is given by

$$\pi_{od}^k = \frac{X_{od}^k}{X_d^k} = \lambda_3^k \, A_o^k \, (r_o T_{od}^k)^{-\theta_k} \, (p_d^k)^{\theta_k}, \tag{5}$$

where $\lambda_3^k = (\lambda_1^k)^{-\theta_k}$, and this equation makes use of the definition of the expected value of prices (ie p_d^k) in equation (4).

Equation (5) characterizes trade flows conditional on the endogenous land rental rate, r_o (and all regions' land rental rates, which appear in p_d^k). It remains to solve for these land rents in equilibrium, by imposing the condition that each region's trade is balanced. Region o's trade balance equation requires that the total income received by land owners in region o ($r_o L_o$) must equal the total value of all commodities made in region o and sent to every other region (including region o itself). That is:

$$r_o L_o = \sum_d \sum_k X_{od}^k = \sum_d \sum_k \pi_{od}^k \, \mu_k \, r_d \, L_d, \tag{6}$$

where the last equality uses the fact that (with Cobb-Douglas preferences) expenditure in region d on commodity k (X_d^k) will be a fixed share μ_k of the total income in region d ($r_d L_d$). Each of the D regions has its own trade balance equation of this form. I take the rental rate in the first region (r_1) as the numeraire good, so the equilibrium of the model is the set of D-1 unknown rental rates r_d that solves this system of D-1 (non-linear) independent equations.

[28] $\Gamma(.)$ is the Gamma function defined by $\Gamma(z) = \int_0^\infty t^{z-1} e^{-t} dt$.

[29] A second price moment that is of interest for welfare analysis is the exact price index over all varieties of commodity k for consumers in region d. Given CES preferences, this is $\widetilde{p}_d^k \doteq \left[\int_0^1 (p_d^k(j))^{1-\sigma_k} dj\right]^{1/1-\sigma_k}$, which is only well defined here for $\sigma_k < 1 + \theta_k$ (a condition I assume throughout). The exact price index is given by $\widetilde{p}_d^k = \lambda_2^k p_d^k$, where $\lambda_2^k \doteq \frac{\gamma^k}{\lambda_1^k}$ and $\gamma^k \doteq [\Gamma(\frac{\theta_k + 1 - \sigma_k}{\theta_k})]^{1/(1-\sigma_k)}$. That is, if statistical agencies sampled varieties in proportion to their weights in the exact price index, as opposed to randomly as in the expected price formulation of equation (4), then this will not jeopardize my empirical procedure because the exact price index is proportional to expected prices.

3.2 Six Predictions

In this section I state explicitly six of the model's predictions. These predictions are presented in the order in which I test for them in my empirical analysis (ie Steps 1-6).

Prediction 1: Price Differences Measure Trade Costs (in Special Cases):
In the presence of trade costs, the price of identical commodities will differ across regions. In general, the cost of trading a commodity between two regions places only an upper bound on their price differential.[30] However, in the special case of a homogeneous commodity that can only be produced in one origin region, equation (4) predicts that the (log) price differential between the origin o of this commodity and any other region d will be equal to the (log) cost of trading the commodity between them. That is:

$$\ln p_d^o - \ln p_o^o = \ln T_{od}^o, \tag{7}$$

where the commodity label k is replaced by o to indicate that this equation is only true for commodities that can only be made in region o. This prediction is important for my empirical work because it allows trade costs (T_{od}^o), which are typically unobserved, to be inferred.[31] But it is important to note that this prediction—essentially just free arbitrage over space, net of trade costs—is common to many models of spatial equilibrium.[32]

Prediction 2: Bilateral Trade Flows Take the 'Gravity Equation' Form:
Equation (5) describes bilateral trade flows explicitly, but I re-state it here in logarithms for reference: (log) bilateral trade of any commodity k from any region o to any other region d is given by

$$\ln X_{od}^k = \ln \lambda_k + \ln A_o^k - \theta_k \ln r_o - \theta_k \ln T_{od}^k + \theta_k \ln p_d^k + \ln X_d^k. \tag{8}$$

This is the gravity equation form for bilateral trade flows: bilateral trade costs reduce bilateral

[30]This can be easily seen in two simple settings where bilateral trade costs are infinite, but bilateral inter-regional price differences are zero: (i) two identical autarkic economies will have a price differential of zero, but infinite trade costs vis-a-vis each other; (ii) two regions that have infinite trade costs vis-a-vis each other could both buy a commodity from some common third region from which they are both separated by the same trade cost (meaning that they face the same price for this commodity and therefore have a price difference of zero).

[31]There are two obstacles to using inter-regional price differentials to infer trade costs in wider settings than that employed here. First, the commodity whose price is being compared over space must be identical in the two regions—for example, Broda and Weinstein (2007) use barcode data to illustrate the misleading inferences that have been drawn from comparing prices of commodities that are similar, but not identical, across the Canada-US border. Second, even with a homogeneous commodity, only if two regions actually trade the commodity will their inter-regional price difference be equal to their bilateral trade cost. Restricting attention to a commodity that is only made in one region but is consumed elsewhere, as I do in this paper, helps to ensure that the commodity is homogeneous and guarantees that the commodity was actually traded between regions.

[32]This prediction is common to most models of spatial equilibrium. A class of exceptions is those with some forms of imperfect competition and in which producers can charge separate prices in separate markets, as in Brander and Krugman (1983) or Melitz and Ottaviano (2007). However, my empirical application of this prediction will be to salt, which was produced under strict government license at a small number of locations and then had to be sold (under conditions of the license) to an unrestricted trading community at the 'factory' gate (United Provinces of Agra and Oudh 1868). That is, in this setting, producers only charged one factory gate price.

trade flows, conditional on importer- and exporter-specific terms.[33]

Prediction 3: Railroads Reduce the Responsiveness of Prices to Local Productivity Shocks: Unfortunately, the multiple general equilibrium interactions in the model are too complex to admit a closed-form solution for the effect of reduced trade costs on agricultural prices. To make progress in generating qualitative predictions (to guide my empirical analysis) I therefore assume a much simpler environment for Predictions 3-5. I assume: there are only three regions (called X, Y and Z); there is only one commodity (so I will dispense with the k superscripts on all variables); the regions are symmetric in their exogenous characteristics (ie $L_o = L$ and $A_o = A$ for all regions o); and the three regions have symmetric trade costs with respect to each other.[34] I consider the comparative statics from a local change around this symmetric equilibrium, where it is straightforward to show that:

1. $\frac{d}{dT_{YX}}\left(\frac{p_X}{dA_X}\right) < 0$: The responsiveness of prices in a region (say, X) to productivity shocks *in the same region* (ie $\frac{dp_X}{dA_X} < 0$) is weaker (ie less negative) when the region has low trade costs to another region (say, Y).

2. $\frac{d}{dT_{YX}}\left(\frac{dp_X}{dA_Y}\right) > 0$: The responsiveness of prices in a region (say, X) to productivity shocks *in other any other region* (say region Y, so the price responsiveness of interest here is $\frac{dp_X}{dA_Y} < 0$) is stronger (ie more negative) when the cost of trading between these two regions (ie T_{YX}) is low.

Prediction 4: Railroads Increase Real Income Levels:
My focus here (and in Prediction 5) is on real income (which, as prediction 6 shows explicitly, is equal to welfare in this model). To simplify notation, let W_o represent real income per unit land area (ie $W_o \doteq \frac{r_o}{\widetilde{P}_o}$, where $\widetilde{P}_o$ is the aggregate price index in region o, defined explicitly in Prediction 6). Then it is straightforward to show that the following results hold around the symmetric three-region equilibrium introduced in Prediction 3:

1. $\frac{dW_X}{dT_{YX}} < 0$: Real income in a region (say, X) rises when the cost of trading between that region and any other region (say, Y) falls.

2. $\frac{dW_X}{dT_{YZ}} > 0$: Real income in a region (say, X) falls when the cost of trading between the two other regions (ie T_{YZ}) falls.

[33] A number of theoretical trade frameworks also predict a gravity equation for trade flows. Examples include Anderson (1979), Deardorff (1998), Helpman, Melitz, and Rubinstein (2008) and Chaney (2008). In a traditional gravity equation, bilateral trade flows (for each commodity) are proportional to the expenditure of the importing region, the output of the exporting region, and inversely proportional to the bilateral cost of trading between the two regions. Equation (5) can be easily manipulated to take this form. However, what matters for my empirical procedure is simply that, conditional on importer and exporter fixed effects, bilateral trade costs reduce bilateral trade flows—as in equation (5) and in a traditional gravity equation.

[34] An alternative means of obtaining analytical predictions would be to invoke the commonly-used assumption that one commodity can be traded at zero trade cost, and is important enough to be produced in positive quantities everywhere and always. (This equates r_o to the nominal productivity in this zero trade cost sector). It is difficult to imagine a commodity that satisfies these conditions in colonial India.

These results suggest that a reduction in trade costs in one part of the network is not good for all regions. A railroad project that reduces trade costs between two regions will raise welfare in these two regions; but this project will reduce welfare in the third, excluded region whose trade costs were unaffected by the project. This negative effect on excluded regions arises because of two effects: first, the excluded region's trading partners' land rental costs have increased (because these partners' own trade costs have fallen), which raises the prices of the commodities that the partners ship to the excluded region; and second, the excluded region loses demand for its exports because its trading partners now have a cheaper supplier (in each other).

Prediction 5: Railroads Reduce Real Income Volatility:

This prediction concerns the effect of an exogenous change in productivity on a region's real income. If the exogenous productivity terms are stochastic (as in my empirical setting) then a reduction in the responsiveness of real income to this stochastic production technology will reduce real income volatility. Around the three-region symmetric equilibrium:

1. $\frac{dW_X}{dA_X} > 0$: Real income in a region (say, X) rises when its productivity (A_X) increases.
2. $\frac{d}{dT_{XY}}\left(\frac{dW_X}{dA_X}\right) > 0$: The effect of productivity (A_X) on real income in a region (say, X) falls when the cost of trading between this region and any other region (say, Y) falls.

This suggests another potential welfare gain from railroads (to the extent that real income volatility affects consumption volatility and consumers are risk averse).

Prediction 6: There Exists a Sufficient Statistic for the Welfare Gains from Railroads:

Given the utility function in equation (1), the indirect utility function per unit of land (denoted by W_o as in Predictions 4 and 5) in region o is

$$W_o = \frac{r_o}{\prod_{k=1}^{K}(\widetilde{p}_o^k)^{\mu_k}} \doteq \frac{r_o}{\widetilde{P}_o}. \tag{9}$$

The numerator of this expression is nominal income (per unit land area) in region o relative to the numeraire, and the denominator is the exact consumer price index across all commodities k denoted by $\widetilde{P}_o$. That is, welfare is equal to real income. Using the bilateral trade equation (5) evaluated at $d = o$, (log) real income per unit of land (defined as W_o as in prediction 4) can be re-written as

$$\ln W_o = \Omega + \sum_k \tfrac{\mu_k}{\theta_k} \ln A_o^k - \sum_k \tfrac{\mu_k}{\theta_k} \ln \pi_{oo}^k, \tag{10}$$

where $\Omega \doteq -\sum_k \mu_k \ln \gamma^k$. This result states that welfare is a function of only two terms: local productivity (A_o^k), and 'openness' (ie π_{oo}^k), the fraction of region o's expenditure that region o buys from itself). Because of the complex general equilibrium relationships in the model, the full vector of trade costs (between every bilateral pair of regions), the full vector of productivity terms in other regions, and the sizes of every region all influence welfare in region o. But these terms (that is, every exogenous variable in the model other than local productivity) affect welfare only through their effect on openness. Put another way, openness (the appropriately weighted sum of π^k_{oo} terms over goods k) is a sufficient statistic for welfare in region o, once local productivity is controlled for. If railroads affected welfare in India through the mechanism in the model (by reducing trade costs, giving rise to gains from trade), then prediction 6 states that they did so only by changing π^k_{oo}.

3.3 From Theory to Empirics

To relate the static model in section 3 to my dynamic empirical setting (with 70 years of annual data) I take the simplest possible approach and assume that all of the goods in the model cannot be stored, and that inter-regional lending is not possible. Furthermore, I assume that the stochastic production process described in section 3.1 is drawn independently in each period. These assumptions imply that the static model simply repeats every period, with independence of all decision-making across time periods. Throughout the remainder of the paper I therefore add the subscript ‘t’ to all of the variables (both exogenous and endogenous) in the model, but I assume that all of the model parameters (θ_k, σ_k and μ_k) are fixed over time.

The six theoretical predictions outlined in section 3.2 take a naturally recursive order, both for estimating the model’s parameters, and for tracing through the impact of railroads on welfare in India. I follow this order in the six empirical sections that follow (ie Steps 1-6). In Step 1, I evaluate the extent to which the railroads reduced trade costs within India. To do this I use Prediction 1 to relate the unobserved trade costs term in the model (T^k_{odt}) to observed features of the transportation network. In Step 2, I use Prediction 2 to measure how much the reduced trade costs found in Step 1 increased trade in India. This relationship allows me to estimate the unobserved model parameter θ_k, and to relate the unobserved productivity terms (A^k_{ot})[35] to rainfall, which is an exogenous and observed determinant of agricultural productivity. Steps 1 and 2 therefore deliver estimates of all of the model’s parameters.

In Step 3, I test Prediction 3 and evaluate the extent to which lower trade costs reduced price responsiveness to rainfall shocks (a test for market integration, as in a small open economy price responsiveness should be zero), and increased the transmission of rainfall shocks between regions. In Step 4, I test Prediction 4 by estimating how the level of a district’s real income is affected when the railroad network is extended to that district, and when it is instead extended to other nearby district. Step 5 performs a similar test in the context of Prediction 5, on the volatility of real income. However, the empirical findings in Steps 4 and 5 are reduced-form in nature and could arise through a number of possible mechanisms.[36] Therefore, in Step 6 I use the sufficient statistic suggested by

[35] The productivity terms A^k_{ot} are unobserved because they represent the location parameter on region o’s *potential* productivity distribution of commodity k, in equation (2). The productivities actually used for production in region o will be a subset of this potential distribution, where the scope for trade endogenously determines how the potential distribution differs from the distribution actually used to produce.

[36] For example, railroads could have: reduced the cost of technology transfer between regions, or the monitoring costs of multi-regional enterprises (as in the model of Ramondo and Rodriguez-Clare (2008), who construct a model

Prediction 6 to compare the reduced-form effects of railroads on the level and volatility of real income (found in Steps 4 and 5) with the effects predicted by the model (as estimated in Steps 1 and 2).

4 Empirical Step 1: Railroads and Trade Costs

In the first step of my empirical analysis I estimate the extent to which railroads reduced the cost of trading within India. Because this paper stresses a trade-based mechanism for the impact of railroads on welfare, it is important to establish that railroads actually reduced trade costs. Further, the relationship between railroads and trade costs, which I estimate in this section, is an important input for the five empirical steps that follow.

4.1 Empirical Strategy

Researchers rarely observe trade costs.[37] But Prediction 1 suggests an instance under which trade costs can be *inferred*: If a homogeneous commodity can only be made in one region, then the difference in retail prices (of that commodity) between the origin region and any other consuming region is equal to the cost of trading between the two regions.[38]

Throughout Northern India, several homogeneous types of salt were consumed, but each of these varieties could only be made in one unique location. Traders and consumers would speak about 'Kohat salt' (which could only be produced at the salt mine in the Kohat region) as a different commodity from 'Sambhar salt' (which could only be produced at the Sambhar Salt Lake).[39] I have collected data on salt prices in Northern India, in which the prices of eight regionally-differentiated types of salt are reported in 124 districts. Crucially, because salt is an essential commodity, it was consumed throughout India both before and after the construction of railroads.

I use this salt price data, with the help of Prediction 1, to estimate how Indian railroads reduced

similar to that here in which there is diffusion of technology and multinational production); encouraged factor mobility, potentially giving rise to efficiency gains if factors are heterogeneous, or increasing the elasticity of labor supply (as Jayachandran (2006) found in post-Independence India); increased the size of the market, encouraging innovation (as Sokoloff (1988) found in the case of US canals and patenting behavior) or allowing economies of scale to be exploited (as found in Ades and Glaeser (1999)); or even altered the political environment in favor of a commercial class that favored growth-enhancing institutions (as Acemoglu, Johnson, and Robinson (2005) argue explained the growth of European port cities with access to the new trade opportunity of Atlantic trade post-1500).

[37]Even when shipping receipts are observed, as in Hummels (2007), these may fail to capture other barriers to trade, such as the time goods spend in transit (a focus of Evans and Harrigan (2005)), or the risk of damage or loss in transit (a major concern in colonial India). In lieu of direct measures of trade costs, a large literature, surveyed by Anderson and van Wincoop (2004), uses a proxy variable strategy (similar to that I employ in this section) to estimate trade costs.

[38]Anderson and van Wincoop (2004) suggest (on p. 78) the solution I pursue here: "A natural strategy would be to identify the source [region] for each product. We are not aware of any papers that have attempted to measure trade barriers this way."

[39]The leading (nine-volume) commercial dictionary in colonial India, Watt (1889), describes the market for salt in this manner, as do Aggarwal (1937) and the numerous provincial *Salt Reports* that were brought out each year.

trade costs. To do this I estimate equation (7) of Prediction 1 as follows:[40]

$$\ln p^o_{dt} = \underbrace{\beta^o_{ot}}_{=\ln p^o_{ot}} + \underbrace{\beta^o_{od} + \phi^o_{od}t + \delta \ln TC(\mathbf{R}_t)_{odt} + \varepsilon^o_{odt}}_{=\ln T^o_{odt}}. \tag{11}$$

In this equation, p^o_{dt} is the price of type-o salt (that is, salt that can only be made in region o) in destination district d in year t. I estimate this equation with an origin-year fixed effect[41] (β^o_{ot}) to control for the price of type-o salt in its region of origin o (ie p^o_{ot}) because I do not observe salt prices exactly at the point where they leave the source. (My price data is at the district level and was recorded as the average price of goods over 10-15 retail markets in a district.)

