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Railroads of the Raj: Estimating the Impact of Transportation Infrastructure[†]

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How large are the benefits of transportation infrastructure projects, and what explains these benefits? This paper uses archival data from colonial India to investigate the impact of India's vast railroad network. Guided by four results 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) *increased real income levels; and* (4) *that a sufficient statistic for the effect of railroads on welfare in the model accounts well for the observed reduced-form impact of railroads on real income in the data.* (*JEL* H54, L92, N75, O22, R12, R42)

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 the costs of trading. In prominent models of international and interregional trade, reductions in trade costs will increase the level of real income in trading regions. 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

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comprehensive new dataset on the colonial Indian economy that I have constructed. First, I estimate the extent to which railroads improved India's trading environment (i.e., reduced trade costs, reduced interregional price gaps, and increased trade flows). Second, I estimate the reduced-form welfare gains (higher real income levels) 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 could be plausibly interpreted as newly exploited gains from trade.

The railroad network designed and built by the British government in India (then known to many as "the Raj") brought dramatic change to the technology of trading on the subcontinent. 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 activity 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, district-level dataset on 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 availability of records on *interregional* trade is 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 Ricardian trade model with many regions, many commodities, and where trade occurs at a cost. Because of geographical heterogeneity, regions have differing productivity levels across commodities, which creates incentives to trade in order 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 reduced trade costs and thereby allowed regions to gain from trade. Four results in the model drive a natural four-step empirical analysis, as follows.

Step 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. Empirically, I use this result to measure trade costs (which, like all researchers, I cannot observe directly) 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 nonlinear least squares (NLS) 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.

Step 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. Empirically, I used the estimate from a gravity equation, in conjunction with the trade cost parameters estimated in Step 1, to identify all of the relevant unknown parameters of the model.

Step 3: *Railroads increase real income levels.* That is, when a district is connected to the railroad network, its real income rises. Empirically, I find that railroad access raises real income by 16 percent. This reduced-form estimate could arise through a number of economic mechanisms. A key goal of Step 4 is to assess how much of the reduced-form impact of railroads on real income can be attributed to gains from trade due to the trade cost reductions found in Step 1.

Step 4: *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 its impact on one endogenous variable: the share of that district's expenditure that it sources from itself. A result similar to this appears in a wide range of trade models but has not, to my knowledge, been explored empirically before.[1] Empirically, I regress real income on this sufficient statistic (as calculated using the model's parameter estimates obtained in Steps 1 and 2) alongside the regressors from Step 3 (which capture the reduced-form impact of railroads). When I do this, the estimated reduced-form coefficients on railroad access (from Step 3) fall by more than one-half and the sufficient statistic variable is itself highly predictive. This finding provides support for Result 4 of the model and implies that decreased trade costs account for about one-half of the real income impacts of the Indian railroad network.

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

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[1] Arkolakis, Costinot, and Rodríguez-Clare (2012) show that this prediction applies to the Krugman (1980), Eaton and Kortum (2002), and Chaney (2008) models of trade, but these authors do not test this prediction empirically.

A natural concern when estimating the impact of infrastructure projects is that of bias due to a potential correlation between project placement and unobserved changes in the local economic environment. These concerns are likely to be less important in my setting because (as described in Section II) military motives for railroad placement usually trumped economic arguments, the networked nature of railroad technology inhibited the ability of planners to target specific locations precisely, and planning documents reveal just how hard it was for technocrats to agree on the efficacy of railroad plans. Nevertheless, to mitigate concerns of selection bias, I estimate the "effects" of over 40,000 km of railroad lines that reached advanced stages of costly surveying but, for three separate reasons that I document in Section VI, were never actually built. Reassuringly, these "placebo" lines never display spurious effects.

This paper contributes to a growing literature on estimating the economic effects of large infrastructure projects,[2] as well as to a literature on estimating the "social savings" of railroad projects.[3] 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.[4] 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 (such as tariff liberalization or road construction) in which the welfare benefits of trade-cost-reducing polices might be sought. By contrast, my reduced-form estimates are more likely to be specific to the context of railroads in colonial India.

This paper also contributes to a rich literature concerned with estimating the welfare effects of openness to trade, because the reduction in trade costs brought about by India's railroad network rapidly increased each district's opportunities to trade.[5] Again, the fact that my empirical approach connects explicitly to an estimable, general equilibrium model of trade offers advantages over the existing literature. The model suggests a theoretically consistent way to measure "openness," sheds light on *why* trade openness raises welfare, and provides a natural way to study changes in openness to both internal and external trade at the same time.

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[2] For example, Dinkelman (2011) 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 fish markets; and Michaels (2008) estimates the effect of the US interstate highway system on the skilled wage premium. An earlier literature, beginning with Aschauer (1989), pioneered the use of econometric methods in estimating the benefits of infrastructure projects.

[3] 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 VE, I compare my estimates to those from using a social savings approach.

[4] The use of general equilibrium modeling, on its own, to evaluate transportation projects here is not novel. For example, both Williamson (1974) and Herrendorf, Schmitz, and Teixeira (2012) use calibrated general equilibrium models to study the impact of railroads on the antebellum US economy.