The remainder of equation (11) describes how I model the relationship between trade costs T^o_{odt}, which are unobservable, and the railroad network (denoted by $\mathbf{R}_t$), which is observable.[42] I use two different proxy variables, denoted by $TC(\mathbf{R}_t)_{odt}$ and explained in detail below, that relate trade costs to the railroad network. This specification includes an origin-destination fixed effect (β^o_{od}) which controls for all of the time-invariant determinants of the cost of trading salt between districts o and d (such as the distance from o to d, or caste-based or ethno-linguistic differences between o and d that may hinder trade).[43] The specification also includes a separate trend term ($\phi^o_{od}t$) for each origin-destination pair; these trend terms control for any trade costs between o and d that vary over time in a (log) constant way. Finally, ε^o_{odt} is an error term that captures any remaining unobserved determinants of trade costs (or measurement error in $\ln p^o_{dt}$).[44]

I use two different measures for $TC(\mathbf{R}_t)_{odt}$, the proxy for the unobservable trade costs between the origin o and destination d districts in any year t:

1. *Bilateral railroad dummy variable:* I denote this variable by $RAIL_{odt}$. This dummy variable is equal to one in all years when it is possible to travel from district o to district d by railroad (and zero otherwise).[45] This proxy variable has the advantage of simplicity. But the coefficient

[40]The model in section 3 underpinning prediction 1 assumes that trade costs take an *ad valorem* (that is, per unit *value*) form, which is inconsistent with the evidence in Hummels and Skiba (2004). To test for a non-*ad valorem* trade cost specification I have estimated equation 11 with an additional interaction term between $\ln TC(\mathbf{R}_t)$ and the level of an excise tax charged on salt as it left the 'factory' gate. This was a very high tax (in the range of 100-300 percent of the value of salt), that initially varied across provinces, but which fell precipitously in 1874, 1878 and 1883 so that all provinces had the same tax rate (I take the data on excise rates from Aggarwal (1937)). However, the coefficient on this interaction term is never statistically significant. This is consistent with my assumption that, regardless of the factory gate price of salt, trade costs took a form that was proportional to the price of the commodity shipped.

[41]That is, each salt origin o has its own fixed effect in each year t. I use this notation when referring to fixed effects throughout this paper.

[42]An alternative empirical strategy would be to estimate trade costs directly from equation (11), by simply equating trade costs to observed price differences. However, this method faces two drawbacks when compared to the method I follow here. First, it would only uncover trade cost estimates for the *o-d-t* observations for which salt prices are observed separately for each region of origin (that is, no estimates would be available in Southern India). Second, it would be vulnerable to the concern that p^o_{ot} is not measured exactly at the point where type-o salt leaves the source in region o.

[43]Rauch (1999) and Anderson and van Wincoop (2004) document a series of findings that are consistent with large communication-based barriers to trade in contemporary international trade data.

[44]In this specification and all others in this paper I allow this error term to be heteroskedastic and serially correlated within districts (or trade blocks, in section 5) in an unspecified manner.

[45]Andrabi and Kuehlwein (2005) and Keller and Shiue (2007b) use this dummy variable approach when studying

on this variable is likely to be biased downwards because the spread of the railroad network will potentially reduce trade costs between o and d in years before they are fully connected by a railroad line. Furthermore, this variable ignores any heterogeneity in the effect of railroads on trade costs between two districts, such as that due to the distance between them, the directness of their railroad connection, or the local non-railroad transportation system.

2. *Lowest-cost route distance:* I denote this variable by $LCR(\mathbf{R}_t, \boldsymbol{\alpha})_{odt}$. This measure models the cost of trading goods between any two locations under the assumption that agents take the lowest-cost route—using any mode of transportation—available to them.[46] Two inputs are needed to calculate the lowest-cost route between districts o and d in year t. The first input is the *network* of available transportation routes open in year t, which I denote by $\mathbf{R}_t$. A network is a collection of nodes and arcs. In my application, nodes are finely-spaced points in space, and arcs are available means of transportation between the nodes (hence an arc could be a rail, river, road or coast connection). In modeling this network I allow agents to travel on navigable rivers, the coastline, the road network (which I take to be continuous over space and hence connecting any two nodes along the straight line between them), and the railroad network open in year t. The second input is the relative cost of traveling along each arc, which depends on which mode of transportation the arc represents. I model these costs as being proportional to distance,[47] where the proportionality, the *relative per unit distance cost*, of using each mode is denoted by the vector of parameters $\boldsymbol{\alpha} \doteq (\alpha^{rail}, \alpha^{road}, \alpha^{river}, \alpha^{coast})$. I normalize $\alpha^{rail} = 1$ so the other three elements of $\boldsymbol{\alpha}$ are costs relative to the cost of using railroads. Because of this normalization, $LCR(\mathbf{R}_t, \boldsymbol{\alpha})_{odt}$ is measured in units of railroad-equivalent kilometers; in this sense, a finding that all of the non-rail elements of $\boldsymbol{\alpha}$ are greater than one implies that railroads effectively shrunk distance, as measured in railroad-equivalent units. The parameter $\boldsymbol{\alpha}$ is unknown, so I treat it as a vector of parameters to be estimated.[48] Conditional on a value of $\boldsymbol{\alpha}$, it is possible to calculate $LCR(\mathbf{R}_t, \boldsymbol{\alpha})_{odt}$—a calculation that is made computationally feasible by Dijkstra's shortest-path algorithm (Ahuja, Magnanti, and Orlin 1993). But since $\boldsymbol{\alpha}$ is unknown, I estimate it using non-linear least squares (NLS). That

the effect of railroads on price differences in 19$^{\text{th}}$ Century India and Europe, respectively.

[46]To the best of my knowledge, this is a new method for measuring trade costs over multiple modes of transportation over a network, where users are free to choose their route over the network. Houde (2008) is related, as he uses Dijkstra's algorithm to find the likely commuting paths of automobile drivers over a road network (in order to define retail gasoline markets). But unlike my procedure, he treats the parameters that govern these users' path choices as known.

[47]This rules out any fixed costs of switching modes of transportation (such as handling charges), or other economies of scale in the transportation sector either internal to trading firms or external to them (such congestion effects). It is difficult to know whether these features were applicable to non-rail transportation in colonial India, but the simple freight rates charged by the railroads did not feature either a fixed handling charge or a bulk discount for large shipments, the trading sector was characterized by a large mass of small-scale traders (Bayly 1983, Yang 1999), and congestion effects on the railroads were rarely a deterrent to trade (Sanyal 1930).

[48]As discussed in section 2, relative freight rates for each mode of transport are available from a number of historical sources. However, as with overall trade costs, the cost of using railroads relative to another mode of transport may include elements (such as increased certainty or time savings) that are not included in observed freight rates. Consistent with this idea, I find in table 2 that my estimates of $\boldsymbol{\alpha}$ are higher (for road, river and coastal travel relative to rail travel), than the relative freight rates observed in these historical sources.

is, I search over all values of $\boldsymbol{\alpha}$, recomputing the lowest-cost routes at each step, to find the value that minimizes the sum of squared residuals in equation (11).

4.2 Data

I use data on retail prices of 8 types of salt, observed annually from 1861-1930 in 124 districts of Northern India (the region in which salt prices were reported broken down by region of origin). Further details on the data I use in this and other sections of the paper are provided in Appendix A.

4.3 Results

Column 1 of Table 2 presents results from estimating equation (11) by OLS using the bilateral railroad dummy ($RAIL_{odt}$) as the proxy for trade costs. The coefficient on this proxy variable is negative and statistically significant, indicating that when two regions are connected by a railroad line the cost of trading between them falls by approximately 10 percent. However, as argued above, this measure is likely to be biased toward zero and to ignore significant heterogeneity in the effect of railroads on trade costs.

To address these shortcomings of the bilateral railroad dummy variable, columns 2-5 present estimates of equation (11) using my alternative proxy variable for trade costs, the lowest-cost route ($LCR(\mathbf{R}_t, \boldsymbol{\alpha})_{odt}$). In column 2 I estimate the effect of the lowest-cost route distance on trade costs when the relative costs of each mode ($\boldsymbol{\alpha}$) are set to observed historical relative freight rates (in 1900). I use the relative per unit distance freight rates described in section 2 (at their midpoints): $\alpha^{road} = 4.5$, $\alpha^{river} = 3.0$, and $\alpha^{coast} = 2.25$ (all relative to the freight rate of railroad transport, normalized to 1). Column 2 demonstrates that the elasticity of trade costs with respect to the lowest-cost route distance, calculated at observed freight rates, is 0.135.

However, as argued above, it is possible that these observed relative freight rates do not capture the full benefits of railroad transport relative to alternative modes of transportation. For this reason the NLS specifications in columns 3-5 estimate the relative freight rates (ie the parameters $\boldsymbol{\alpha}$) that minimize the sum of squared residuals in equation (11). In column 3 I estimate equation (11) without district-source specific trends included and find an elasticity of salt prices with respect to the lowest-cost route distance 0.255.

A potential concern with the specification in column 3 is that the lowest-cost route distance may be trending over time because an approaching railroad line will steadily reduce trade costs. Unobserved determinants of trade costs (such as a steadily improving institutional environment conducive to interregional trade) may also be trending over time, and there is a risk that these unobserved determinants may be attributed to the railroad network. I therefore allow each district-salt source pair to have its own (log) linear trend term in column 4. This reduces the coefficient on the lowest-cost route measure by a small amount, but this coefficient is still economically and statistically significant. Column 4 is my preferred specification. Even when controlling for all unobserved, time-constant and trending determinants of trade costs between all salt sources and destinations, reductions in trade costs along lowest-cost routes (estimated from time variation in these routes alone) have a large effect on salt prices.

The non-linear specification in column 4 also estimates the relative trade costs by mode that best explain observed salt price differentials. Each of the three alternative modes of transport is larger than one, implying that these alternative modes are more expensive (per unit distance) than rail travel. Further, each of these non-rail modes has higher estimated costs, relative to railroads, than historically observed freight rates. This suggests that the advantages of railroads to encouraging trade were significant, but not entirely reflected in observed freight rates.

To summarize the results in column 4: the coefficient on the lowest-cost route distance ($\widehat{\delta}$) is positive, which implies that trade costs increase with effective distance (in railroad-equivalent kilometers); and the estimated mode-specific per-unit distance costs ($\widehat{\boldsymbol{\alpha}}$) are all much greater than one, implying that railroads were instrumental in reducing effective distance when compared to alternative modes of transportation (especially when compared to roads, which I find were almost eight times more costly to use per unit distance than railroads).

Finally, in column 5 I include both the bilateral railroad dummy variable, and the lowest-cost route variable. The bilateral railroad dummy is no longer statistically significantly different from zero, and its point estimate is much smaller than in column 1. By contrast, the lowest-cost route trade costs variable is still large and statistically significant, and its magnitude is similar to that in column 4. This suggests that the lowest-cost route measure is explaining genuine features of the railroad network as it impacted on salt prices. I use the estimates in column 4, my preferred specification, in the next stages of my empirical strategy.

5 Empirical Step 2: Railroads and Trade Flows

The first step of my empirical strategy demonstrated that railroads reduced trade costs. I now estimate the extent to which the reduction in trade costs brought about by India's railroad network (estimated in Step 1) affected trade flows within India, and trade flows between India and its international trade partners. This step is important for two reasons. First, an expansion of trade volumes as a result of the railroad network is a necessary condition for the mechanism linking railroads to welfare gains in the model. Second, as I show below, estimating the model's gravity equation allows all of the model's parameters to be inferred. Equipped with these parameter estimates I am better able to test Predictions 3-6 in the sections that follow.

5.1 Empirical Strategy

Prediction 2 of the model suggests a particular relationship between bilateral trade flows and bilateral trade costs—a gravity equation describing trade between any two regions. Substituting the empirical specification for T^k_{odt} introduced in equation (11) into equation (8) yields

$$\ln X^k_{odt} = \beta^k_{od} + \phi^k_{od} t + \ln A^k_{ot} - \theta_k \ln r_{ot} - \theta_k \delta \ln TC(\mathbf{R}_t)_{odt} + \theta_k \ln p^k_{dt} + \ln X^k_{dt} + \varepsilon^k_{odt}. \tag{12}$$

Here, X^k_{odt} refers to the value of exports of commodity k from region o to region d in year t (and the other variables were defined in section 3.

I estimate two versions of this bilateral exports equation, each with a different goal in mind. The *first version* investigates whether the construction of India's railroad network increased trade in India. To do this I estimate the equation

$$\ln X^k_{odt} = \beta^k_{ot} + \beta^k_{dt} + \beta^k_{od} + \phi^k_{od} t + \rho \ln TC(\mathbf{R}_t)_{odt} + \varepsilon^k_{odt}. \tag{13}$$

In this specification, the term β^k_{ot} is an origin-year-commodity fixed effect and β^k_{dt} is a destination-year-commodity fixed effect (the inclusion of these two fixed-effects are suggested by the model in equation (12)); β^k_{od} is an origin-destination-commodity fixed effect and the term $\phi^k_{od} t$ allows for each origin-destination-commodity to have its own trend term (these two terms were motivated in section 4 by the concern that some costs of trading may be unobservable). The coefficient ρ on the trade costs proxy variable $\ln TC(\mathbf{R}_t)_{odt}$ is therefore estimated purely from time variation in the railroad network that affects an exporter differently across its trading destinations. Prediction 2 is that the coefficient ρ will be negative—that, conditional on importer and exporter fixed effects (for each commodity), the lower trade costs brought about by railroads increase trade.[49]

In following sections of this paper I assume that the trade cost parameters for salt (which I estimated in Step 1) apply to other commodities as well. One potential concern with this assumption is that the parameter δ, which relates the lowest-cost route variable ($LCR(\mathbf{R}_t, \boldsymbol{\alpha})_{odt}$) to trade costs, may vary across commodities. To explore this possibility while estimating equation (13) (which is pooled across commodities), I use $LCR(\mathbf{R}_t, \boldsymbol{\alpha})_{odt}$ as a proxy for the trade cost term $TC(\mathbf{R}_t)_{odt}$ and also include interaction terms between $LCR(\mathbf{R}_t, \boldsymbol{\alpha})_{odt}$ and commodity-specific characteristics.[50] The characteristics I include are weight per unit value and the 'freight class' in which each commodity was placed by railroad companies—both measured at the start of the period. If the effect of $LCR(\mathbf{R}_t, \boldsymbol{\alpha})_{odt}$ on trade flows does not vary across commodities according to these characteristics (which capture the most obvious reasons why per unit distance trade costs could differ by commod-

[49]The coefficient ρ is not the general equilibrium elasticity of trade flows with respect to trade costs. This is because equation (12) also contains the endogenous variables, land rental rates r_{ot}, goods prices p^k_{dt}, and aggregate expenditure X^k_{dt}. I control for these endogenous variables (by the use of fixed effects) in my estimating equation (13), so they do not present a risk of bias to the estimation of ρ; however, comparative statics exercises (such as the general equilibrium elasticity of trade costs with respect to trade flows) must allow these endogenous variables to adjust. Following Anderson and van Wincoop (2003), the coefficient ρ is best thought of as a partial equilibrium elasticity, which holds constant all of these necessary adjustments in other goods markets and the factor market. However, as these authors note, the sign of the true (general equilibrium) elasticity will be of the same sign as the partial equilibrium elasticity estimated here.

[50]In this specification $\ln LCR(\widehat{\boldsymbol{\alpha}}, \mathbf{R}_t)_{odt}$ is a generated regressor because the parameter $\boldsymbol{\alpha}$ was estimated in Step 1. I therefore correct the standard errors in this regression to account for the presence of a generated regressor using a two-step bootstrap procedure.

ity) then this would be consistent with the assumption that trade costs for salt are representative of trade costs for other commodities. A second concern with this assumption is that the relative per unit distance cost of using each mode of transportation ($\boldsymbol{\alpha}$) may also vary across commodities, so that my parameter estimates of $\boldsymbol{\alpha}$, also obtained from salt, do not carry over to other commodities. I discuss evidence that is inconsistent with this second concern below.

The *second version* of equation (12) that I estimate takes the model more seriously in order to estimate unknown parameters of the model. Two sets of parameters remain unknown: the technology parameter θ_k (for each commodity), and the productivity parameters A_{ot}^k (for each district, year and commodity). I first estimate the parameters θ_k by substituting the lowest-cost route distance proxy for trade costs estimated in Step 1 (ie $\widehat{\delta} \ln LCR(\widehat{\boldsymbol{\alpha}}, \mathbf{R}_t)_{odt}$, where $\widehat{\delta}$ and $\widehat{\boldsymbol{\alpha}}$ were estimated in Step 1) into equation (12) to obtain

$$\ln X_{odt}^k = \beta_{ot}^k + \beta_{dt}^k + \beta_{od}^k + \phi_{od}^k t - \theta_k \widehat{\delta} \ln LCR(\mathbf{R}_t, \widehat{\boldsymbol{\alpha}})_{odt} + \varepsilon_{odt}^k. \tag{14}$$

In this specification, the coefficient on the lowest-cost route distance variable ($\hat{\delta} \ln LCR(\widehat{\boldsymbol{\alpha}}, \mathbf{R}_t)_{odt}$) is exactly θ_k. Intuitively, the scope for comparative advantage (the inverse of θ_k) governs how much a reduction in trade costs translates into an expansion of trade. I therefore estimate this equation separately for each of the 85 commodities in my trade flows dataset, in order to estimate 85 values of θ_k (one for each commodity k).