[5] Frankel and Romer (1999), Alcalá and Ciccone (2004), Feyrer (2009), and others use cross-country regressions of real GDP levels on "openness" (defined in various ways) to estimate the effect of openness on welfare. Pavcnik (2002), Trefler (2004), and Topalova (2010) among others instead analyze trade liberalizations within one country by exploiting cross-sectional variation in the extent of liberalization across either industries or regions.

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 II, I outline a model of trade in colonial India and the model's four results. Sections III through VI present a four-step empirical analysis that follows these four theoretical results. Section VII concludes.

I. Historical Background and Data

In this section I discuss some essential features of the colonial Indian economy and the data that I have collected in order to analyze how this economy changed with the advent of railroad transport. 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.

A. *New Data on the Indian Economy, 1870–1930*

In order to evaluate the impact of the railroad network on economic welfare in colonial India, I have constructed a new panel dataset on 235 Indian districts. The dataset tracks these districts annually from 1870–1930, 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. Online 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).[6] For this reason, district-level output and area data were only collected systematically in the agricultural sector. Data on agricultural output were recorded for each of 17 principal crops (which accounted for the vast majority of the cropped area of India in 1900): bajra, barley, cotton, gram, indigo, jowar, jute, linseed, maize, opium, ragi, rice, sesamum, sugarcane, tea, tobacco, and wheat. Retail prices for these 17 crops were also recorded at the district level. I use these price, quantity, and area figures to construct a measure of real agricultural income per acre that 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 35 percent growth between the beginning and end of the sample (approximately 1870 to 1930), according to my estimates.[7] Real incomes were low because crop yields were low, both by contemporaneous international standards and by Indian standards today.[8] One explanation for low yields that featured heavily in Indian agricultural textbooks

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[6] Factory-based industry, which Atack, Haines, and Margo (2011) argue benefited from access to railroads in the United States, amounted to only 1.6 percent of India's GDP in 1900.

[7] 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 purchasing power parity (PPP) rates.

[8] 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 by 2010 were an order of magnitude greater than those in 1896 (https://data.gov.in/catalog/district-wise-season-wise-crop-production-statistics).

Table 1—Descriptive Statistics

	Number of observations	Beginning of available data	End of available data
Real agricultural income per acre (base year rupees)	7.086	29.96	40.41
		(16.35)	(50.56)
Price of salt, all sources (current rupees per maund)	7,336	5.17	3.21
		(1.49)	(0.54)
Crop-specific rainfall shock (meters)	120,462	0.75	1.29
		(0.67)	(1.38)
Total agricultural exports per trade block (millions of 1870 rupees)	1,193	19.07	44.63
		(45.68)	(58.76)

Notes: Values are sample means over all observations for the year and variable in question, with standard deviations in parentheses. Earliest beginning and latest end of available data are: 1870 and 1930 for agricultural output and real agricultural income; 1861 and 1930 for salt prices; 1870 and 1930 for rainfall; and 1882 and 1920 for trade data. Land area used to calculate income per acre is total cultivated area in first year of sample. A "maund" is equal to 37.3 kg and was the standardized unit of weight in colonial India. Total agricultural exports (aggregating across commodities and destination blocks) per trade block converted from quantities to values (in 1870 rupees) using all-India average prices in 1870. Data sources and construction described further in online Appendix A.

of the day (such as Wallace 1892) was inadequate water supply. Only 12 percent of cultivated land was irrigated in 1885 and while this figure had risen to 19 percent in 1930, the vast majority of agriculture maintained its dependence on rainfall.[9]

Because rainfall was important for agricultural production, 3,614 meteorological stations were built throughout the country to record the amount of rainfall at each station on every day of the year. Daily rainfall data were 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 IV and VI, I use daily rainfall data collected from India's meteorological stations to construct crop-specific measures of rainfall and use these as a source of rainfall and employ these as exogenous variation in crop-specific productivity.

Commensurate with the increase in real agricultural income levels in India was a significant rise in interregional and international trade. The final component of the dataset that I have constructed on colonial India consists of data on these internal and external trades whenever they occurred via railroad, river, or sea (data on road trade were only very rarely collected). The role that these data play in my analysis is explained in Section IV.

B. *Transportation in Colonial India*

Prior to the railroad era, goods transport within India took place on roads, rivers, and coastal shipping routes.[10] The bulk of inland travel was carried by bullocks, along the road network. On the best road surfaces and during optimal weather

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[9] 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 online Appendix A. 1885 is the first year in which comprehensive irrigation statistics were collected.

[10] The description of pre-rail transportation in this section draws heavily on the comprehensive treatments of Deloche (1994, 1995) and Derbyshire (1985).

conditions, bullocks could pull a cart of goods and cover 20–30 km per day. However, high-quality roads were extremely sparse and the roads that did exist were virtually impassable in the monsoon season. For this reason most trade was carried by "pack" bullocks (which carried goods strapped to their backs and usually traveled directly over pasture land), which were considerably slower and riskier than cart bullocks.

Water transport was far superior to road transport, but it was only feasible on the Brahmaputra, Ganges, and Indus river systems.[11] In optimal conditions, downstream river traffic (with additional oar power[12]) 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. Coastal shipping, however, was perennially available along India's long coastline. This form of shipping was increasingly steam-powered after 1840. Steamships were fast and could cover over 100 km per day but could only service 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). Trains 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, and without any serious threat of piracy or damage (Johnson 1963). Railroad freight rates were also considerably cheaper: 4–5, 2–4, and 1.5–3 times cheaper in terms of freight rates, than road, river, and coastal transport, respectively. A principal goal of Section III is to estimate how much railroad technology reduced total trade costs, costs which combine all of these attractions of railroads over other modes.

C. *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 made the case for a vast railroad network in India and military motives for railroad-building appeared on virtually every page of this document.[13] These arguments gathered new momentum when the 1857 "mutiny" highlighted the importance of military communications (Headrick 1988). Dalhousie's 1853 minutes described five "trunk lines" that would connect

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

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

[13] 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).

India's five major provincial capitals along direct routes and maximize the "political advantages" of a railroad network.

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 their competing, and 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, along with Kennedy's proposal, were debated and surveyed at length, but were never actually built. As discussed in Section VD, 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.

As is clear from Figure 1, 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. Track open for traffic reached 67,247 km, 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. 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,[14] and Mahatma Gandhi argued simply that "it is beyond dispute that [railroads] promote evil" (Gandhi 1938, p. 36). 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.

II. 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), but with more than one commodity, and serves two purposes. First, it delivers four results concerning the response of observables to trade cost reductions. Second, I estimate the unknown parameters of the model and use the estimated model 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.

A. *Model Environment*

The economy consists of D regions (indexed by either o or d depending on whether the region in question is the origin, o, or the destination, d, of a trade). There are K commodities (indexed by k), each available in a continuum (with mass normalized to 1) 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

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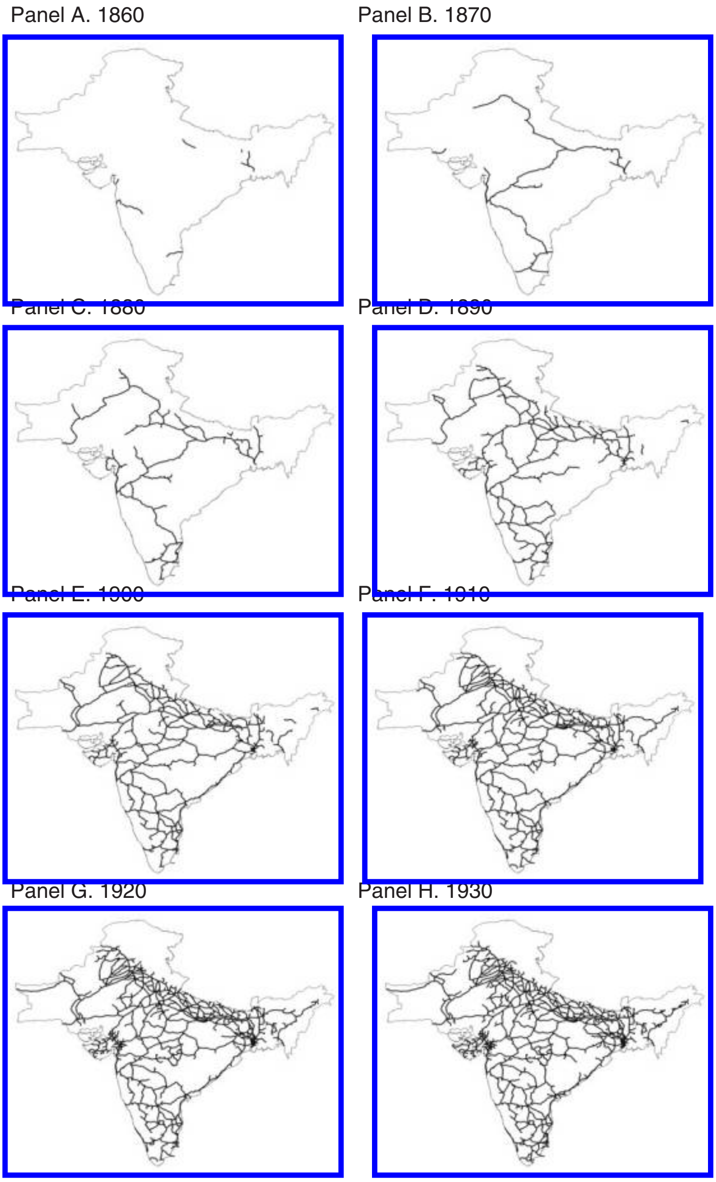
[14] For example, from his landmark textbook on Indian economic history: "Railways … did not add to the produce of the land" (Dutt 1904, p. 174).



Panel A. 1860

Panel B. 1870

Panel C. 1880

Panel D. 1890

Panel E. 1900

Panel F. 1910

Panel G. 1920

Panel H. 1930

Figure 1. The Evolution of India's Railroad Network, 1860–1930

Notes: 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. The figure is based on a GIS database in which each (approximately) 20 km long railroad segment is coded with a year of opening variable.

Source: Author's calculations based on official publications. See online Appendix A for details.

of annual observations, for simplicity the model is static; I therefore suppress time subscripts until they are necessary.

Consumer Preferences.—Each region o is home to a mass (normalized to 1) 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 (CES) preferences over varieties (j) within each commodity; that is, their utility function is

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

where $C_o^k(j)$ is consumption, $\varepsilon_k \doteq \frac{\sigma_k - 1}{\sigma_k}$ (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.