Armed with the parameter estimates $\widehat{\theta_k}$ it is then possible to estimate the other unknown variable in the model, the unobserved productivity term, A_{ot}^k (though this is only possible for agricultural commodities). I relate A_{ot}^k to observables by assuming that A_{ot}^k is a function of a *crop-specific rainfall shock*, denoted by $RAIN_{ot}^k$. As argued in section 2, rainfall was an important determinant of agricultural productivity in India because irrigation was uncommon. However, a given distribution of annual rainfall would affect each crop differently because each crop has its own annual timetable for sowing, growing and harvesting, and these timetables differ from district to district. To shed light on these crop- and district-specific agricultural timetables, I draw on the 1967 publication, the *Indian Crop Calendar* (Directorate of Economics and Statistics 1967), which lists sowing, growing and harvesting windows for each crop and district in my sample.[51] To construct the variable $RAIN_{ot}^k$, I use daily rainfall data to calculate the amount of rainfall in year t that fell between the first sowing date and the last harvest date listed for crop k in district o.

It is then possible to estimate the relationship between rainfall and productivity by noting that

[51]This publication describes the technology of agricultural practice (related to scheduling of activities) in each district. This particular aspect of agricultural technology is unlikely to have changed between my sample period and 1967 because the optimal sowing date for a crop depends on the amount of water in the soil on that date, which is governed by the type of soil and the local climate (Mukerji 1915), both of which are unlikely to change over this time frame. Nevertheless, to test for this stability of agricultural scheduling I use the earliest *Crop Calendar* that I was able to access, which is from 1908. This volume presents data at larger geographic areas than the district. However, when I calculate crop-specific sowing and growing rainfall amounts for these larger geographic areas the correlation between these and the (area-weighted average) 1967 district-level amounts is 0.78. This is a strong correlation, especially given that the district-level data is aggregated, indicating that the timing of agricultural activities has not changed dramatically (from 1908 to 1967 at least).

the exporter-commodity-year fixed effect (β_{ot}^k) in equation (14) can be interpreted in the model as $\beta_{ot}^k = \ln A_{ot}^k - \theta_k \ln r_{ot}$, by comparing equations (12) and (14).[52] I model the relationship between productivity (A_{ot}^k) and rainfall ($RAIN_{ot}^k$) in the simplest possible semi-log manner: $\ln A_{ot}^k = \kappa RAIN_{ot}^k$.[53] Guided by this relationship, I estimate the parameter κ in the following estimating equation:

$$\widehat{\beta}_{ot}^k + \widehat{\theta}_k \ln r_{ot} = \beta_o^k + \beta_t^k + \beta_{ot} + \kappa RAIN_{ot}^k + \varepsilon_{odt}^k. \tag{15}$$

In this equation, $\widehat{\beta}_{ot}^k$ is the estimated exporter-commodity-year fixed effect, and $\widehat{\theta}_k$ is the estimated technology parameter, both of which are estimated in equation (14) above. The terms β_o^k, β_t^k, and β_{ot} represent exporter-commodity, commodity-year and exporter-year fixed effects, respectively. I include these terms to control for unobserved determinants of exporting success that do not vary across regions, commodities *and* time. For example, the exporter-commodity fixed effect (β_o^k) controls for all time-invariant factors that make region o successful at exporting commodity k (such as the region's altitude). As a result, the coefficient κ is estimated purely from the variation in rainfall over space, commodities and time. The final term in equation (15) is an error term (ε_{odt}^k) that includes any determinants of exporting success, other than rainfall, that vary across regions, commodities and time.

In summary, the method described in this second version of estimating equation (12) estimates the parameter θ_k for each of the 85 goods k for which I have trade data. This method also estimates the relationship between the unobserved productivity terms A_{ot}^k and crop-specific rainfall $RAIN_{ot}^k$ (governed by the parameter κ).

5.2 Data

I estimate equations (13), (14) and (15) using over six million observations on Indian trade flows that I have collected. The trade flow data relate to both internal trade data (between 45 trade blocks of India) and external trade data (between each of these 45 internal trade blocks and 23 foreign countries), over rail, river and coastal transport routes, for 85 commodities, annually from 1880 to 1920. When estimating equation (15), I use the crop-specific rainfall measure ($RAIN_{ot}^k$) described briefly above (and in more detail in Appendix A) and, lacking reliable data on land rental rates, I use nominal agricultural GDP per acre as a measure of r_{ot} (since in my model these two measures are equivalent).

[52] Intuitively, higher productivity in commodity k (A_{ot}^k) will increase region o's propensity to export to any location, leading to a higher exporter fixed effect β_{ot}^k; however, higher productivity will also raise the land rental rate (r_{ot}), decreasing the propensity to export, and a lower exporter fixed effect.

[53] It is also possible that the marginal productivity of rainfall is diminishing, becoming detrimental to production at some point. With such effects in mind I have also estimated a specification where I include both $RAIN_{ot}^k$ and $(RAIN_{ot}^k)^2$. However, in this alternative specification, the coefficient on the squared amount of rainfall is actually positive (implying increasing marginal productivity of rainfall), but never statistically significant.

5.3 Results

Table 3 presents results from this section. Column 1 contains estimates of equation (13) using OLS, where the trade costs proxy used is the bilateral railroad dummy variable.[54] The coefficient on the railroad dummy variable is positive and statistically significant—even though, as argued in section 4, the coefficient on this trade costs proxy is likely to be biased downwards. very precisely estimated. This suggests that railroads significantly boosted trade, and provides support for prediction 2.

In column 2 of table 3 I estimate equation (13) again, this time with the lowest-cost route variable used to proxy for trade costs instead of the railroad dummy variable. The lowest-cost route distance proxy depends on the unknown parameters $\boldsymbol{\alpha}$, the per unit distance trade costs along each mode of transportation, relative to rail transport. In order to compute the lowest-cost route distance in estimating equation (13), I use the estimated value of the parameters $\boldsymbol{\alpha}$ presented in column 4 of table 2. This requires the maintained assumption that the *relative* cost of transporting any commodity by rail (relative to other modes) is the same as that for salt; that is, the per-unit distance trade cost may differ across commodities, but in a way such that the relative cost of using non-rail transport relative to rail transport is the same for all commodities.[55] The results in column 2 provide further support for prediction 2, as the lowest-cost route measure is estimated to reduce bilateral trade (conditional on the fixed effects used) with a statistically significant elasticity of (minus) 1.3. This result is in line with a large body of work on estimating gravity equations.[56]

In column 3 of table 3 I investigate the possibility that the elasticity of trade flows with respect to lowest-cost route distance routes varies by commodity. I do this by including interaction terms between the lowest-cost route distance variable and two commodity-specific characteristics: weight per unit value (as observed in 1880 prices, averaged over all of India), and 'freight class' (an indicator used by railroad companies in 1880 to distinguish between 'high-value' and 'low-value' goods). The results in column 3 are not supportive of the notion that commodities had trade flow elasticities with respect to trade costs that depend on weight, or freight class; that is, neither of these interaction terms is significantly different from zero (nor are they jointly significantly different from zero). This lends support to the maintained assumption throughout this paper that trade cost parameters

[54] Because my trade flow data is available for trade blocks, which are larger than districts, I define the 'bilateral railroad dummy' variable here ($RAIL_{odt}$) as the share of district pairs between trade block o and trade block d that are connected by the railroad network.

[55] One piece of evidence consistent with this assumption comes from data on district-to-district trade flows (for each of 15 goods, one of which is salt) in Bengal from 1877 to 1881, along each of the three modes of transport available in that area (rail, river and road). I regress log bilateral exports by road relative to exports by rail on exporter-importer-year fixed effects, and a fixed effect for each commodity. The F-test that these commodity-level fixed effects are all equal to each other has a p-value of 0.34, so it cannot be rejected at the 5 percent level. A similar test for a regression with exports by river relative to exports by rail has a p-value of 0.28. These results are consistent with the view that, within an exporter-importer-year cell, goods do not have systematically different trade costs.

[56] Head and Disdier (2008) conduct a meta-study of 103 papers estimating the coefficient on bilateral distance in a gravity equation. They find a mean estimate of this coefficient of 0.9 (with 90 percent of estimates lying between 0.28 and 1.55). That my result is higher than the mean estimate in these 103 papers is unsurprising because they were estimated primarily on post-1960 data. Technological improvements in transportation (ocean shipping and air freight) and telecommunications are likely to have reduced the trade-impeding effects of distance, when compared to railroad transportation and communication in 1880-1920 India.

for the shipment of salt can be applied to other commodities, without doing injustice to the data.

Finally, I estimate equation (14) in a manner that allows me to estimate all of the remaining unknown parameters of the model. I begin by estimating equation (14), one commodity at a time (for each of the 85 commodities in the trade flows data), in order to obtain estimates of the comparative advantage parameters θ_k for each commodity. The mean across all of these 85 commodities is 5.2 (with a standard deviation across commodities of 2.1). This is slightly lower than the preferred estimate of 8.28 in Eaton and Kortum (2002) obtained from intra-OECD trade flows in 1995, treating all of the manufacturing sector as one commodity.[57] However, the mean value of θ_k across only the 17 principal agricultural commodities for which I have output and price data (and therefore use heavily below) is 3.8 (with a standard deviation of 1.2). This suggests a greater scope for comparative advantage based gains from trade among agricultural goods than among manufacturing goods, at least in colonial India.

I then estimate equation (15) to obtain an estimate of κ, the parameter that relates crop-specific rainfall to (potential) productivity (A^k_{ot} in the model). I estimate a value of 0.441 for κ (with a standard error of 0.082), implying that a one standard deviation (0.605 m) increase in crop-specific rainfall causes a 27 percent increase in agricultural productivity (as defined by A^k_{ot} in the model). This suggests that rainfall has a positive and statistically significant effect on productivity, as expected given the importance of water in crop production and the paucity of irrigated agriculture in colonial India (as discussed in section 2).

In summary, the results from this section demonstrate that railroads significantly expanded trade in India. This finding is in line with Prediction 2 and suggests that the expansion of trade brought about by the railroad network could have given rise to welfare gains due to increasingly captured gains from trade. A second purpose of this section was to use the empirical relationship between trade costs (estimated in Step 1) and trade flows to estimate the remaining unknown model parameters, θ_k and A^k_{ot}. These parameters are important inputs for Steps 3 to 6 below.

6 Empirical Step 3: Railroads and Price Responsiveness

The results in Steps 1 and 2 indicate that India's railroad network significantly reduced trade costs and expanded trade. I now investigate the impact of this change in the trading environment on the prices of tradable commodities. In particular, following prediction 3 of the model, I test the hypothesis that railroads reduced the responsiveness of local agricultural prices to local rainfall (an exogenous determinant of local productivity). In a small open economy (SOE), price responsiveness is zero since local prices are equal to the (exogenous) world price level. However, as trade costs rise and an economy departs from the SOE limit, price responsiveness in that economy should rise (as in prediction 3). The extent of price responsiveness in a district is therefore a novel and powerful

[57] Using two alternative methods Eaton and Kortum (2002) also obtained estimates of 3.60 and 12.86.

test of its openness to trade, which motivates the empirical exercise in this section.[58] A second goal of this section is to evaluate the performance of my model at predicting the price behavior seen in the data in an 'out-of-sample' sense (because the model was estimated in Steps 1 and 2 using no agricultural price information).

6.1 Empirical Strategy

Prediction 3 has two parts: (1) when a district is connected to the railroad network, agricultural goods prices in that district will be less responsive to productivity shocks in that district; and (2), when a railroad line connects two districts, agricultural goods prices in a district will be more responsive to productivity shocks in the other district.

I test this prediction by estimating the following linear specification (which can be interpreted as a linear approximation to the model to the model around a symmetric point):

$$\begin{aligned} \ln p^k_{dt} = \beta^k_d \quad &+ \quad \beta^k_t + \beta_{dt} + \chi_1 RAIN^k_{dt} + \chi_2 RAIL_{dt} \times RAIN^k_{dt} + \chi_3 (\tfrac{1}{N_d}) \sum_{o \in \mathbf{N}_d} RAIN^k_{ot} \\ &+ \quad \chi_4 (\tfrac{1}{N_d}) \sum_{o \in \mathbf{N}_d} RAIN^k_{ot} \times RAIL_{odt} + \varepsilon^k_{dt}. \end{aligned} \tag{16}$$

Here, p^k_{dt} represents the retail price of agricultural crop k in district d and year t. $RAIN^k_{dt}$ is the amount of crop-specific rainfall that fell in district d in year t (this variable is described in full in section 5 where it was first used). The variable $RAIL_{dt}$ is a dummy variable equal to one when the railroad network enters the boundary of district d, while the variable $RAIL_{odt}$ is a dummy variable equal to one when it is possible to travel from district o to district d using only the railroad network. Finally, the variable $RAIN^k_{ot}$ represents the amount of crop-specific rainfall in district o, where district o is a neighbor of district d—one of the the N_d districts ($o \neq d$) in district d's neighborhood $\mathbf{N}_d$ (taken to be all districts that lie even partially inside a 250 km radius of district d's centroid).[59] The summation terms in equation (16) are divided by the number of districts N_d in the neighborhood $\mathbf{N}_d$ to reflect an average effect.

I estimate equation (16) using fixed effects for each district-year (β_{dt}), which control for any

[58] To my knowledge, this is a novel test for assessing a change in market integration. However, two papers are closely related. First, Shiue (2002) examines how the price correlation (over many years) between pairs of markets in 19th Century China is related to the weather correlation (over the same years) in these pairs, comparing this correlation in inland locations to that along rivers or the coast. Second, Keller and Shiue (2007a) estimate formally, in the same setting, how the spatial dependence of weather shocks (on prices) varies between inland and water-accessible regions. Neither of these papers focuses on the responsiveness of local prices to local rainfall, nor on whether the spatial transmission of weather shocks is different along some transportation links (such as railroads) than along others (such as roads), in the manner I do here.

[59] While in principle the rainfall in any district o could affect prices in district d, my model suggests that these effects are likely to die out quickly over distance. In a partial equilibrium sense (that is, without allowing for the land rental rate r_o to adjust), this can be seen easily in equation (4). Here, each distant district's productivity term A^k_o affects local prices p^k_d in a manner proportional to $(T^k_{od})^{-\theta_k}$, where T^k_{od} is the trade cost (proportional to distance) and θ_k was estimated in Step 2 as 3.8. I therefore restrict the effect of non-local rainfall on district d's prices to that in a short (250 km) range, though my results are insensitive to using smaller (eg 100 km) or larger (eg 500 km) ranges.

unobservable variables affecting prices that are constant across crops within a district and year. This means that I identify price responsiveness through variation in how a given amount of annual rainfall in a district affects each of that district's crops differently. I also include fixed effects for each district-crop (β_d^k) to control for unobservables that permanently affect a district's productivity of a given crop (such as the district's soil type), and fixed effects for each crop-year (β_t^k) to control for country-wide shocks to the price of each crop.

To the extent that rainfall is a significant determinant of productivity (as I found to be the case revealed in trade flows, in Step 2), the coefficients χ_1 and χ_3 will be negative. Prediction 3 (a) states that the coefficient χ_2 is positive (prices in district d are less responsive to rainfall in district d if district d is on the railroad network). And prediction 3 (b) states that the coefficient χ_4 is negative (lower transport costs should make prices in district d more responsive to rainfall shocks in neighboring districts to d). A positive coefficient χ_2 is consistent with railroads increasing the extent of market integration in India.

6.2 Data

I estimate equation (16) using annual data on the retail price of 17 agricultural commodities, in 239 districts, from 1861-1930. These prices were collected by district officers who visited the 10-15 largest retail markets in each district once every two weeks. India-wide instructions were issued to each province to ensure that prices of each commodity were recorded in a consistent manner across the provinces. The other variables used to estimate equation (16), concerning railroads and rainfall, were described in sections 4 and 5, respectively.

6.3 Results

Table 4 presents results from OLS estimates of equation (16). Column 1 begins by regressing (log) agricultural prices in a district on the district's crop-specific local rainfall. The coefficient on local rainfall is negative and statistically significant, suggesting that rainfall has a positive impact on crop output, and this increase in supply transmits into local retail prices. This is indicative of imperfect market integration in these agricultural commodities *on average* over the time period 1861-1930 in India. The coefficient estimate implies a large amount of price responsiveness on average over the period: a one standard deviation (ie 0.604 m) increase in a crop's crop-specific rainfall decreases that crop's prices by approximately 15 percent.

Column 2 of table 4 then tests the first part of prediction 3: that a district's prices will be less responsive to local rainfall after the district is connected to the railroad network. In this specification the coefficient on local rainfall (χ_1 in equation (16)) represents price responsiveness before railroads penetrate a district. The estimated coefficient is negative, statistically significant, and demonstrates a great deal of price responsiveness in the pre-railroad. Further, in line with prediction 3, the coefficient χ_2 on rainfall interacted with a dummy for railroad access ($RAIL_{dt}$) is positive and statistically significant. The sum of the coefficients χ_1 and χ_2 represents the extent of price responsiveness after the district is brought into the railroad network. The estimated coefficients sum to -0.014 which implies that prices are still responsive to local rainfall, but in a dramatically reduced sense when compared to the coefficient of -0.428 that measures price responsiveness in the pre-rail era. However, I cannot reject the null of zero price responsiveness in the post-rail era. These findings suggests that the imperfect market integration from 1861-1930 found in column 1 reflects an average of two extreme regimes separated by the arrival of a railroad line in a district: a first regime of imperfect integration before the railroad arrives (where local supply shocks have large effects on local prices), and a second regime of near-perfect integration after the railroad arrives (where local supply shocks have a negligible effect on local prices).