Production and Market Structure.—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.[15] Importantly, land is homogeneous and can be allocated to the production of any variety of any commodity without adjustment costs, consistent with a long-run interpretation that informs the empirical analysis below. Let $z_o^k(j)$ denote the amount of variety j 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 in the following manner:

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

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

There are many competitive firms in region o with access to the technology above; consequently, firms make zero profits.[16] These firms therefore charge a pre-trade costs (i.e., "free on board") 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

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[15] This is clearly an extreme assumption, made here for parsimony (though all results would be unaffected if agricultural production were a Cobb-Douglas aggregator of land and other inputs as long as those inputs are immobile). However, if crops differ in their factor intensities (as in Heckscher-Ohlin models of trade), factor intensities are endogenous to factor prices, or factors are mobile, then while the four results in Section IIB would be unaffected the procedure used to compute π_{oot}^k in equation (18), based on the factor market-clearing equilibrium of the model, would need to be altered. I return to the discussion of labor mobility in Section VA.

[16] My empirical application is 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 the 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, or proprietors of extremely small-scale farms (Risley and Gait 1903).

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 "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.) 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, under perfect competition, any variety in region d will cost T_{od}^{k} times more than it does 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 indifferent about where a given variety is made: they simply buy from the region that can provide the variety at the lowest cost (after accounting for trade costs). I therefore solve for the equilibrium prices that consumers in a region d actually pay, given that they will only buy any particular 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 cumulative distribution function (CDF) in equation (2), $p_{od}^{k}(j)$ is the realization of a random variable P_{od}^{k} drawn from the CDF

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

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:

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

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 relevant 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

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

where $\lambda_1^k \doteq \Gamma(1 + \frac{1}{\theta_k})$.[17] In my empirical application below I treat these expected prices as equal to the observed prices collected by statistical agencies.[18]

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 (i.e., 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

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

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

Equation (5) characterizes trade flows conditional on the endogenous land rental rate, r_o (and all other 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

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

[18] 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 $\tilde{p}_d^k \doteq \left[\int_0^1 (p_d^k(j))^{1-\sigma_k}\, dj\right]^{1/1-\sigma_k}$, which is only well defined here for $\sigma_k < 1 + \theta_k$ (a condition I assume throughout). The exact price index is given by $\tilde{p}_d^k = \lambda_2^k p_d^k$, where $\lambda_2^k \doteq \frac{\gamma^k}{\lambda_1^k}$ and $\gamma^k \doteq \left[\Gamma\left(\frac{\theta_k + 1 - \sigma_k}{\theta_k}\right)\right]^{1/(1-\sigma_k)}$. 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 would not jeopardize my empirical procedure because the exact price index is proportional to expected prices.

commodities made in region o and sent to every other region (including region o itself).[19] 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 (i.e., of $r_d L_d$). 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 numéraire good, so the equilibrium of the model is the set of $D - 1$ unknown rental rates r_d that solves this system of $D - 1$ (nonlinear) independent equations.

B. *Four Results*

In this section I state explicitly four important results that emerge from the model outlined above, in the order in which they drive my empirical analysis (i.e., Steps 1–4).

RESULT 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. 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 result is important for my empirical work below because it allows trade costs (T_{od}^o), which are never completely observed, to be inferred. But it is important to note that this result, essentially just the assumption of free arbitrage over space, net of trade costs, is not a testable prediction in the absence of direct data on T_{od}^o.

RESULT 2:

Bilateral trade flows take the "gravity equation" form. Equation (5) describes bilateral trade flows explicitly, but I restate 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

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

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[19] The essential assumption here is that the trade balance is fixed and exogenous, not that it is fixed to zero. The assumption of fixed district-level trade balance is not innocuous but I am unaware of any direct evidence on this point.

This is the gravity equation form for bilateral trade flows, which is common to many widely used trade models: bilateral trade costs reduce bilateral trade flows, conditional on importer- and exporter-specific terms.

RESULT 3:

Railroads increase real income levels. In this model, welfare in district o is equal to its real income (per unit land area), W_o, which is given by real land rents:[20]

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

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 welfare.[21] To make progress in generating qualitative predictions (to guide my empirical analysis) I therefore assume a much simpler environment for the purpose of obtaining Result 3 only. 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 (i.e., L_o and A_o); and the three regions have symmetric trade costs with respect to each other. I consider the comparative statics from a local change around this symmetric equilibrium that reduces the bilateral trade cost symmetrically between two regions (say X and Y). It is straightforward to show (as is done in online Appendix B) that

$$\frac{dW_X}{dT_{YX}} < 0. \tag{10}$$

That is, real income in a region (say, X) rises when the bilateral cost of trading between that region and any other region (say, Y) falls.

RESULT 4:

There exists a sufficient statistic for the welfare gains from railroads. Using the bilateral trade equation (5) evaluated at $d = o$, (log) real income per unit of land can be rewritten as

$$\ln W_o = \Omega + \sum_k \frac{\mu_k}{\theta_k} \ln A_o^k - \sum_k \frac{\mu_k}{\theta_k} \ln \pi_{oo}^k, \tag{11}$$

where $\Omega \doteq -\sum_k \mu_k \ln \gamma^k$. This result states that welfare is (up to the constant, Ω) a function of only two terms, one involving (exogenous) local productivity levels (A_o^k), and a second term that I will refer to as "the trade share" (i.e., the fraction of region o's expenditure that region o buys from itself, π_{oo}^k, which equals 1 in autarky). Because of the complex general equilibrium relationships in the model,

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[20] Recall that $\tilde{p}_o^k$ is the CES price index for commodity k in region o, defined in footnote 18.

[21] Eaton and Kortum (2002, p. 1758) derive analytical expressions for the case of one sector and multiple regions but only under the extreme cases in which trade costs are either zero ($T_{od} = 1$) or prohibitive ($T_{od} \rightarrow \infty$ for all $o \neq d$).

the full matrix of trade costs (between every bilateral pair of regions), the full vector of productivity terms in all regions, and the sizes of all regions 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 the trade share. Put another way, the trade share (the appropriately weighted sum of π_{oo}^k 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 Result 4 states that one should see no additional effects of railroads on welfare once the trade share (π_{oo}^k) is controlled for.

C. *From Theory to Empirics*

To relate the static model in Section II 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 interregional lending is not possible. Furthermore, I assume that the stochastic production process described in Section IIA 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 four theoretical results outlined in Section IIB 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 four empirical sections that follow (i.e., Steps 1–4). In Step 1, I evaluate the extent to which railroads reduced trade costs within India using Result 1 to relate the unobserved trade costs term in the model (T_{odt}^k) to observed features of the transportation network. In Step 2, I use Result 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 (the elasticity of trade flows with respect to trade costs), and to relate the unobserved productivity terms (A_{ot}^k)[22] 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, following Result 3 I estimate how the level of a district's real income is affected by the arrival of railroad access to the district. However, the empirical finding in Step 3 is reduced-form in nature and could arise through a number of possible mechanisms (such as enhanced mobility labor, capital, or technology). Therefore, in Step 4 I use the sufficient statistic suggested by Result 4 to compare the reduced-form effects of railroads on the level of real income (found in Step 3) with the effects predicted by the model (as estimated in Steps 1 and 2).

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[22] The productivity terms A_{ot}^k 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.

III. 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 explores a trade-based mechanism for the impact of railroads on welfare, it is important to assess whether railroads actually reduced trade costs. Further, the relationship between railroads and trade costs, which I estimate in this section, is an important input for Steps 2 and 4 that follow.

A. *Empirical Strategy*

Researchers never observe the full extent of trade costs.[23] But Result 1 suggests a situation in 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.[24]

Throughout Northern India, several different types of salt were consumed, each of which was regarded as homogeneous and each of which was only capable of being made at one unique location. For example, traders and consumers would speak of "Kohat salt" (which could only be produced at the salt mine in the Kohat region) or of "Sambhar salt" (which could only be produced at the Sambhar Salt Lake).[25] And official price statistics would report a distinct price for each different type of salt. I have collected data on salt prices in Northern India, in which the prices of six regionally differentiated types of salt are reported annually from 1861–1930. Crucially, because salt is an essential commodity, it was consumed (and therefore sold at markets where its price could be easily recorded) throughout India both before and after the construction of railroads.

I use these salt price data, with the help of Result 1, to estimate how Indian railroads reduced trade costs. To do this I estimate equation (7) of Result 1 as follows:

$$\ln p^o_{dt} = \underbrace{\beta^o_{ot}}_{=\ln p^o_{ot}} + \underbrace{\beta^o_{od} + \delta \ln LCRED(\mathbf{R}_t, \boldsymbol{\alpha})_{odt} + \varepsilon^o_{odt}}_{=\ln T^o_{odt}}. \tag{12}$$

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

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[23] 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, or the risk of damage or loss in transit.

[24] In their survey of attempts to estimate trade costs, Anderson and van Wincoop (2004, p. 78) suggest 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." Recent work by Keller and Shiue (2008) on nineteenth century Germany and Andrabi and Kuehlwein (2010) on colonial India documents that when two markets are connected by railroad lines, these markets' prices (for similar commodities) converge. This approach demonstrates that railroads lowered trade costs, but does not aim to estimate the level of trade costs or the magnitude of the effect of railroads on trade costs.

[25] 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. Based on the descriptions in Watt (1889), it is plausible that consumers (and price data collectors) could distinguish between the salt types that would typically sell in a given region. Kohat salt, for example, is a rock salt with a pink hue; Sambhar salt, by contrast, is powdery and often contained, at that time, small amounts of yellow or brown residue.

origin-year fixed effect[26] (β^o_{ot}) to control for the price of type-o salt at its origin o (i.e., p^o_{ot}) because I do not observe salt prices exactly at the point where they leave the source. (My price data are at the district level and are based on records of the price of a commodity averaged over 10–15 retail markets in a district.)