Column 3 repeats the specification in column 1, but with the inclusion of average rainfall in neighboring districts. The effect of neighboring districts' rainfall on local prices is negative and statistically significant, which implies that, on average over the period from 1861-1930, neighboring districts' supply shocks affected local prices, as is consistent with some degree of market integration.

However, the estimates in column 4 demonstrate that, as was the case in column 2, the average effect in column 3 is masking the behavior of two different regimes. Column 4 estimates equation (16) in its entirety by including an interaction term between each neighboring district's rainfall and a dummy variable for whether that district is connected to the 'local' district by railroad (ie $RAIL_{odt}$). As is consistent with the second part of prediction 3, the coefficient on this interaction term is negative and statistically significant. Furthermore, the coefficient on neighboring districts' rainfall (which is now the effect of rainfall in districts not connected by railroad to the local district) is not significantly different from zero. Column 4 therefore suggests that local prices do respond to neighboring districts' supply shocks when those neighbors are connected to the local district by railroads; however, neighboring districts' supply shocks are irrelevant to local prices when there is no railroad connection.

To summarize the results from this section, I find that railroads played a dramatic role in facilitating market integration, as revealed by price responsiveness, among the 17 agricultural goods in my sample. This is consistent with both parts of prediction 3 of the model, and suggests that railroads significantly improved the trading environment in colonial India.

6.4 Model Evaluation

The results in table 4 find significant support for the price responsiveness relationships in prediction 3. A more direct test of the model's predictions on price behavior is to compare prices in the model (for each district, year and crop) to those in the data. To do this I estimate the regression:

$$\ln p_{dt}^k = \beta_d^k + \beta_t^k + \beta_{dt} + \varpi \ln \widehat{p}_{dt}^k + \varepsilon_{dt}^k, \tag{17}$$

where p_{dt}^k is the observed set of prices and $\widehat{p}_{dt}^k$ is the predicted set of prices. If the model is specified correctly then the coefficient ϖ should be equal to one. I include the fixed effects β_d^k, β_t^k and β_{dt} in this specification in order to test the model using the same variation as in equation (16).

I estimate this equation using the same data as described earlier in this section. In order to compute predicted prices ($\widehat{p}^k_{dt}$), I solve the model completely (in each period) using the estimated parameters from Steps 1 and 2 and the observed exogenous variables (railroads, rainfall and land area) in each period.[60]

I find an estimated coefficient of $\widehat{\varpi} = 0.913$ (with a standard error of 0.189), which implies that the model has significant predictive power. Since the model's parameters are estimated using data that did not include the agricultural price data that I use to estimate equation (17) here, this constitutes an 'out-of-sample' test of the model at which the model performs well. This increases my confidence that the model is capable of replicating features of the data, and its ability to inform the mechanisms behind my reduced-form estimates (a use to which I put the model in Step 6).

7 Empirical Step 4: Railroads and Real Income Levels

Steps 1 to 3 have established that Indian railroads significantly reduced trade costs, expanded trade, and reduced price responsiveness. These findings suggest that railroads dramatically changed the trading environment in India. I now go on to investigate the welfare consequences of railroad expansion in India by estimating the effect of railroads on real income levels (in this section) and real income volatility (in Step 5, the next section).

7.1 Empirical Strategy

Prediction 4 of my model states that a district's real income will increase when it is connected to the railroad network, but that its real income will fall as one of its neighbors is connected to the railroad network (holding its own access constant). These predictions motivate an estimating equation of the form

$$\ln\left(\frac{r_{ot}}{\widetilde{P}_{ot}}\right) = \beta_o + \beta_t + \gamma RAIL_{ot} + \psi(\tfrac{1}{N_o}) \sum_{d \in \mathbf{N}_o} RAIL_{dt} + \varepsilon_{ot}. \tag{18}$$

In this estimating equation, $\frac{r_{ot}}{\widetilde{P}_{ot}}$ represents real agricultural income per acre in district o and year t. In my model, r_{ot} is the nominal land rental rate, but I have been unable to find systematic data on land rents in this time period. However, in my model, nominal land rents are equal to nominal output per unit area, on which data was collected in the agricultural sector (the dominant sector of the colonial Indian economy), so I use this to measure r_{ot}.[61] The denominator, $\widetilde{P}_{ot}$, is a consumer

[60] This is laid out in more detail in section 9, when I use a similar procedure.

[61] Real income per acre is equal to welfare (for a representative agent) in my model, but may not be in my empirical setting because output per acre may diverge from output per capita if the population of each district is endogenous, and related to railroad expansion. Population could be endogenous for two reasons. First, fertility and mortality may have been endogenous in the setting of colonial India—in a Malthusian limit, fertility and mortality would adjust to any agricultural productivity improvements (due to railroads) and hold output per capita constant. However, the potential for endogeneous fertility and mortality responses is likely to vary from setting to setting so while an effect of railroads on output per acre is transferable to alternative settings, an effect on output per

price index.[62]

The first regressor in equation (18) is $RAIL_{ot}$, a dummy variable that is equal to one in all years t in which some part of district o is on the railroad network. The summation term captures the effect of railroads in other, neighboring districts on the level of real income in the district of observation o.[63] Finally, I estimate equation (18) using fixed effects at the district (β_o) and year (β_t) levels, so that the effect of railroads is identified entirely from variation within districts over time, after accounting for common macro shocks affecting all districts. The district fixed effect is particularly important because it controls for permanent features of districts that may have made them both agriculturally productive, and attractive places to build railroads.

Prediction 4 states that the coefficient γ on district o's own railway access will be positive, but the coefficient ψ on district o's neighbors' access will be negative. A number of alternative theories (whether stressing trade mechanisms or otherwise) could make similar predictions about the signs of these coefficients (especially about γ). For this reason, in Step 6 I go beyond the qualitative test of my model provided by the signs of γ and ψ and assess the *quantitative* performance of the model in predicting real income changes due to the expansion of the railroad network.

I begin below (in section 7.3) by estimating equation (18) using OLS. Unbiased OLS estimates require there to be no correlation between the error term (ε_{ot}) and the regressors ($RAIL_{ot}$ and $(\frac{1}{N_o})\sum_{d\in\mathbf{N}_o} RAIL_{dt}$), conditional on the district and year fixed effects. This requirement would fail if railroads were built in districts and years that were expected to experience real agricultural income growth, or if railroads were built in districts that were on differing unobserved trends from non-railroad districts. For this reason I pursue three strategies to assess the potential magnitude of bias in my OLS results due to non-random railroad placement: four placebo specifications (section 7.4), instrumental variable estimates (section 7.5) and a bounds check (section 7.6).

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capita is potentially less so. Second, migration could respond to differential productivity improvements over space. Migration, however, was extremely limited in colonial India when compared to other countries in the same time period (a feature that is still true today, and that Munshi and Rosenzweig (2007) argue is due to informal insurance provided by localized caste networks), and the little migration that occurred was vastly skewed toward women migrating to marry (Davs 1951, Rosenzweig and Stark 1989). Nevertheless, to test the hypothesis that the limited migration was correlated with railroad construction I have collected data on district-to-district bilateral migration as revealed from birthplaces, recorded in the decadal censuses in colonial India. I find (in OLS regressions that control for district pair fixed-effects) that there is no statistically significant net migration into districts receiving a railroad line from neighboring districts left off the railroad network (so migration is unlikely to have been strong enough to act to equalize output per capita), and that bilateral railroad connections between districts do not statistically significantly correlate with bilateral migration between districts (so the railroads do not seem to have facilitated migration). However, I do not observe intra-district migration, which may have been significant.

[62]In the model this price index is given in equation (9). However, it would be unsurprising if a price index calculated in the manner suggested by my theory fits my model well. To perform a more powerful test of the model I therefore use a flexible price index (the Fisher ideal price index) of the sort that is commonly used to construct real GDP measures from national income statistics.

[63]As in section 6, I take the neighborhood of district o (denoted by $\mathbf{N}_o$, and containing N_o districts) to consist of any districts for which any part of the district lies within a 250 km radius of the centroid of district o.

7.2 Data

I estimate equation (18) using annual data on real agricultural income (per acre of land) in 239 districts, from 1870 to 1930. This variable (calculated as nominal agricultural GDP calculated from 17 crops, deflated by a consumer price index and then divided by the district's land area) was described briefly in section 2 and in more detail in Appendix A. The variables $RAIL_{ot}$ and $RAIL_{dt}$ were described in section 5.

7.3 Results

Column 1 of table 5 presents OLS estimates of equation (18), with only the own-district regressor included. The coefficient estimate is 0.164, implying that in the average district, the arrival of the railroad network raised real agricultural income by over sixteen percent.

Prediction 4, along with the customs union literature in international trade theory, predicts that a district can suffer from trade diversion when one or more of its trade partners gains improved access to a third region's market. Because the arrival of the railroad network is spatially correlated, the specification in column 1 may confound the positive effects of a district's own access to the railroad network with the negative effect of access by its neighbors. Column 2 of table 5 checks for this negative effect of railroads by including as an additional regressor the extent to which a district's neighbors are connected to the railroad network (as in equation (18)). The coefficient on this additional variable is negative and statistically significant, indicating that losses from trade diversion are at work when a district's trading partners reduce trade costs between them but not the district of observation. In addition, the coefficient on own-district railroad access is higher in column 2 than in column 1—the point estimate (which is still statistically significant) now suggests that railroad access increases real agricultural income per acre by over 18 percent.

The results from including, in column 2, neighbors' railroad access highlight that railroad projects had a treatment externality on untreated districts. It is important to control for this treatment externality to prevent bias in estimates of the effect of railroad access. This result also highlights potential distributional consequences of railroad construction, whereby a project that is good for one region may be bad for its neighbors. [64]

The OLS results described here are in line with Prediction 4 and suggest that railroads has a large effect on real income in India. In the following three sections I pursue three strategies to explore the robustness of these findings to concerns over the non-random placement of railroads.

[64] My estimates suggest that the districts where railroads are built could feasibly make transfers to their neighbors that would compensate neighbors while leaving the constructing district better off. Unfortunately, I have been unable to find any data that would shed light on the extent of such transfers. Duflo and Pande (2007) use data from a household consumption survey to measure the effect of dam construction on consumption and poverty; the use of consumption data, which was recorded after any potential compensating transfers, allows these authors to argue that compensation of districts harmed by dam construction appears to be incomplete (and especially incomplete in districts with a history of relatively more extractive institutions). Unfortunately, such household consumption surveys only began in India in 1950.

7.4 Four Placebo Specifications

Empirical Strategy:

The first strategy I use to mitigate concerns of bias due to non-random railroad placement is to estimate the effects of 'placebo' railroad lines: over 40,000 km of railroad lines that went through various stages of the planning process, but were never actually built.[65] I group these placebo lines into four categories:

1. *Four-stage planning hierarchy:* From 1870-1947, India's Railways Department used one constant system for the evaluation of new railroad projects.[66] Line proposals received from the Indian and provincial governments would appear as *proposed* in the Department's annual *Railway Report*. This invited further discussion, and if the proposed line survived this criticism it would be *reconnoitered*. Providing this reconnaissance uncovered no major problems, every meter of the proposed line would then be *surveyed*, this time in painstaking and costly detail (usually taking several years to complete).[67] These detailed surveys would provide accurate estimates of expected construction costs, and lines whose surveys revealed modest costs would then be passed on to the Government to be *sanctioned*, or given final approval. The railroad planning process was therefore arranged as a four-stage hierarchy of tests that proposed lines had to pass.[68] I estimate equation (18), but additionally include regressors for railroad lines abandoned at each of these four planning stages (with separate coefficients on each). If line placement decisions were driven by unobservable determinants of agricultural income, it is likely that unbuilt lines would exhibit spurious effects (relative to the excluded category, areas in which lines were never even discussed) on agricultural income in OLS regressions. Further, it is likely that the lines that reached later planning stages would exhibit larger spurious effects than the lines abandoned early on (because higher expected benefits would be required to justify the increasingly costly survey process). The absence of such a pattern would cast doubt on the extent to which India's Railways Department was selecting districts for railroad projects on the basis of correlation with the error term in equation (18).

2. *Lawrence's proposal:* In 1868, Viceroy John Lawrence (head of the Government of India) proposed and had surveyed a 30-year expansion plan, broken into 5-year segments, that would

[65]This strategy is similar in spirit to that in Greenstone and Moretti (2004), who study the welfare impact of large industrial plants in the United States. They compare economic outcomes in the counties where these plants were built to outcomes in the plant's second-choice county (where the plant was not built).

[66]Strachey and Strachey (1882) review the early history of the Railways Department (part of the Department of Public Works until 1878). The Railway Department's annual *Railway Reports* describe the planning system in each year through to 1947.

[67]Reconnaissance was a form of low-cost survey of possible track locations (typically within 100 m of their eventual location), along with a statement of all necessary bridges, tunnels, cuttings and embankments. As Davidson (1868) and Wellington (1877) make clear, surveying was much more detailed, as its end goal was to identify the exact position of the intended lines, and a precise statement of all engineering works (down to the number of bricks required to build each bridge).

[68]This process of sequentially more detailed investigation is echoed in Wellington (1877), the standard textbook for railroad engineers and surveyors, in all English-speaking countries, in its day (which ran to six editions by 1906).

begin where Dalhousie's trunk lines (described in section 2.3) left off.[69] Lawrence consulted widely about the optimal routes for this railroad expansion, and drew upon his twenty-six years of experience as an administrator in India. Upon his retirement (from his fixed, five-year term) in 1869, construction on Lawrence's plan had just begun. But Lawrence's successor, the Earl of Mayo, immediately halted construction and vetoed Lawrence's proposal. Mayo was an outsider (who had never been to India before his appointment) and a fiscal conservative, and he wasted no time in criticizing the high costs of railroad construction in India. Instead, Mayo followed a more cautious approach to railroad expansion and Lawrence's plan was never built. However, Lawrence's plan provides a useful window on the trajectory that he and his Government expected in the districts where they planned to expand the railroad network. If anyone was capable of forecasting developments in each district's trading environment, developments that may be correlated with the error term in equation (18), it was likely to be Lawrence. To check for this, I estimate equation (18) and additionally include lines that were part of Lawrence's proposal. Because Lawrence's proposal was broken into six, five-year segments, I allow for separate coefficients on each of these segments and assume that the stated lines in a given five-year period would have opened at the beginning of the period. This provides an additional check: lines that Lawrence proposed to be built in relatively early time segments were presumably more attractive, higher priority proposals, that in addition were made under a shorter forecast horizon. Therefore, to the extent that Lawrence was able to forecast district-level developments, larger spurious effects should be found on these segments.

3. *Bombay and Madras Chambers of Commerce proposals:* In 1883, the Bombay and Madras Chambers of Commerce (bodies representing commercial interests) were invited to submit railroad expansion proposals. Their proposals recommended railroad expansion into areas with unrealized commercial potential (where the Chambers' interests lay). However, the Chambers' proposals were dismissed for paying too little attention to the potential costs of building these lines (costs that the Chambers would not incur). Because it is plausible that the Chambers possessed a great deal of expertise in the identification of commercial opportunities,[70] the Chambers' expansion proposals provide a unique window on the expected commercial trajectory in the regions where the Chambers recommended construction. I estimate equation (18) and additionally include lines that were mentioned in the Bombay and Madras Chambers of Commerce proposals. If the expected commercial trajectories identified by these Chambers are correlated with the error term in equation (18), then unbuilt lines in the Chambers' proposals should display spurious effects on real agricultural income. If no such effects are observed then this would call into question the ability for less commercially-interested agents, such as the Government of India (which planned India's railroad network)

[69] These segments appear in the plan (published in 1868) as "to be built over the next 5 years", "to be built between 6 and 10 years from now", etc.

[70] The potential for such expertise is clear in histories of the Bengal, Madras, Upper India, and Indian Chambers of Commerce in Tyson (1953), Times of India (1938), Tirumalai (1986), and Namjoshi and Sabade (1967), respectively.

to systematically forecast commercial developments in India's districts.

4. *Kennedy's proposal:* India's early line placement followed the suggestions of Lord Dalhousie (then head of the Government of India), but only after Dalhousie's decade-long debate with Major Kennedy (then India's Chief Engineer, who was charged with planning India's first railroad lines) over optimal route choice. Kennedy was convinced that railroad construction would be extremely expensive in India (Davidson 1868). He therefore sought to connect Dalhousie's chosen provincial capitals with a network of lines that followed the gentlest possible gradients, along river gradients and the coastline wherever possible.[71] Kennedy's proposal is useful for my identification strategy because it identifies districts with low railroad construction costs. Geographical features that favor low construction costs (such as topography, vegetation, and climate) may also favor agricultural production, and may result in differential unobservable trends in the real agricultural income of districts with favorable construction conditions; if favorable construction conditions drove railroad placement decisions then OLS estimates of equation (18) would erroneously attribute unobserved trends to railroad construction. I therefore estimate equation (18) including a variable that is an interaction between an indicator variable that captures districts that would have been penetrated by Kennedy's proposed network and a time trend.[72] If this variable predicts real agricultural income then this would be a concern for my identification strategy as it would suggest that the features that Kennedy found favorable for railroad construction (features that are presumably just as favorable to his successors) are correlated with real agricultural income growth. Because Kennedy's subdivided his proposal into high and low priority lines I also look for differential trends across these designations.