The remainder of equation (12) 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. The core of this specification is the variable $LCRED(\mathbf{R}_t, \boldsymbol{\alpha})$, which measures the *lowest-cost route effective distance* between the origin o and destination d districts in any year t. I describe this variable in detail below. The parameter δ captures the elasticity of trade costs with respect to "effective distance." This specification also 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 ethnolinguistic differences between o and d that may hinder trade). Finally, ε^o_{odt} is an error term that captures any remaining unobserved determinants of trade costs (or measurement error in $\ln p^o_{dt}$).[27]

The variable $LCRED(\mathbf{R}_t, \boldsymbol{\alpha})$ models the cost of trading goods between any two locations under the assumption that agents take the lowest-cost route, using any modes of transportation, available to them. Two inputs are needed to calculate the effective length of 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 (detailed in online Appendix A) I allow agents to travel on navigable rivers, the coastline, the road network, 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, where the proportionality, the 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 $\boldsymbol{\alpha}$ represent costs relative to the cost of using railroads. Since only relative costs affect the identity of the lowest cost route, this normalization has no bearing on the actual route taken between any pair of districts. Because of this normalization, $LCRED(\mathbf{R}_t, \boldsymbol{\alpha})_{odt}$ is measured as a railroad-equivalent distance; in this sense, a finding that all of the non-rail elements of $\boldsymbol{\alpha}$ are greater than 1 would imply that India's expanding railroad network shrunk "effective distance," or distance measured in a railroad-equivalent sense.

The parameter $\boldsymbol{\alpha}$ is unknown, so I treat it as a vector of parameters to be estimated. Conditional on a value of $\boldsymbol{\alpha}$, it is possible to calculate $LCRED(\mathbf{R}_t, \boldsymbol{\alpha})_{odt}$ quickly using Dijkstra's shortest-path algorithm (Ahuja, Magnanti, and Orlin 1993). But since $\boldsymbol{\alpha}$ is unknown, I estimate it using nonlinear least squares (NLS). That is, I

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[26] 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.

[27] 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 IV) in an unspecified manner.

search over values of α, recomputing the lowest-cost routes at each step, to find the value that minimizes the sum of squared residuals in equation (12).[28]

B. *Data*

I use data on retail prices of six types of salt, observed annually from 1861–1930 in an unbalanced panel of 133 districts of Northern India (in other regions, reported salt prices were not broken down by region of origin). Further details on the data I use in this and other sections of this paper are provided in online Appendix A.

C. *Results*

Table 2 presents ordinary least squares (OLS) estimates of equation (12). In column 1 I estimate the effect of the lowest-cost route effective distance on trade costs when the relative costs of each mode (α) are set to observed historical relative freight rate estimates. I use the relative per unit distance freight rates described in Section IB (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 1 demonstrates that the elasticity of trade costs with respect to the lowest-cost route effective distance, calculated at observed freight rates, is 0.088, and this is statistically significant at the 5 percent level.

However, as argued in Section IB, it is possible that these observed relative freight rates do not capture the full benefits (such as increased certainty or time savings) of railroad transport relative to alternative modes of transportation. For this reason the NLS specification in column 2 estimates the relative freight rates (i.e., the parameters α) that minimize the sum of squared residuals in equation (12). Column 2 is my preferred specification. When the mode-wise distance costs (i.e., α) are not restricted to be equal to the observed freight rates, the estimated elasticity of trade costs with respect to effective distance (i.e., δ) rises to 0.169. Even when controlling for all unobserved, time-constant determinants of trade costs between all salt sources and destinations, as well as unrestricted shocks to the source price of each salt type, reductions in trade costs along lowest-cost routes (estimated from railroad-driven time variation in these routes alone) have a large effect on reducing salt price gaps over space.

The nonlinear specification in column 2 also estimates the relative trade costs by mode that best explain observed salt price differentials. The estimated relative cost of each of the three alternative modes of transport is larger than 1 (and has an estimated bootstrapped 95 percent confidence interval that exceeds 1), implying that these alternative modes are more expensive (per unit distance) than rail travel. These non-rail mode estimates are, by and large, similar to the historically observed freight rate estimates used in column 1, with estimated confidence intervals that span the historical rates, except for the case of coastal shipping which evidently had a greater cost elasticity with respect to distance than one might conclude from freight rates alone.

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[28] In practice, I use a grid search over values of α from 1 to 10 with grid sizes of 0.125. Standard errors are bootstrapped using a similar grid search (but with a coarser grid size of 0.5).

TABLE 2—RAILROADS AND TRADE COSTS: STEP 1

Dependent variable: log salt price at destination	(1)	(2)
log effective distance to source, along lowest-cost route (at historical freight rates)	0.088 (0.028)	
log effective distance to source, along lowest-cost route (at estimated mode costs)		0.169 [0.062, 0.296]
Estimated mode costs per unit distance:		
Railroad (normalized to 1)		1 N/A
Road		2.375 [1.750, 10.000]
River		2.250 [1.500, 6.250]
Coast		6.188 [5.875, 10.000]
Observations	7,345	7,345
R^2	0.946	0.946

Notes: Regressions estimating equation (12) using data on 6 types of salt (listed in online Appendix A), from 133 districts in Northern India, annually from 1861 to 1930. Column 1 and column 2 estimated by OLS and NLS respectively; both include salt type × year and salt type × destination fixed effects. "Effective distance to source, along lowest-cost route" measures the railroad-equivalent kilometers (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. Standard errors corrected for clustering at the destination district level are reported in parentheses of column 1, and bootstrapped 95 percent confidence intervals are reported in column 2.

An important caveat when interpreting the results in this section, and the results in Steps 2 and 4 that depend on the estimates here, is that railroads may have done more to reduce trading frictions, as estimated here, than simply to reduce the physical costs of transporting goods. For example, railroads may have made it easier for price information to spread, whether directly via the movement of traders or post (which traveled for free on the railroads) or indirectly via the telegraph lines that followed railroad lines in space (since telegraph lines were used for the railroads' traffic signaling technology).[29] Because of the symbiotic relationship among railroads, telegraphs, and the postal service (Kerr 2007), the results here capture the composite effects of railroads on trade costs that combine a number of possible channels.