Results:

Table 6 presents estimates of the four placebo specifications described above. Column 1 compares the effect of railroad lines that were actually built to unbuilt railroad lines that were abandoned at various stages of the *four-stage planning hierarchy.* The coefficients on unbuilt lines are never statistically significantly different from zero, or of the same order of magnitude as built lines. Importantly, the coefficients on each hierarchical stage of the approval process do not display a tendency to increase as they reach advanced stages of the planning process.

Column 2 looks for spurious effects from lines identified in *Lawrence's proposal.* The coefficients on the lines that he proposed are all close to zero, an order of magnitude smaller than the coefficient

[71] The network that was built, by contrast, took straight lines in almost all circumstances, requiring in many cases (such as the Thal and Bhor Ghats) some of the most advanced railroad engineering works the world had ever seen (Andrew 1883). By 1869 it was clear that Kennedy's anticipated construction costs were, if anything, underestimates. These high construction costs were a major factor in Mayo's decision to abort Lawrence's plan, as described in my second placebo variable.

[72] Since Kennedy's proposal was first submitted in 1848, but my real agricultural income data begins in 1870, I cannot estimate the contemporaneous impact of Kennedy's proposed lines in the same manner as my other three placebo specifications.

on built lines, and never statistically significant. Further, the estimated coefficients on Lawrence's early proposals are no larger on average than those on his later proposals.

Column 3 performs a similar exercise using lines chosen by the *Bombay and Madras Chambers of Commerce*. The coefficients on the two Chambers' proposed lines are positive but very close to zero and not statistically significantly different from zero. And, as in column 2, these coefficients are an order of magnitude smaller than the (statistically significant) coefficients on built railroad lines.

Finally, column 4 examines the extent to which districts identified in *Major Kennedy's proposal*, as inexpensive districts in which to construct railroads, display different real agricultural income trends from other districts. The coefficients on Kennedy's two types of identified lines (high and low priority) are both close to zero and not statistically significantly different from zero. Crucially, the inclusion of this variable does not change appreciably the coefficient on built railroads.

These four sets of results display a consistent pattern. Regardless of the expert choosing potential railroad lines (India's public works department, India's most senior administrator at the height of his 26-year career, commercial interest groups, or India's chief engineer), or the motivation for doing so (lines attractive to the government for many potential reasons, commercially attractive lines, or low costs of construction) unbuilt lines identified by these experts are uncorrelated with time-varying unobservable determinants of real agricultural income growth. These results cast doubt on the extent to which the Government of India was willing or able to allocate railroads to districts on the basis of their expected evolution (or factors correlated with this evolution) in real agricultural income.

7.5 Instrumental Variable Estimates

Empirical Strategy:

After the 1876-78 famine in India, an official UK parliamentary commission—the 1880 Indian Famine Commission—met in London to inquire into the causes of this famine, and how future famines might be prevented. Of the 11 commissioners, nine were Members of Parliament, and no commissioner possessed particular expertise in Indian railroads (Bhatia 1967). Nevertheless, the Commission was unique among previous and subsequent famine commissions in recommending that railroads could prevent famine. Regions that received inadequate rainfall (and therefore suffered from famine) in the 1876-78 agricultural years were highlighted for railroad construction.[73]

This Commission's recommendation motivates my instrumental variable (IV) approach. I instrument for railroad construction in a district with a variable that is an interaction between the deviation of rainfall in the district in the 1876-78 agricultural years (May 1876 to April 1878) from its long-run (1870-1930) mean (over pairs of agricultural years),[74] and an indicator for the post-1884 period.[75] I demonstrate below that this variable has significant predictive power for railroad

[73]The 1880 Commission argued that the 1876-78 famine had been exacerbated by slow transportation of food into famine-stricken districts.

[74]For simplicity, I use the total amount of rainfall that fell in this period. However, I obtain similar results when I instead use a weighted average over the 17 crop-specific rainfall variables introduced in section 6, with weights suggested by the model (and introduced in section 8 below).

[75]I allow four years for the Commission's recommended lines to be constructed because the average length of time

construction in a district.

The exclusion restriction required for this instrument to provide consistent estimates of the coefficient γ in equation (18) is that rainfall shortages in the 1876-78 agricultural year affect real agricultural income six years later only because of their effect on railroad construction (due to the 1880 Famine Commission). There are two potential concerns with this exclusion restriction. The first potential concern is that rainfall may affect real agricultural income directly, because rainfall is an important input for rain-fed agriculture (I find direct evidence for this in Step 5 below, and indirect evidence for this as revealed in trade flows and price responsiveness in Steps 2 and 3, respectively). For this reason, I control for rainfall and rainfall lagged up to 10 years in my IV regressions. As I show below, there is no evidence for statistically significant effects of rainfall after a lag of more than one year, which casts doubt on the concern that rainfall shortages in 1876-78 have a direct effect on real agricultural income post-1884.

A second potential concern with this IV strategy is that famines (or the official inquiries that followed them) may have long-lived effects on real income by potentially changing policies, institutions, demographics (through mortality, fertility, or out-migration), or (animal and human) capital stocks. For this reason, I examine whether rainfall deviations (from long-run means) in the ten other years in which famine was officially declared (and official inquiries were conducted) in India appear to affect either railroad construction or real agricultural income six years later.[76] First, I find that rainfall in non-1876-78 famine years does not predict railroad construction six years later; this is an important falsification exercise because, of all the ten non-1880 famine inquiries, it was only the 1880 inquiry that mentioned railroad construction. Second, I find that in no other (ie non-1876-78) famine year do rainfall anomalies affect real agricultural income six years later. To the extent that all famines and their inquiries had the same potential for long-lived effects on agriculture, this suggests that it was not the famine or its inquiry *per se* that caused rainfall shortages in 1876-78 to have long-lived effects on real agricultural income.

In the light of these checks, a remaining concern with my instrumental variable's exclusion restriction is that the 1876-78 famine, or its 1880 Commission, was unique in some way other than its effect on railroad construction.[77] While the exclusion restriction is fundamentally untestable, it is comforting that the most obviously unique feature of the 1880 Commission was its recommendation of railroad construction (Bhatia 1967).

Results:

between a line first being proposed and being opened for traffic in my sample was 4.3 years.

[76] There were official parliamentary famine commissions after the 1896-97 and 1899-1900 famines, in addition to that after the 1876-78 famine. Official government inquiries were also commissioned after the 1866-67, 1868-70, 1873-74, 1888-89, 1905-06, 1906-07, 1907-08 and 1911-12 famines.

[77] This seems unlikely. For example, Visaria and Visaria (1983) summarize (in Appendix Table 5.2) the famines in my sample period in tabular form along four dimensions: the number of people killed, and the geographic regions (ie districts), land area, and number of people "affected". The 1876-78 famine is not an outlier in any of these dimensions. Lengthier treatments of famines in this time period, such as Bhatia (1967), McAlpin (1983), and Maharatna (1996), do not see the 1876-78 famine as particularly unique among India's colonial-era famines, especially when compared to the more severe 1896-97 and 1899-1900 famines.

Table 7 presents instrumental variable estimates of equation (18), beginning with first-stage estimates for the 1880 Famine Commission instrumental variable in column 1. These estimates demonstrate that the instrumental variable has a strong and statistically significant effect on railroad location (even after controlling for contemporaneous rainfall, lagged rainfall (of up to 3 lags) and district and year fixed effects). As this instrument has a high t-statistic, and the model is just-identified, standard concerns over weak instruments are unlikely to arise here (Stock, Wright, and Yogo 2002).[78] Column 1 also demonstrates that contemporaneous and lagged rainfall variables (up to three years of lags) do not predict railroad construction in general—these four variables are individually and jointly insignificant.[79] However, rainfall anomalies in one particular period, the 1876-78 agricultural years that were under the remit of the 1880 Famine Commission, do predict railroad construction after 1884.

Column 2 checks whether rainfall anomalies in ten other famine years that were officially declared as famines by the Government of India, other than 1876-78, predict railroad construction. After each of these famine years, official reports were commissioned to recommend policies for future famine, just as after the 1876-78 famine. To avoid estimating ten coefficients (one for each of the ten famines) I estimate only two different effects from these non-1876-78 famines: one for the five famines that were relatively more extreme (as defined by the number of people "affected"),[80] and one for the five that were relatively less extreme. The report on the 1876-78 famine was unique in strongly recommending railroad construction for famine prevention, and the results in column 2 are consistent with this view: I find that rainfall anomalies in other officially-declared famine years do not predict railroad construction, but anomalies in 1876-78 do.

The second-stage results, using the instrument to predict the railroad dummy variable ('railroad in district'), are presented in columns 3 and 4 of table 7. Column 3 includes the own-railroad and neighboring district railroad dummy variables; these IV estimates are statistically significantly different from zero, and of a very similar magnitude to the OLS results presented in table 5. This suggests that railroad line placement decisions were not driven by unobservable and time-varying determinants of real agricultural income, other than those already controlled for. Importantly, in column 3 I find that while contemporaneous rainfall has a large and statistically significant effect on real agricultural income (in line with OLS results in table 5), lagged values of rainfall (up to three lags) appear to have no effect.[81] This is reassuring from the perspective of the exclusion restriction for the use of rainfall in 1876-78 as an instrument for railroad construction post-1884. Finally, in column 4 I check whether rainfall anomalies in officially-declared famine years (other than 1876-78) have an effect on real agricultural income. I find no statistically significant coefficients on these vari-

[78]The (herteroskedasticity and serial correlation robust) F-statistic on the excluded instrument in the first stage is 7.91 (ie the square of this variable's t-statistic).

[79]An F-test for their joint significance has a p-value of 0.78 implying that the null hypothesis that their coefficients are all zero cannot be rejected.

[80]I take this measure from Visaria and Visaria (1983), Appendix 5.2. This is a more reliable measure of famine intensity than the number of people killed because of the difficulty of measuring deaths in these instances. The five most severe famines were those in 1868-70, 1873-74, 1896-97, 1899-1900 and 1907-08.

[81]I find that the same is true for rainfall lags up to 10 years.

ables (individually or jointly), which suggests that there are no long-run effects of rainfall anomalies in famine years, other than in 1876-78. This is likely to be due to the unique feature of the 1880 Famine Commission—that it recommended railroad construction.

7.6 Bounds Check

Empirical Strategy

A concern when estimating equation (18) is that of indeterminate bias due to either positive or negative selection on time-varying unobservables: some railroad projects may have targeted districts where growth was expected and infrastructure would earn higher returns (which would introduce positive bias due to selection on unobservables); other railroad projects may have targeted lagging districts that were nonetheless politically important (which would introduce negative bias due to selection on unobservables). The final strategy I employ to mitigate concerns about non-random placement explores the empirical relevance of this positive and negative bias due to potential selection on unobservables.

All lines built between 1883 and 1904 were required to be placed in one of four categories: 'productive' (expected to be commercially remunerative), 'protective' (intended to promote development in poorer, famine-prone regions), 'productive and protective', or 'military' (built for strategic motives). These categories were used for administrative purposes, but did not have any bearing on how a line could be used.[82] I interpret the lines that were categorized as 'productive' as being expected to earn high returns (and lead to positive bias), and the lines categorized as 'protective' as being targeted towards lagging regions (leading to negative bias). Therefore, a comparison of the effects of lines that are designated as 'productive' and 'protective' will reveal bounds on the true effect of railroads.[83] If these bounds are tight then bias due to non-random railroad placement is unlikely to be quantitatively important. As a further check on this procedure, the effect of lines designated as 'protective and productive' should lie in between those from 'protective' and 'productive' lines. Finally, the lines designated as 'military' could be biased in either direction.

To implement this strategy I estimate equation (18) with five separate coefficients on the own-railroad regressor ($RAIL_{ot}$): one coefficient on each of the four categories of lines built between 1883 and 1904 inclusive, and a fifth coefficient on lines built before 1883 or after 1904 (during which the categorization of railroad lines did not occur).

Results:

Table 8 contains the results of the bounds check that I use to assess the magnitude of potential bias due to non-random placement. For purposes of comparison with earlier results, column 1 replicates

[82]The annual *Railway Reports* reported railroad projects according to these categories. The initial motivation for this categorization scheme first appeared in House of Commons Papers (1884).

[83]An alternative interpretation of differential effects would be that different types of railroad projects have heterogeneous treatment effects. As long as protective lines have lower treatment effects than productive lines, the average treatment effect will still be bounded by the OLS estimates from these two different types of lines. This concern simply widens the bounds.

column 2 of Table 5.

Column 2 of Table 8 presents OLS estimates from five different types of railroad lines used in equation (18)—four from the four different categories in which lines were placed between 1883 and 1904, and one for all lines built before 1883 or after 1904. The point estimates on these five types of lines are all similar to each other. As anticipated by the argument above, lines categorized as 'productive' have the highest estimated coefficients, reflecting a potential upward bias on these estimates (due to selection on unobservables). Likewise, the coefficient on lines categorized as 'protective' is the lowest of the five coefficients, reflecting bias due to negative selection on unobservables. However, the difference between these two coefficients is very small in comparison with the magnitude of the effect of an average line. This suggests that the scope for positive or negative bias due to endogenous selection is small. Put another way, the coefficient on 'protective' lines—which is likely to be an underestimate of the effect of railroads on real agricultural income—is still almost 17 percent, suggesting an important role for railroads in increasing real income.[84]

7.7 Summary and Interpretation

Taken together, the results from my placebo, instrumental variable, and bounds procedures suggest that my earlier OLS results in table 5 can be interpreted as close approximations to unbiased estimates of the effect of railroads on real agricultural income in India. The impression left by these three procedures is that administrators in colonial India allocated railroads to districts at times that were not related to unobservable, time-varying determinants of real agricultural income. This is perhaps unsurprising given the strong military motivations for building railroads in India outlined in section 2, and the difficulty in forecasting the attractiveness of competing railroad plans (as evidenced by the stark disagreements among top-level Indian administrators described in section 7.4).

The results from this section suggest that railroads caused a large (18 percent) increase in real agricultural income in India. This estimate is slightly larger than the estimate I would obtain from using a social savings methodology, of 14.8 percent.[85] The social savings approach is known to suffer from indeterminate bias, so my results here suggest that the net bias to social savings estimates, in the case of India, is negative.[86] Both the results in this section and those obtained from a social

[84]Two further points are of note in table 8. First, the lines categorized as 'productive and protective' have a coefficient that lies between those on 'productive' and 'protective' lines. This is sensible, but was in no way preordained, so it provides a check on the logic of the bounds procedure. Second, the lines categorized as 'military' have a coefficient that is similar in magnitude to that on all other types of lines. This coefficient is difficult to interpret without a clear prior on the direction of its bias. Nevertheless, it is reassuring that this coefficient is similar to that on other types of lines (though I cannot rule out the case that military lines had both a different treatment effects from other types of lines, and a countervailing bias due to selection on unobservables).

[85]The social savings approach (Fogel 1964) seeks to estimate the decrease in national income that would have resulted had railroads not existed, and if the factors of production used in the railroad sector had instead been employed in their next-best substitute (O'Brien (1977) and Fishlow (2000) review this literature). Hurd (1983) performs a social savings calculation for India, which I adapt here. Hurd uses a transportation price reduction of a factor of four due to railroads; my results from Table 2 suggest that this was an underestimate, so I instead us a reduction of a factor of 5.3 (the average reduction between any pair of districts in my sample). Using this reduction of 5.3 rather than four leads to a social savings of 9.7 percent of aggregate GDP; expressed as a fraction of real agricultural income this is 14.8 percent.

[86]Bias arises from two sources. First, because he was arguing against the 'indispensability' of railroads, Fogel

savings calculation ignore any welfare effects from changes in the volatility of real income due to railroads. In the next section I look for evidence of such effects, as predicted by my model.

8 Empirical Step 5: Railroads and Volatility

Step 4 of this paper has argued that railroads increased the level of real agricultural income in India. Prediction 5 of my model suggests that railroads may have caused a second source of potential welfare gains—a reduction in the volatility of real incomes. Indeed, as discussed in section 7.5, the 1880 Famine Commision recommended railroad construction for exactly this reason. In this section I test prediction 5 of the model, and shed light on the potential for railroads to reduce the second moment of income.

8.1 Empirical Strategy

Prediction 5 states that railroads will reduce the responsiveness of real agricultural income in a district to its own rainfall shocks. Since rainfall was a stochastic input to production, a reduction in the responsiveness of income to this input will reduce income volatility. To test prediction 5 I estimate the following specification:

$$\begin{aligned}\ln\left(\frac{r_{ot}}{P_{ot}}\right) = \beta_o + \beta_t &+ \gamma RAIL_{ot} + \psi_1(\tfrac{1}{N_o})\sum_{d\in\mathbf{N}_o} RAIL_{dt} + \psi_2\left[\sum_k \frac{\hat{\mu_k}}{\hat{\theta_k}}\hat{\kappa} RAIN^k_{ot}\right] \\ &+ \psi_3 RAIL_{ot}\times\left[\sum_k \frac{\hat{\mu_k}}{\hat{\theta_k}}\hat{\kappa} RAIN^k_{ot}\right] + \varepsilon_{ot}. \end{aligned} \tag{19}$$

This equation augments equation (18) to allow rainfall, $\left[\sum_k \frac{\hat{\mu_k}}{\hat{\theta_k}}\hat{\kappa} RAIN^k_{ot}\right]$, to affect agricultural production, and for railroad access, $RAIL_{ot}$, to moderate the influence of rainfall on real agricultural income. The rainfall variable is the weighted sum of crop-specific rainfall measures (introduced in section 6), where the weights are suggested by equation (10) of the model. Because the weights depend on the parameters θ_k, μ_k and κ, I use the values of these parameters estimated in Steps 1 and 2 to calculate the weights. (The weights sum to 0.1, not to one, because of the presence of κ and θ_k).

Earlier results (on trade flows and price responsiveness) suggested that rainfall is an important input to agricultural production; the coefficient ψ_2 is therefore expected to be positive. Prediction 5 states that the coefficient ψ_3 will be negative, implying less responsiveness of real agricultural income to rainfall variation when a district has railroad access. Finally, in line with prediction 4 (and as I found in Step 4), the coefficients γ and ψ_1 are expected to be positive and negative, respectively.

(1964) chose to evaluate social savings in a manner (assuming that the demand for transportation was perfectly inelastic) that was deliberately biased upwards. Second, as Fishlow (1965), David (1969), Williamson (1974), and Fogel (1979) have argued, the social savings methodology ignores several effects of railroads (and hence arrives at an underestimate). For my analysis, the most relevant of these uncounted effects is that, by reducing trade costs, railroads may have given rise to aggregate efficiency gains due to reallocations in transport-using sectors. This is the mechanism stressed in the trade model that I develop (and find empirical support for) here.

8.2 Results

Table 9 presents the results of this test of prediction 5. Column 1 confirms that rainfall is an important determinant of agricultural production, and therefore real agricultural income. This is in line with my results from Step 2 (where high rainfall was found to promote exporting success) and from Step 3 (where high rainfall was found to decrease prices).

However, the results in column 2 demonstrate that rainfall is a much stronger determinant of real agricultural income before a district gains railroad access than after. That is, the coefficient on rainfall ('rainfall in district') is 2.4, much larger than in column 1 (and still statistically significant). This coefficient represents the responsiveness of real agricultural income to rainfall before the district is connected to the railroad network. By contrast, the effect of rainfall on real agricultural income after a district gains railroad access (represented by the sum of the coefficients on the 'rainfall in district' term and the interaction term between railroad access and rainfall) is just 1.3. Further, the pattern of all four coefficients in column 2 is in line with that predicted by predictions 4 and 5.

These results suggest that—in line with prediction 5—railroads played an important role in reducing real income volatility in India because they reduced the responsiveness of a district's real income to its rainfall.[87] A reduction in the volatility of real income may have contributed to welfare gains in this setting, where most citizens had no access to formal insurance or banking facilities.[88]

9 Empirical Step 6: A Sufficient Statistic for Railroads

Steps 1 to 3 of this paper have argued that railroads significantly improved the trading environment in India. Steps 4 and 5 demonstrated that railroads also raised the level of real agricultural income, and reduced the volatility of real agricultural income. These two sets of results are qualitatively consistent with each other, in the context of my model. In this section I explore whether these two sets of results are also *quantitatively* consistent with each other in the context of my model. Because the reduced-form impact could arrive through a number of mechanisms, the exercise in this section can also be thought of as determining the share of the observed reduced form impact of railroads that can be explained by the trade-based mechanism in my model.

[87]It is possible that while railroad access reduced the responsiveness of a district's real income to its own rainfall, railroad connections could have increased the responsiveness to neighboring districts' rainfall (as I found in the case of prices, in Step 3). I have estimated a specification similar to equation (19) but with an extension to include dependence on neighboring districts' rainfall and an interaction term for neighboring districts that are bilaterally connected by rail to the district of observation. However, the coefficients on these two additional terms (neighbors' rainfall and neighbors' rainfall for railroad connected neighbors) are small and not statistically different from zero (jointly or individually).

[88]Roy (2001) describes how even even the wealthiest members of society in colonial India (outside of major cities) resorted to money-boxes and jewelery as the only means to save. Rosenzweig and Binswanger (1993) and Rosenzweig and Wolpin (1993) document limited access to insurance in post-Independence India. The gains from reduced consumption volatility may have been even more important to poor consumers due to subsistence concerns (or if risk aversion decreases with income more generally).

9.1 Empirical Strategy

In order to compare the reduced-form impact of the railroad network on each district's real agricultural income (estimated in Steps 4 and 5) to the impact that is predicted by my model, I exploit prediction 6. This prediction is equation (10), restated here for convenience:

$$\ln\left(\frac{r_{ot}}{\widetilde{P}_{ot}}\right) = \sum_k \frac{\mu_k}{\theta_k} \ln A^k_{ot} - \sum_k \frac{\mu_k}{\theta_k} \ln \pi^k_{oot}. \tag{20}$$

Prediction 6 thus states that real agricultural income ($\frac{r_{ot}}{\widetilde{P}_{ot}}$) is a function of only two terms: technology (A^k_{ot}) and 'openness' (π^k_{oot}, the share of district o's expenditure that it buys from itself), appropriately summed over all commodities k.

To estimate this equation I need to substitute in observable variables for the unobserved terms A^k_{ot} and π^k_{oot},[89] and the unobserved parameters θ_k and μ_k. I estimated the function $\ln A^k_{ot} = \kappa RAIN^k_{ot}$ (where $RAIN^k_{ot}$ is observable) and the parameters θ_k in Step 2 (using trade data), and the parameter μ_k is simply the consumer's budget share.[90] Finally, I *compute* the openness term that emerges in equilibrium in my model when it is evaluated at the parameters $\widehat{\kappa}$, $\widehat{\theta}_k$, and $\widehat{\mu}_k$, and $\widehat{\delta}$ and $\widehat{\boldsymbol{\alpha}}$ (estimated in Step 1 using salt price data). I refer to the computed openness term as $\pi^k_{oot}(\widehat{\Theta}, \mathbf{RAIN}_t, \mathbf{R}_t, \mathbf{L})$ to denote its dependence on the full vector of estimated model parameters $\widehat{\Theta} \equiv (\widehat{\boldsymbol{\theta}}, \widehat{\boldsymbol{\mu}}, \widehat{\boldsymbol{\alpha}}, \widehat{\delta}, \widehat{\kappa})$, as well as the full vector (across districts, commodities and years) of exogenous variables, rainfall ($\mathbf{RAIN}_t$), the transportation network ($\mathbf{R}_t$), and land sizes ($\mathbf{L}$).

Prediction 6 (ie equation (20)) states that, once rainfall (ie A^k_{ot}) is controlled for (and weighted over commodities k in the manner suggested by this equation), openness (π^k_{oot}) in year t is a sufficient statistic for the impact of the entire railroad network open in year t on real income in year t. To test prediction 6 I estimate equation (19), but additionally include the sufficient statistic variable, openness (π^k_{oot}):

$$\begin{aligned} \ln\left(\frac{r_{ot}}{\widetilde{P}_{ot}}\right) &= \beta_o + \beta_t + \gamma RAIL_{ot} + \psi_1\left(\frac{1}{N_o}\right) \sum_{d \in \mathbf{N}_o} RAIL_{dt} + \psi_2 \left[\sum_k \frac{\hat{\mu_k}}{\hat{\theta_k}} \hat{\kappa} RAIN^k_{ot}\right] \\ &+ \psi_3 RAIL_{ot} \times \left[\sum_k \frac{\hat{\mu_k}}{\hat{\theta_k}} \hat{\kappa} RAIN^k_{ot}\right] + \eta \sum_k \frac{\hat{\mu_k}}{\hat{\theta_k}} \ln \pi^k_{oot}(\widehat{\Theta}, \mathbf{RAIN}_t, \mathbf{R}_t, \mathbf{L}) + \varepsilon_{ot}. \end{aligned} \tag{21}$$

If openness is truly a sufficient statistic, as predicted by my model, then when openness is included in equation (21) all other railroad variables should lose predictive power. That is, prediction 6 states that the coefficients γ, ψ_1 and ψ_3 should be zero in this regression. Further, taking the model equation (20) literally, prediction 6 also states that the coefficients ψ_2 and η will equal one

[89] While it would be possible in principle to use trade data to observe π^k_{oot} in the data, this faces two limitations: first, as the model makes clear, π^k_{oot} is endogenous to the error term in equation (20), so an instrumental variables methodology would be necessary; and second, the only internal trade data available from colonial India are presented at a more aggregated level, and begin in a later year, than the data on all other variables in equation (20).

[90] I estimate these Cobb-Douglas weights as the average (over trade blocks and years) expenditure share for commodity k, where expenditure is calculated as output minus trade.

and minus one, respectively.[91]

9.2 Results

Table 10 presents OLS estimates of equation (21) in order to test Prediction 6 and shed light on the role for a trade-based mechanism, such as that highlighted in my model, to account for the reduced-form impact of railroads on real income levels and volatility.

Column 1 restates column 2 of table 9 (discussed in the previous section) as a point of departure. This specification makes it clear that there is a large reduced-form impact of railroads on both the level and volatility of real agricultural income in the average district in India. While these results could reflect the increased opportunities to trade that railroads brought about (an effect for which I found evidence in Step 1), other possible mechanisms could also be at work.

Following the strategy laid out in equation (21), column 2 of table 10 adds a variable, 'openness' (which I compute in my model using parameter estimates from Steps 1 and 2), to the regression in column 2. Consistent with prediction 6 of the model, the coefficients on own-railroad access, neighboring districts' railroad access, and the interaction between own-railroad access and rainfall—all of which were statistically and economically significant in column 2—have all fallen to a level that is close to zero (and whose 95 percent confidence intervals include zero). This is consistent with the idea that openness is a sufficient statistic for the impact of railroads on real agricultural income (and its responsiveness to rainfall), as predicted by the model.

In further agreement with prediction 6, the coefficient on the openness term is close to minus one, implying that openness, when measured in a model-consistent manner, is a strong determinant of real agricultural income. Notably, the model parameters that enter the openness term were not estimated using data that enters the current estimating equation, so the impressive fit of the openness term was not preordained. Finally, the last part of prediction 6, that the coefficient on the rainfall measure should be one, is now also corroborated in a statistical sense; the coefficient on rainfall has fallen (when compared to column 1) to a level that is close to one.

Finally, taking the point estimate of 0.021 on own-railroad access ($RAIL_{ot}$) seriously, implies that only 12 percent (ie 0.021 divided by 0.186, expressed as a percentage) of the total impact of the railroads estimated in column 1 *cannot* be explained by the mechanism of enhanced opportunities to trade according to comparative advantage, represented in the model. That is, 88 percent of the total impact of the railroads on real income in an average district can be explained by the model.

The results in table 10 establish a firm, quantitative connection between the earlier results in this paper—that railroads improved the ability to trade within India (Steps 1, 2 and 3), and that

[91] The computed openness term, $\pi^k_{oot}(\widehat{\Theta}, \mathbf{RAIN}_t, \mathbf{R}_t, \mathbf{L})$ is a generated regressor, so conventional standard errors obtained when using it will be incorrect. In principle, it is possible to obtain correct standard errors by using a bootstrap procedure (as in Step 2), but this is computationally expensive here because this is the third step of an estimation procedure (and hence a three-step bootstrap procedure would be required). Adding to the difficulty, the first step is non-linear and the second step involves 85 separate regressions. I have not calculated bootstrapped standard errors for the regressions in this section because of the computation time required. However, the empirical procedure in this section is concerned primarily with the magnitude of point estimates rather than statistical inference about these estimates.

railroads raised real incomes (Step 4) and reduced the volatility of real income (Step 5) in India. These results suggest that the important welfare gains that railroads brought about can be well accounted for by the specific mechanism of comparative advantage based gains from trade.

10 Conclusion

This paper has made three contributions to our understanding of the effects of large transportation infrastructure projects, in the context of an enormous expansion in transportation infrastructure—the construction of India's railroads. Using new district-level data that I have collected from archival sources, my first contribution is to estimate the effect of India's railroads on the trading environment there. I find that railroads reduced the cost of trading, reduced inter-regional price gaps, increased trade volumes, and brought India's district economies close to the small open economy limit where local prices are unresponsive to local productivity shocks.

My second contribution is to estimate the effect of India's railroads on welfare in colonial India. I find that that when the railroad network was extended to the average district, real agricultural income in that district rose by approximately 18 percent. I also find that railroads reduced real income volatility. While it is possible that railroads were deliberately allocated to districts on the basis of time-varying characteristics unobservable to economists today, I find little evidence for this potential source of bias to my results in placebo, instrumental variable, or bounds checks. These reduced-form findings suggest that railroads brought welfare gains to colonial India, but say very little about the economic mechanisms behind these gains.

Finally, my third contribution is to shed light on the mechanisms at work by relating the observed railroad-driven reduction in trade costs to the observed railroad-driven increase in welfare. To do so requires a calibrated, general equilibrium model of trade with many regions, many goods, and unrestricted trade costs. I extend the work of Eaton and Kortum (2002) to construct such a model and estimate its unknown parameters using auxiliary model equations. The model identifies a sufficient statistic for the effect of trade cost reductions on welfare, which accounts empirically for virtually all of the observed effects of railroads. This suggests that railroads raised welfare in India primarily because they reduced the cost of trading, and enabled districts to enjoy more of the gains from trade due to comparative advantage.

One limitation of the present study is its focus, due to data constraints, on the real income of a representative agent in each district. This focus removes the possibility that a trade cost reduction could reduce the real returns to some factors of production (or leave their real incomes more exposed to climatic variation). Such distributional concerns feature prominently in modern theories of the causes of famines, such as Sen (1981). Large transportation infrastructure improvements, such as India's railroads, offer the chance to probe empirically these distributional concerns, and to test economic models of famine.

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A Data Appendix

This appendix provides information (supplementary to that in section 2) on the variables used in this paper.

Sample of Districts:
The data I use in this paper cover the areas of modern-day India, Pakistan and Bangladesh, most of the area known as British India. I work with a panel of 239 geographic units of analysis that I refer to as districts, for as much of the period 1861 to 1930 as possible.[92]

Trade Cost Proxy Variables:
I construct trade cost proxy variables using a newly constructed GIS database on the Indian transportation network, from 1851 to 1930. The database covers four modes of transportation: railroads, roads, rivers and coastal shipping.[93] Each segment (approximately 20 km long) of the railroad network is coded according to the year in which it was opened.[94] For river transport I keep only those rivers that are reported in Schwartzberg (1978) or Bourne (1849) as navigable in 1857. The final component of the colonial India GIS database that I construct is the location of each district and salt source. To calculate district locations I digitize a map of the district borders in India (as they existed in 1891).[95] I use this to calculate district centroids, which I take to be the 'location' of each district. Finally, I obtain the location of each salt source from contemporary maps.

I then convert the GIS database of transportation lines and district/salt source locations into a graph of nodes and arcs, as is common in the transportation literature (Black 2003). I work with a simplified graph representation of the Indian transportation network, where the number of nodes and the sparsity of arcs is low enough for network algorithms to be feasibly operated on it using a desktop computer (the resulting network has 7651 nodes).[96] Because the density of informal roads was extremely high (Deloche 1994), I allow road transport to occur along the straight line between any two nodes on the network, but only if the two nodes either represent districts or salt sources, or the two nodes are within 1000 km of each other.[97] The result is a network with 7651 nodes, 5616 of which rep-

[92]The majority of British India was under direct British control, and was divided into nine large, administrative units known as provinces. Each province was further sub-divided into a total of 223 districts, which are the units of analysis that I track from 1861 to 1930. Areas not under direct British control were known as 'Princely States'. For administrative purposes these were grouped into divisions similar to the provinces and districts described above, so in princely state areas I use the lower administrative units as my units of analysis and refer to them as districts, following the *Indian Administrative Atlas* (Singh and Banthia 2004). There were 251 of these districts in my sample area, but data collection in the princely states was extremely incomplete and I include only 16 districts from the princely state regions in my final sample.

[93]To construct this database, I begin with a GIS database that contains the locations of contemporary railroad, river and coast lines from the *Digital Chart of the World*.

[94]To do this I use the publication *History of Indian Railways, Constructed and in Progress* (1918 and 1966 volumes), the 1966 volume of which refers to railway lines in modern-day India only. To obtain years of opening for line segments in modern-day Pakistan and Bangladesh from 1919 to 1930 I use the annual *Railway Reports* published by the Railways Department, which list all line section openings in each year.

[95]I use the maps in the *Indian Administrative Atlas* and *Constable's Hand Atlas of India* (Bartholomew 1893) to create this digital map.

[96]To do this, I use the 'simplify' command in ArcGIS. A line in ArcGIS is a series of vertices connected by straight lines. The 'simplify' command removes vertices in such a way as to minimize the sum of squared distances between the original line and a the simplified line. The original *Digital Chart of the World* railway layer, for example, consists of approximately 33,000 vertices; I simplify the railway layer to one of only 5616 vertices.

[97]Allowing straight-line road travel between any two nodes would yield a network with over 58 million arcs. The shortest path between each of the nodes on such a dense network cannot be calculated using a desktop computer, so I restrict many of these arcs to be non-existent; the result is that the 7651-by-7651 matrix representing the network can be stored as a sparse matrix, and analyzed using sparse matrix routines (that increase computation

resent the railroad network, 660 of which represent the navigable river network, 890 of which represent coastal shipping routes, 477 of which represent the centroids of the 477 districts in India (in 1891 borders), and 8 of which represent the locations of the sources of 8 different types of salt. Because the railroad arcs are coded with a year of opening indicator, this network can be restricted to represent the transportation network for any year from 1851 to 1930 by simply turning these arcs on or off.

Finally, I use this network representation of the Indian transportation system to calculate the two trade cost proxy variables described in section 4. One such proxy is a measure of the cost of traveling between any two points (where a point is either a district or a salt source) in a year using the lowest-cost route along the network (available in that year). The lowest-cost route depends on the value of the relative freight rates, $\boldsymbol{\alpha}$, and the available network, $\mathbf{R}_t$. Conditional on values of $\boldsymbol{\alpha}$, I use a standard algorithm from graph theory and transportation science (Dijkstra's algorithm) to calculate the shortest path between every pair of points, along the transportation network available in each year from 1861 to 1930. The resulting measure, $LCR_{odt}(\boldsymbol{\alpha}, \mathbf{R}_t)$, is in units of railroad-equivalent kilometers. The second proxy variable for trade costs is a dummy variable that indicates when it is possible to travel between two districts without leaving the railroad network. This is easily constructed using the transportation network representation and digital map of Indian districts described above.