To summarize, the results in column 2 of Table 2 contain two important findings. First, the coefficient on the lowest-cost route effective distance ($\hat{\delta}$) is positive, which implies that trade costs increase with effective distance (in railroad-equivalent kilometers). And second, the estimated mode-specific per-unit distance costs ($\hat{\boldsymbol{\alpha}}$) are all greater than 1 (and statistically significantly so), implying that railroads played a

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[29] Describing the movement of traders, Kerr (2007, p. 109) quotes from an account (from 1878) in a Madras newspaper (emphasis and parentheses in original): "The Madras Chetty [Chetty = Chettiar, a Tamil trading caste] hears of something to be bought at Coimbatore, he no longer sends a note, he goes there, views the article he proposes to buy and buys them *himself*. Nothing suits him so well, no one need to be trusted, not even his own brother, he himself has the iron horse at his disposal, and can do the work himself."

role in reducing effective distance when compared to alternative modes of transportation. I use the estimates in column 2 in Steps 2 and 4 to follow.

IV. Empirical Step 2: Railroads and Trade Flows

The first step of my empirical strategy demonstrated that India's railroad network reduced trade costs. I now estimate the extent to which this reduction in trade costs affected trade flows within India. 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 able to explore empirically Result 4 in Section VI.

A. *Empirical Strategy*

Result 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 (12) into equation (8) yields

$$\ln X^k_{odt} = \beta^k_{od} + \ln A^k_{ot} - \theta_k \ln r_{ot} - \theta_k \hat{\delta} \ln LCRED(\mathbf{R}_t, \hat{\alpha})_{odt} + \theta_k \ln p^k_{dt} + \ln X^k_{dt} + \varepsilon^k_{odt}. \tag{13}$$

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 II. Note that this substitution assumes that the empirical estimates of trade cost parameters $(\hat{\delta}, \hat{\alpha})$ obtained from Step 1, using data on salt, are valid for any commodity k. This assumption is made out of necessity (since trade cost estimates are not available for any commodity but salt), but I discuss below some tests that fail to reject it.

I estimate a version of equation (13) in two stages, with two goals in mind. My first goal is to estimate the unknown parameters θ_k. As is typical in the empirical gravity equation literature, estimation of equation (13) is complicated by the presence of endogenous regressors (r_{ot}, p^k_{dt}, and X^k_{dt}). Fortunately, because my interest here lies in the coefficient θ_k, that is, in how the trade cost reductions brought about by railroads translated into expansions in trade flows, I estimate this equation in the following manner:

$$\ln X^k_{odt} = \beta^k_{ot} + \beta^k_{dt} + \beta^k_{od} - \theta_k \hat{\delta} \ln LCRED(\mathbf{R}_t, \hat{\alpha})_{odt} + \varepsilon^k_{odt}. \tag{14}$$

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 absorbs the terms $\ln A^k_{ot}$, $\theta_k \ln r_{ot}$, $\ln p^k_{dt}$, and $\ln X^k_{ot}$ in equation (13)) and β^k_{od} is an origin-destination-commodity fixed effect (the inclusion of which was motivated in Section III by the concern that some costs of trading may be unobservable). I estimate this equation separately for each of the agricultural commodities in my trade flows dataset, in order to estimate a value of θ_k for each commodity k.

My second goal in estimating equation (13) is to estimate the determinants of the underlying productivity terms, A^k_{ot}. Armed with estimates of $\hat{\theta}_k$, obtained from estimating equation (14) above, it is possible to estimate the determinants of A^k_{ot} in a second stage as follows. I relate A^k_{ot} to observables by assuming that A^k_{ot} is a function of a crop-specific rainfall shock, denoted by $RAIN^k_{ot}$. As argued in Section I, rainfall was an important determinant of agricultural productivity in India because most land was un-irrigated. 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 use the 1967 edition of the *Indian Crop Calendar* (Directorate of Economics and Statistics 1967), which lists sowing, growing, and harvesting windows for crops and districts in my sample. To construct the variable $RAIN^k_{ot}$, 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.[30]

It is then possible to estimate the relationship between rainfall and productivity by noting that the exporter-commodity-year fixed effect (β^k_{ot}) in equation (14) can be interpreted in the model as $\beta^k_{ot} = \ln A^k_{ot} - \theta_k \ln r_{ot}$, by comparing equations (13) and (14). I model the relationship between productivity (A^k_{ot}) and rainfall $(RAIN^k_{ot})$ in a parsimonious semi-log manner: $\ln A^k_{ot} = \kappa RAIN^k_{ot}$. Guided by this relationship, I define the variable $\ln \tilde{X}^k_{odt} \doteq \ln X^k_{odt} + \hat{\theta}_k \ln r_{ot} + \hat{\theta}_k \hat{\delta} \ln LCRED(\mathbf{R}_t, \hat{\alpha})_{odt}$ and estimate the parameter κ in the following estimating equation:

$$(15) \qquad \ln \tilde{X}^k_{odt} = \beta^k_{od} + \beta^k_{dt} + \beta_{ot} + \kappa RAIN^k_{ot} + \varepsilon^k_{odt}.$$

The terms β^k_o, β^k_t, 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. As a result, the coefficient κ is estimated purely from the variation in rainfall over space, commodities and time.[31] The final term in equation (15) is an error term (ε^k_{odt}) that includes any determinants of exporting success, other than rainfall, that vary across regions, commodities and time.