Bilateral Trade Flows:

The data I use on bilateral trade flows was collected from a variety of different sources, one for each mode of transportation. I describe each of these modes in turn, and then how they were combined into aggregate data on trade flows.

Data on *railroad trade* within India were published separately for each province. The geographic unit of analysis in these records is the 'trade block', which spans between four and five districts.[98] The railroad trade flow data, like that on all modes of transportation described below, represents final shipments between two regions (even if a shipment changed railroad companies).[99] Only if a shipment was taken off the railroad system and re-shipped onwards would it be counted as two separate shipments. I collecte this data from various annual, provincial publications from 1880 onwards.[100] Data on *river-borne trade* within India was published in a similar manner to the railroad trade data, for the Brahmaputra, Ganges and Indus river systems. I collecte the river-borne trade data from the railroad trade statistics publications for the provinces of Assam, Bengal, Northwestern Provinces, and Sind. Data on trade within India that occurred via *coastal shipping* was published by

speed dramatically) in Matlab.

[98]Trade blocks split into smaller blocks over time, but I aggregate over these splits to maintain constant geographic units. The trade blocks were always drawn so as to include whole numbers of districts.

[99]All bilateral block-to-block intra-provincial trade flows were published, except that from a block to itself (which was always unreported). Inter-provincial trade flows were published from each internal block to each external province (and vice versa), but not by trade block within the external province. I therefore create a full set of inter-provincial block-to-block flows by following an analogous procedure to that used to prepare bilateral trade data on provincial-state trade between Canada and the United States in McCallum (1995) and Anderson and van Wincoop (2003). This method assigns a province's trade block's imports from each of another province's trade blocks in proportion to the exporting blocks' stated exports to the entire importing province (and vice versa for exports). In order to match the internal block-level railroad trade data to international trade data (leaving via specified ports, as described below), I apply a similar proportionality method. This is possible because the railroad trade data differentiate railroad trade to/from principal ports (in each province) from trade bound for non-port consumption.

[100]The titles of these publications changed over time, from *Returns of the Rail [and River-borne] Trade of [Province]* to *Report on the trade carried by rail [and river] in [Province]* to *Report on Inland Trade of [Province].* In the province of Madras, these statistics were only published from 1909 onwards. Railroad trade statistics were not published by the princely states themselves, but each province's external trade to/from each of the large princely states were published. I therefore treat each large princely state (Central India Agency, Hyderabad, Mysore, Rajputana and Travancore) as a single trade block.

each of the coastal provinces (Bengal, Bombay, Madras and Sind) in a similar manner to the railroad trade data. I collected the coastal trade data from various annual, provincial publications.[101]

Data on *international trade* leaving India was published separately for trade by maritime shipping and by roads. Each province published its own maritime international trade statistics, with each reporting the trade to and from its major and minor ports.[102] This international maritime trade data was presented disaggregated into over 30 foreign countries, but to maintain consistent geographic units over time I aggregate these 30 countries into 24 foreign regions. Foreign trade by land occurred (in extremely small volumes) between Bengal, Northwest Provinces and Punjab provinces and neighboring foreign countries (modern-day Nepal, China, Afghanistan and Bhutan). This trade data was published by each of these provinces, disaggregated by the border post through which trade left or arrived. I collect this data from various annual, provincial publications.[103]

Trade data by all modes of transport discussed above was published disaggregated by commodities.[104] In order to compare commodities across these different levels of aggregation, I aggregate all data to the 85-commodity level.[105] Finally, I aggregate the trade data on each of the modes (for each commodity separately) into one trade dataset.[106] All of the above trade data are available from (at least) 1861 to 1930 (and beyond), except for the railroad trade data. The railroad trade data only starts in a coherent manner in 1880, and was discontinued in 1920. I therefore use bilateral trade data from 1880 to 1920 only.

Rainfall Data:

A thick network of 3614 rain gauges at metorological stations (illustrated in Figure 1) recorded daily rainfall amounts from 1891-1930. From 1901 onwards, these records have been digitized by the Global Historical Climatology Network (Daily) project; the GHCN dataset also provides the latitude and longitude of each station. For the years 1891-1900, I collect the data from the publication *Daily Rainfall for India in the year...*. In the years 1865 to 1890, very little daily rainfall data was published in colonial India, but monthly data from 365 stations (spread throughout India) was published by each province.[107] I convert monthly station-level data to daily station-level data using a procedure that is common in the meteorological statistics literature (eg, Ngo-Duc, Polcher, and Laval (2005)).[108] I convert station-level data to district-level data by simply averaging over the

[101]The coastal trade data were published in publications whose titles changed from *Annual Statement of the Sea-borne Trade and Navigation of [Province]* to *Report on the Maritime Trade of [Province]*.

[102]The maritime international trade data was published in the same publications as those containing the coastal trade data, described above.

[103]The overland international trade data was published in: *Annual Report on the Trans-frontier Trade of Bihar and Orissa with Nepal*, *Bengal Frontier Trade: Trade of Bengal with Nepal, Tibet, Sikkim and Bhutan*, *Accounts Relating to the Trade by Land of British India with Foreign Countries*, *Annual Report on the Foreign Trade of the United Provinces*, and *Report on the External Land Trade of the Punjab*. I assign each of these border posts to the internal trade block in which it is located, and assume that all of the foreign land trade came to/from these blocks only.

[104]The railroad and river-borne trade data reported 85-100 commodities (depending on the year and province), the coastal shipping data 200-400 commodities, and the international maritime shipping data over 400 commodities.

[105]I use the commodity classification in the international maritime shipping publications (used to organize the over 400 commodities in these publications) to do this.

[106]Wherever relevant, I treat the regions of modern-day Afghanistan, Myanmar and Sri Lanka as foreign countries, since they are outside of the region on which I have other data from India.

[107]These publications included the *Administration Reports* for each province, described in the agricultural price data section below. I use additional data (to increase the number of stations) that was published in selected provinces' *Sanitary Reports*.

[108]Using daily data from 1891 to 1930, I estimate the district-specific relationship between the pattern of monthly rainfall in a year and the rainfall on any day of that year; I then use these estimated relationships to predict the rainfall on any day in a given district and year from 1865 to 1890, conditional on the pattern of monthly rainfall actually observed in that district and year. While these daily rainfall predictions are likely to be imprecise, much

many stations in each district.[109]

Prices of Salt and Agricultural Commodities:
I use data on eight different types of salt[110] for each of the six provinces in Northern India. And I use data on 17 agricultural commodities[111] from all of India. I collect this price data from various annual, provincial publications.[112] Prices reported in these publication were an average of observations taken by district officers once per fortnight at each of 10-15 leading retail markets per district.

Real Agricultural Income:
I use data that present the area under each of 17 crops (the 17 for which price data are available), and the yield per acre for each of these crops, in each district and year.[113] I take the product of each area and yield pair to create a measure of real output for each crop, district and year. I then evaluate this bundle of 17 real output measures at the prices prevailing for these crops (from the agricultural price data described above), in each district and year, to create a measure of total nominal agricultural output for each district and year. Finally, I divide nominal output by a consumer price index (the Fisher ideal index) to create a measure of real income.[114]

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of the imprecision is averaged over when I construct crop-specific rainfall shocks, which are measures of the total rainfall in a given period (a length ranging from 55 to 123 days.)

[109]If a given district-day has no reported rainfall observations I impute this missing observation by using an inverse distance-weighted average of that day's rainfall in the 5 closest reporting stations (know as "Shepard's method" in the meteorological literature (Shepard 1968).

[110]These eight salt types are those from: the Bombay sea salt sources near the city of Bombay, salt from the UK distributed via Calcutta, the Didwana salt source in Punjab, the Kohat mines in Punjab (principally the Jatta mine, according to Watt (1889)), the Mandi mine in Punjab, the Salt Range mines in Punjab (principally the Mayo mine, according to Watt (1889)), the Sambhar Salt Lake in Rajputana, and the Sultanpur source in the Central India Agency.

[111]These crops are: bajra, barley, bengal gram, cotton, indigo, jowar, kangni, linseed, maize, opium, ragi, rape and mustard seed, rice, sesamum, sugarcane, tur and wheat.

[112]These publications were: *Prices and Wages in India*; *Administration Reports* from all provinces; the *Salt Report of Northern India*; the *Statistical Atlas of Andhra State* with agricultural price data (for the Madras Presidency); the *Season and Crop Reports* from various provinces with agricultural price data; and the *Sanitary Reports* from various provinces with data on prices of food grains.

[113]These data were published in *Agricultural Statistics of India* from 1884 to 1930. For the years 1870-1883 I use data on crop areas and yields in the provincial *Administration Reports*, as described in the agricultural prices data section above. Data on agricultural output was published in each province's *Administration Report* except for Punjab and Bengal. For supplementary data I use each province's *Season and Crops Report* between 1904 and 1930. While Blyn (1966) and Heston (1973) have discussed the potential for measurement error in these sources, these authors have not been concerned with mechanisms through which measurement error might be correlated with the regressors I use in this paper.

[114]In order to compute this consumer price index I use district and year specific consumption weights from the internal trade data, computing consumption as output minus net exports.

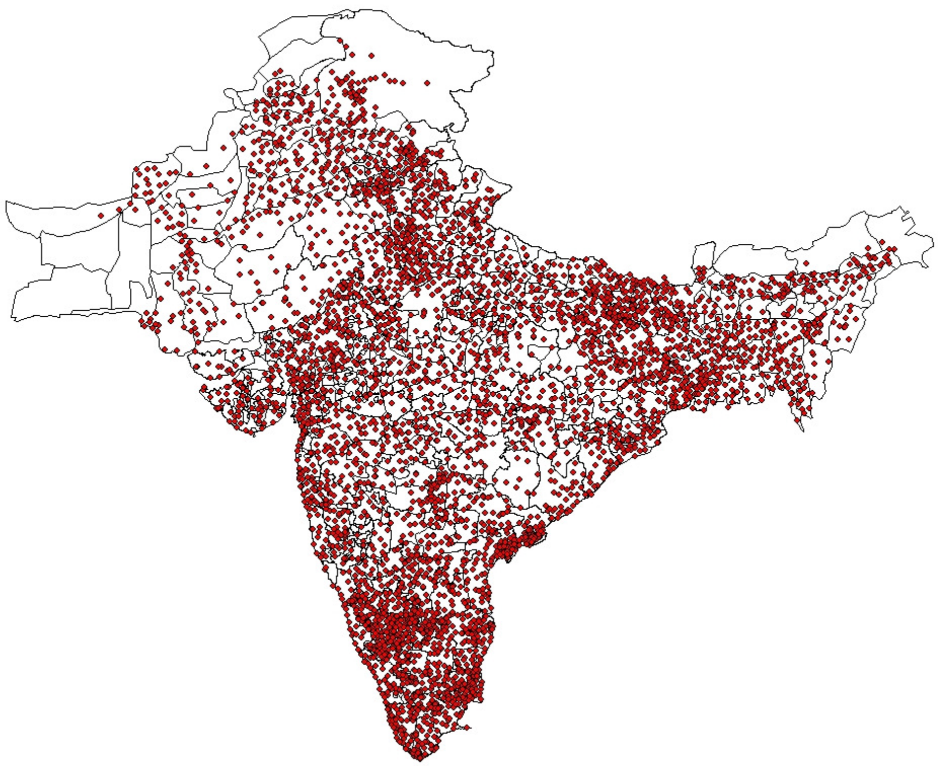

Figure 1: Meteorological stations in colonial India: Dots represent the 3914 meteorological stations with rain gauges collecting daily rainfall in the period from 1891-1930. District borders are also shown. Source: *Global Historical Climatological Network* and author's calculations; see Appendix A for full details.

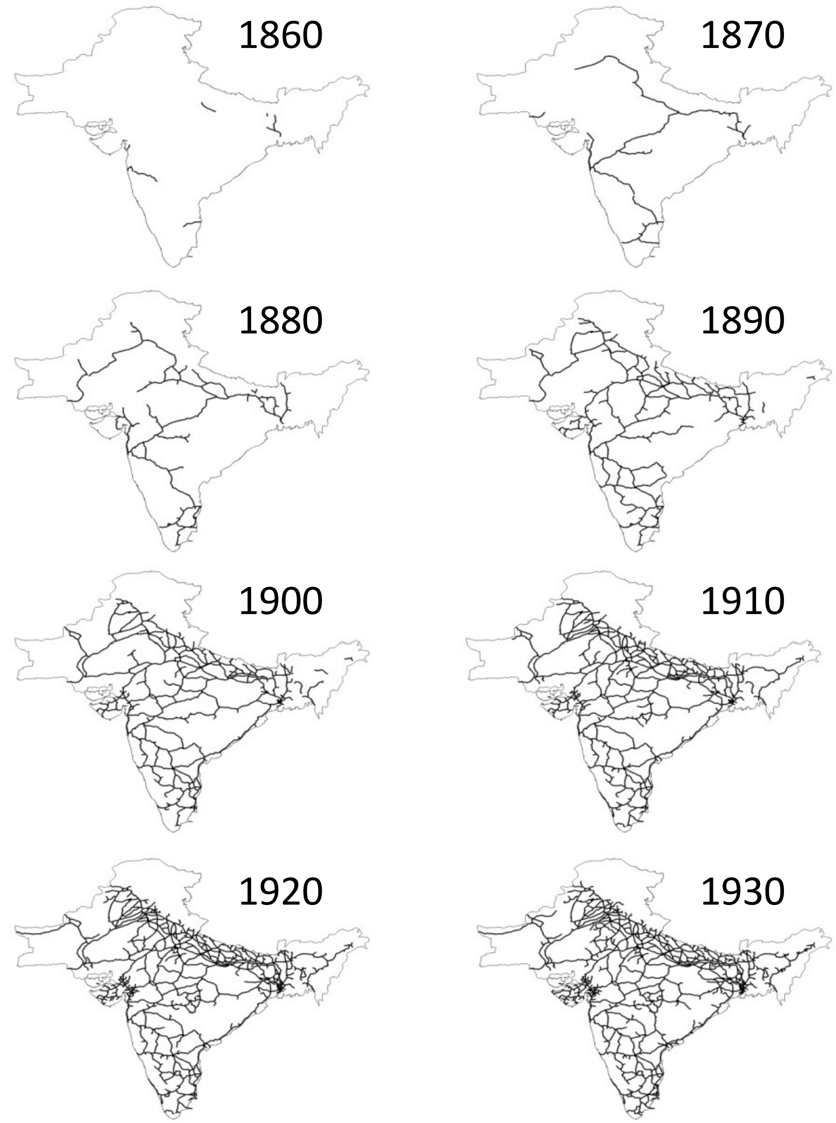

Figure 2: The evolution of India's railroad network, 1860-1930: These figures display the decadal evolution of the railroad network (railroads depicted with thick lines) in colonial India (the outline of which is depicted with thin lines). The first railroad lines were laid in 1853. This figure is based on a GIS database in which each 20 km railroad segment is coded with a year of opening variable. Source: Author's calculations based on official publications. See Appendix A for details.

Table 1: Descriptive Statistics

	Number of Observations	Beginning of Available Data	End of Available Data
Value of agricultural output per acre, all crops (current rupees)	14,340	27.3	111.3
		(10.4)	(40.8)
Agricultural prices (average over all crops, current rupees per maund)	14,340	2.37	5.07
		(1.37)	(2.35)
Real agricultural income per acre (1870 rupees)	14,340	27.3	38.0
		(10.4)	(13.8)
Real agricultural income per acre, coefficient of variation over past 5 years	13,384	0.06	0.04
		(0.04)	(0.03)
Price of salt, all sources (current rupees per maund)	7,329	5.19	3.45
		(1.96)	(0.465)
Total annual rainfall (meters)	14,340	1.011	1.145
		(0.798)	(1.302)
Crop-specific rainfall shock (meters)	73,000	0.638	0.662
		(0.614)	(0.602)
Crop-specific rainfall shock, coefficient of variation over past 5 years	68,821	0.520	0.541
		(0.417)	(0.480)
Exports per trade block (millions of 1870 rupees)	6,581,327	0.711	3.581
		(0.649)	(2.444)

Notes: Values are sample means over all observations for the year and question, with standard deviations in parentheses. Beginning and end of available data are: 1870 and 1930 for agricultural output and real agricultural income; 1861 and 1930 for agricultural prices and salt prices; 1867 and 1930 for all rainfall variables; and 1880 and 1920 for trade data. A 'maund' is equal to 37.3 kg and was the standardized unit of weight in colonial India. Data sources and construction are described in full in Appendix A.

Table 2: Railroads and Trade Costs (Step 1)

Dependent variable: Log salt price at destination	(1)	(2)	(3)	(4)	(5)
Source connected to destination by railroad	-0.112				0.023
	(0.046)***				(0.342)
Log distance to source, along lowest-cost route		0.135			
(at historical freight rates)		(0.038)***			
Log distance to source, along lowest-cost route			0.255	0.247	0.233
(at estimated mode costs)			(0.059)***	(0.063)***	(0.074)***
Estimated mode costs:					
Railroad (normalised to 1)			1	1	1
			N/A	N/A	N/A
Road			7.341	7.880	7.711
			(1.687)***	(1.913)***	(2.032)***
River			3.396	3.821	4.118
			(0.760)***	(1.034)***	(1.381)***
Coast			3.213	3.942	3.612
			(1.893)*	(2.581)	(2.674)
Salt type x Year fixed effects	YES	YES	YES	YES	YES
Salt type x Destination district fixed effects	YES	YES	YES	YES	YES
Salt type x Destination district trends	YES	YES	NO	YES	YES
Observations	7329	7329	7329	7329	7329
R-squared	0.841	0.960	0.953	0.974	0.975

Notes: Regressions estimating equation (11) using data on 8 types of salt (listed in Appendix A), from 124 districts in 5 Northern Indian provinces (listed in Appendix A), annually from 1861 to 1930. Columns 1 and 2 are OLS regressions, and columns 3-5 are NLS regressions (with block-bootstrapped standard errors). 'Source connected to destination by railroad' is a dummy variable equal to one in all years when it is possible to travel by railroad from any point in the district containing the salt source to any point in the destination district. The 'distance to source, along lowest-cost route' variable is a measure of the railroad-equivalent kilometres (because railroad freight rate is normalized to 1) between the salt source and the destination district, along the lowest-cost route given relative mode costs per unit distance. 'Historical freight rates' used are 4.5, 3.0 and 2.25 respectively for road, river and coastal mode costs per unit distance, all relative to rail transport. Data sources and construction are described in full in Appendix A. Heteroskedasticity-robust standard errors corrected for clustering at the destination district level are reported in parentheses. *** indicates statistically significantly different from zero at the 1% level; ** indicates 5% level; and * indicates 10% level.

Table 3: Railroads and Trade Flows (Step 2)

Dependent variable: Log value of exports	(1)	(2)	(3)
Fraction of origin and destination districts connected by railroad	1.482		
	(0.395)***		
Log distance beween origin and destination along lowest-cost route		-1.303	-1.284
		(0.210)***	(0.441)***
(Log distance beween origin and destination along lowest-cost route)			-0.054
x (Weight per unit value of commodity in 1880)			(0.048)
(Log distance beween origin and destination along lowest-cost route)			0.031
x (High-value railroad freight class of commodity in 1880)			(0.056)
Origin trade block x Year x Commodity fixed effects	YES	YES	YES
Destination trade block x Year x Commodity fixed effects	YES	YES	YES
Origin trade block x Destination trade block x Commodity fixed effects	YES	YES	YES
Origin trade block x Destination trade block x Commodity trends	YES	YES	YES
Observations	6,581,327	6,581,327	6,581,327
R-squared	0.943	0.963	0.964

Notes: Regressions estimating equations (13) and (14), using data on 85 commodities, 45 trade blocks, and 23 foreign countries, annually from 1880 to 1920. 'Fraction of origin and destination districts connected by railroad' is the share of the district pairs between trade block o and traded block d that for which it is possible to travel entirely by railroad from any point in one district to any point in the other district. The 'distance between origin and destination along lowest-cost route' variable is a measure of the railroad-equivalent kilometres (due to the normalized railroad freight rate to 1) between the centroid of the origin and destination trade blocks in question, along the lowest-cost route given relative freight rates for each mode of transport (as estimated in table 2). 'Weight per unit value in 1880' is the weight (in maunds) per rupee, as measured by 1880 prices. 'Railroad freight class in 1880' is an indicator variable for all commodities that were classified in the higher (more expensive) freight class in 1880; salt was in the omitted category (low-value commodities). Data sources and construction are described in full in Appendix A. Standard errors are reported in parentheses. In column 1 these are heteroskedasticity robust standard errors adjusted for clustering at the exporting block level. In columns 2-3 these are bootstrapped standard errors (using a two-stage block bootstrap at the exporting block level) to correct for the generated regressor. *** indicates statistically significantly different from zero at the 1% level; ** indicates 5% level; and * indicates 10% level.

Table 4: Railroads and Price Responsiveness (Step 3)

Dependent variable: Log price	(1)	(2)	(3)	(4)
Local rainfall in sowing and growing periods	-0.256	-0.428	-0.215	-0.402
	(0.102)**	(0.184)***	(0.105)**	(0.125)***
(Local rainfall) x (Railroad in district)		0.414		0.375
		(0.195)**		(0.184)**
Rainfall in neighboring districts			-0.051	-0.021
			(0.023)**	(0.018)
Average: (Rainfall in neighboring districts) x (Connected to neighboring districts by railroad)				-0.082
				(0.036)***
Crop x Year fixed effects	YES	YES	YES	YES
Crop x District fixed effects	YES	YES	YES	YES
District x Year fixed effects	YES	YES	YES	YES
Observations	73,000	73,000	73,000	73,000
R-squared	0.891	0.892	0.894	0.899

Notes: OLS Regressions estimating equation (16) using data on 17 agricultural crops (listed in Appendix A), from 239 districts in India, annualy from 1861 to 1930. 'Local rainfall in sowing and growing period' (abrev. 'local rainfall') refers to the amount of rainfall (measured in meters) in the district in question that fell during crop- and district- specific sowing and harvesting dates. 'Railroad in district' is a dummy variable whose value is one if any part of the district in question is penetrated by a railroad line. 'Rainfall in neighboring districts' is the variable 'local rainfall' averaged over all districts within a 250 km radius of the district in question. 'Connected to neighboring district' is a dummy variable that is equal to one if the district in question is connected by a railroad line to each neighboring district within 250 km. Data sources and construction are described in full in Appendix A. Heteroskedasticity-robust standard errors corrected for clustering at the district level are reported in parentheses. *** indicates statistically significantly different from zero at the 1% level; ** indicates 5% level; and * indicates 10% level.

Table 5: Railroads and Real Income Levels (Step 4) - OLS Estimates

Dependent variable: Log real agricultural income per acre	(1)	(2)
Railroad in district	0.164	0.182
	(0.056)***	(0.071)**
Railroad in neighboring district		-0.042
		(0.020)**
District fixed effects	YES	YES
Year fixed effects	YES	YES
Observations	14,340	14,340
R-squared	0.744	0.758

Notes: OLS Regressions estimating equation (18) using real income constructed from crop-level data on 17 principal agricultural crops (listed in Appendix A), from 239 districts in India, annualy from 1870 to 1930. 'Railroad in district' is a dummy variable whose value is one if any part of the district in question is penetrated by a railroad line. 'Railroad in neighboring districts' is the variable 'railroad in district' averaged over all districts within a 250 km radius of the district of observation. Data sources and construction are described in full in Appendix A. Heteroskedasticity-robust standard errors corrected for clustering at the district level are reported in parentheses. *** indicates statistically significantly different from zero at the 1% level; ** indicates 5% level; and * indicates 10% level.

Table 6: Railroads and Real Income Levels (Step 4) - Placebo Specifications

Dependent variable: log real agricultural income per acre	(1)	(2)	(3)	(4)
Railroad in district	0.172	0.190	0.167	0.188
	(0.099)	(0.099)*	(0.083)**	(0.075)**
Railroad in neighboring district	-0.031	-0.028	-0.058	-0.047
	(0.039)	(0.031)	(0.029)**	(0.034)
Unbuilt railroad in district, abandoned after proposal stage	0.008			
	(0.021)			
Unbuilt railroad in district, abandoned after reconnoitering stage	-0.002			
	(0.048)			
Unbuilt railroad in district, abandoned after survey stage	0.014			
	(0.038)			
Unbuilt railroad in district, abandoned after sanction stage	0.010			
	(0.082)			
(Unbuilt railroad in district, included in Lawrence Plan 1869-1873)		0.010		
x (post-1869 indicator)		(0.056)		
(Unbuilt railroad in district, included in Lawrence Plan 1874-1878)		-0.054		
x (post-1874 indicator)		(0.067)		
(Unbuilt railroad in district, included in Lawrence Plan 1879-1883)		0.008		
x (post-1879 indicator)		(0.051)		
(Unbuilt railroad in district, included in Lawrence Plan 1884-1888)		0.068		
x (post-1884 indicator)		(0.104)		
(Unbuilt railroad in district, included in Lawrence Plan 1889-1893)		-0.092		
x (post-1889 indicator)		(0.087)		
(Unbuilt railroad in district, included in Lawrence Plan 1894-1898)		0.041		
x (post-1894 indicator)		(0.058)		
(Unbuilt railroad in district, in Bombay Chamber of Commerce plans)			0.003	
x (post-1883 indicator)			(0.033)	
(Unbuilt railroad in district, in Madras Chamber of Commerce plans)			-0.063	
x (post-1883 indicator)			(0.098)	
(Unbuilt railroad in district, included in Kennedy plan, high-priority)				0.0005
x (year-1848)				(0.038)
(Unbuilt railroad in district, included in Kennedy plan, low-priority)				-0.001
x (year-1848)				(0.026)
District fixed effects	YES	YES	YES	YES
Year fixed effects	YES	YES	YES	YES
Observations	14,340	14,340	14,340	14,340
R-squared	0.769	0.769	0.770	0.770

Notes: OLS regressions similar to those in Table 5. 'Railroad in district' and 'Railroad in neighboring districts' are defined in the notes to Table 5. 'Unbuilt railroad in district, abandoned after X stage' is a dummy variable whose value is one if a line that was abandoned after 'X' stage penetrates a district, in all years after then line was first mentioned as reaching stage 'X' in official documents. Stages 'X' are: 'proposal', where line was mentioned in official documents; 'reconnoitering', where line route was explored by surveyors in rough detail; 'survey', where the exact route of the line and nature of all engineering works were decided on after detailed survey; and 'sanction', where the surveyed line was given official permission to be built. 'Lawrence 1868 plan' was a proposal for significant railroad expansion by India's Governor General that was not implemented; the plan detailed proposed dates of construction (in 5-year segments) over the next 30 years, which are used in the construction of this variable. 'Chambers of Commerce plans' were invited expansion proposals by the Madras and Bombay Chambers of Commerce in 1883, which were never implemented. 'Kennedy plan' was an early construction-cost minimizing routes plan drawn up by India's chief engineer in 1848 (divided into high- and low-priorities), which was rejected in favor of Dalhousie's direct routes plan. Heteroskedasticity-robust standard errors corrected for clustering at the district level are reported in parentheses.

Table 7: Railroads and Real Income Levels (Step 4) - IV Estimates

Dependent variable:	Railroad in district (First Stage)	Railroad in district (First Stage)	Log real ag. income (Second Stage)	Log real ag. income (Second Stage)
Estimation method:	OLS	OLS	IV	IV
	(1)	(2)	(3)	(4)
(Rainfall in 1876-78 ag. year minus long-run mean) x (Post-1884 indicator)	-0.051	-0.047		
	(0.018)***	(0.019)**		
Railroad in district			0.184	0.193
			(0.084)**	(0.082)**
Railroad in neighboring district			-0.056	-0.052
			(0.034)	(0.031)
Rainfall in district	0.013		1.123	1.118
	(0.089)		(0.518)**	(0.429)**
Rainfall in district (lagged 1 year)	-0.003		0.328	
	(0.048)		(0.294)	
Rainfall in district (lagged 2 years)	0.009		0.024	
	(0.064)		(0.182)	
Rainfall in district (lagged 3 years)	-0.001		-0.043	
	(0.058)		(0.195)	
(Rainfall in severe famine ag. year minus long-run mean) x (Indicator for 6 years after famine year)		0.015		0.010
		(0.034)		(0.025)
(Rainfall in mild famine ag. year minus long-run mean) x (Indicator for 6 years after famine year)		-0.003		0.006
		(0.027)		(0.021)
District fixed effects	YES	YES	YES	YES
Year fixed effects	YES	YES	YES	YES
Observations	14,340	14,340	14,340	14,340
R-squared	0.651	0.650	0.733	0.743

Notes: Regressions estimating equation (18) using real income constructed from crop-level data on 17 principal agricultural crops (listed in Appendix A), from 239 districts in India, annualy from 1870 to 1930. 'Railroad in district' is a dummy variable whose value is one if any part of the district in question is penetrated by a railroad line. 'Rainfall in 1876-78 agricultural year minus long-run mean' is the amount of rainfall (in metres) in a district from 1 May 1876 to 31 April 1878, minus the district's average annual rainfall in agricultural years from 1870 to 1930. 'Railroad in neighboring districts' is the variable 'railroad in district' averaged over all districts within a 250 km radius of the district of observation. 'Rainfall in district' is a measure (in meters) of the amount of crop-specific rainfall that fell in the district, averaged over all 17 crops using the appropriate weighting in equation (20) of the text. 'Rainfall in severe/mild famine agricultural year minus long-run mean' is similar to the variable defined above for the 1876-78 famine, but for five other famines designated as either 'severe' or 'mild' as in the text. Data sources and construction are described in full in Appendix A. Heteroskedasticity-robust standard errors corrected for clustering at the district level are reported in parentheses. *** indicates statistically significantly different from zero at the 1% level; ** indicates 5% level; and * indicates 10% level.

Table 8: Railroads and Real Income Levels (Step 4) - Bounds Check

Dependent variable: log real agricultural income per acre	(1)	(2)
Railroad in district	0.182	
	(0.071)***	
Railroad in neighboring district	-0.042	-0.037
	(0.020)**	(0.031)
Railroad in district, built pre-1883 or post-1904		0.174
		(0.100)*
Railroad in district, line labelled as 'productive'		0.212
		(0.119)
Railroad in district, line labelled as 'protective'		0.168
		(0.144)
Railroad in district, line labelled as 'productive and protective'		0.173
		(0.138)
Railroad in district, line labelled as 'military'		0.204
		(0.197)
District fixed effects	YES	YES
Year fixed effects	YES	YES
Observations	14,340	14,340
R-squared	0.758	0.760

Notes: OLS regressions estimating equation (18) using real income constructed from crop-level data on 17 principal agricultural crops (listed in Appendix A), from 239 districts in India, annualy from 1870 to 1930. 'Railroad in district' is a dummy variable whose value is one if any part of the district in question is penetrated by a railroad line (calculated over all years in the sample). 'Railroad in neighboring district' was defined in Table 5. 'Railroad in district, built pre-1883 or post-1904' is a similar variable defined in these time periods only, because in these time periods lines were not designated according to primary intended use. 'Railroad in district, line labelled as X' is a dummy variable whose value is one if any part of the district in question is penetrated by a line that whose primary intended use was designated (between 1883 and 1904, when all lines required such a designation) as 'X'. The intended primary uses 'X' are: 'productive', where line was expected to be commercially remunerative; 'protective', where line was intended to be redistributive towards lagging regions; 'productive and protective', where the line was intended to have both of the previous primary uses; and 'military' if the line was built for military/strategic reasons. Heteroskedasticity-robust standard errors corrected for clustering at the district level are reported in parentheses. *** indicates statistically significantly different from zero at the 1% level; ** indicates 5% level; and * indicates 10% level.

Table 9: Railroads and Real Income Volatility (Step 5)

Dependent variable: Log real agricultural income per acre	(1)	(2)
Railroad in district	0.186	0.252
	(0.085)**	(0.132)*
Rainfall in district	1.248	2.434
	(0.430)***	(0.741)***
(Railroad in district) x (Rainfall in district)		-1.184
		(0.482)**
Railroad in neighboring district	-0.031	-0.022
	(0.021)*	(0.027)
District fixed effects	YES	YES
Year fixed effects	YES	YES
Observations	14,340	14,340
R-squared	0.767	0.770

Notes: OLS Regressions estimating equation (19) using real income constructed from crop-level data on 17 principal agricultural crops (listed in Appendix A), from 239 districts in India, annualy from 1870 to 1930. 'Railroad in district' is a dummy variable whose value is one if any part of the district in question is penetrated by a railroad line. 'Rainfall in district' is a weighted sum of a district's crop-specific rainfall amounts (in meters), summed over all 17 crops with weights as suggested by my model, as in equation (19). 'Railroad in neighboring districts' was defined in the notes to Table 5. Data sources and construction are described in full in Appendix A. Heteroskedasticity-robust standard errors corrected for clustering at the district level are reported in parentheses. *** indicates statistically significantly different from zero at the 1% level; ** indicates 5% level; and * indicates 10% level.

Table 10: A Sufficient Statistic for Railroad Impact (Step 6)

Dependent variable: Log real agricultural income per acre	(1)	(2)
Railroad in district	0.252	0.021
	(0.132)*	(.0096)
Rainfall in district	2.434	1.044
	(0.741)***	(0.476)**
(Railroad in district) x (Rainfall in district)	-1.184	0.042
	(0.482)**	(0.64)
Railroad in neighboring district	-0.022	0.003
	(0.027)	(0.041)
"Openness", as computed in model		-0.942
		(0.152)***
District fixed effects	YES	YES
Year fixed effects	YES	YES
Observations	14,340	14,340
R-squared	0.770	0.788

Notes: OLS Regressions estimating equation (19) in column 1 and equation (21) in column 2, using real income constructed from crop-level data on 17 principal agricultural crops (listed in Appendix A), from 239 districts in India, annualy from 1870 to 1930. 'Railroad in district' is a dummy variable whose value is one if any part of the district in question is penetrated by a railroad line. 'Rainfall in district' is a weighted sum of a district's crop-specific rainfall amounts (in meters), summed over all 17 crops with weights as suggested by my model, as in equation (20) (where for reasons explained in the text, the weights sum to 4.6). 'Railroad in neighboring districts' was defined in the notes to Table 5. 'Openness' is the share of a district's expenditure that it buys from itself; this varible is computed in the equilibrium of the model, where the model parameters are set to those estimated in Steps 1 and 2, and the exogenous variables (the transportation network, rainfall, and district land sizes) are as observed. Data sources and construction are described in full in Appendix A. Heteroskedasticity-robust standard errors corrected for clustering at the district level are reported in parentheses. *** indicates statistically significantly different from zero at the 1% level; ** indicates 5% level; and * indicates 10% level.