In summary, the two-stage method described above estimates the parameter θ_k for each of the agricultural goods k for which I have trade data. This method also estimates the relationship between the unobserved productivity terms A^k_{ot} and crop-specific rainfall $RAIN^k_{ot}$ (governed by the parameter κ).

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[30] The results are largely insensitive to alternatively measuring $RAIN^k_{to}$ as the total rainfall between the first sowing date and the first harvest date since very little rain fell in the harvest window.

[31] This within-block-year identification strategy therefore estimates the effect, κ, that is common to all crops. While in practice crops may differ in their rainfall sensitivities some of this heterogeneity is likely to be captured by the use of crop-specific rainfall amounts, $RAIN^k_{ot}$.

B. *Data*

I estimate equations (14) and (15) using data on the physical quantities of internal trade (among 47 regions known as trade blocks), over rail and river transport routes, for 14 principal agricultural commodities plus salt, annually from 1882 to 1920.[32] Because four of the trade blocks comprise major port cities and (as explained in detail in online Appendix C) the internal trade data to/from each major port included trade to/from foreign countries via the major port city in question, these estimates also incorporate the bulk of international trade flows. When estimating equation (15), I use the crop-specific rainfall measure ($RAIN_{ot}^{k}$, averaged over districts within trade block o) described briefly above (and in more detail in online Appendix A) and, lacking reliable data on land rental rates, I use nominal agricultural output per acre as a measure of r_{ot} (since in the model these two measures are equivalent).

C. *Results*

Table 3 presents OLS estimates of variants of equation (14). While the ultimate reason for estimating equation (14) is to estimate the unknown parameters θ_k for each commodity k, I begin by reporting estimates from a specification that pools estimates of equation (14) across commodities. I do this to explore the plausibility of my assumption that the parameter δ, which relates the lowest-cost route effective distance variable ($LCRED(\mathbf{R}_t, \hat{\alpha})_{odt}$) to trade costs and was estimated using only one commodity (salt), is constant across all agricultural commodities.

Column 1 of Table 3 presents estimates of equation (14) pooled across commodities. The results in column 1 provide support for Result 2 of the model, 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) 1.603. This pooled point estimate is in line with a large body of work on estimating gravity equations reported in Head and Disdier (2008).

In column 2 of Table 3 I investigate the possibility that the elasticity of trade flows with respect to lowest-cost route effective distance varies by commodity in a manner that would suggest that trade costs differ in an important way across commodities. I do this by including interaction terms between the $LCRED(\mathbf{R}_t, \hat{\alpha})_{odt}$ variable and two commodity-specific characteristics (each measured in the earliest cross-section for which data are available): weight per unit value (as observed in 1890 export data, averaged over all of India), and "freight class" (an indicator used by railroad companies in 1859 to distinguish between "high-value" and "low-value" goods). The results in column 2 are not supportive of the notion that commodities had elasticities of trade with respect to distance that depend on either weight or

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[32] Data on many disaggregated manufacturing products were similarly collected but are not necessary for the estimates in this paper. The agricultural commodities available cover the 17 crops listed in Section IA, with the exception of barley, maize, and ragi which were not disaggregated separately in trade data publications. In addition, the crops of bajra and jowar were tabulated as one aggregate commodity. Because I estimate equation (14) at the trade block level, I construct the regressor $\ln LCRED(\mathbf{R}_t, \hat{\alpha})_{odt}$ from the average of all district pairs within the od trade block pair (and take the location of external regions to be their largest commercial centers: (Goalpara for the province of Assam, Hyderabad for the composite native states region, and Karachi for the province of Sindh). As in most international and intranational trade settings, I do not observe trade from region o to itself so those trade flows do not enter my gravity equation estimates here.

Table 3—Railroads and Trade Flows: Step 2

Dependent variable: log value of exports	(1)	(2)
log effective distance beween origin and destination along lowest-cost route	-1.603	-1.701
	(0.533)	(1.141)
(log effective distance beween origin and destination along lowest-cost route) × (weight per unit value of commodity in 1890)		-0.946
		(3.634)
(log effective distance beween origin and destination along lowest-cost route) × (high-value railroad freight class of commodity in 1859)		1.286
		(1.243)
Observations	142,541	142,541
R^2	0.901	0.901

Notes: Regressions estimating equation (14) using data on 15 commodities and 47 trade blocks annually from 1882 to 1920. Regressions include origin and destination fixed effects, separately for each commodity and year. "Effective distance between origin and destination along lowest-cost route" measures the railroad-equivalent kilometers (due to the normalization of railroad distance cost 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 1890" is the weight (in maunds) per rupee, as measured by 1890 prices. "Railroad freight class in 1859" is an indicator variable for all commodities that were classified in the higher (more expensive) freight class in 1859; salt is in the omitted category (low-value commodities). Heteroskedasticity robust standard errors adjusted for clustering at the exporter-importer block level are reported in parentheses for columns 1 and 2 respectively.

freight class in a statistically significant manner.[33] This lends support to the maintained assumption throughout this paper that trade cost parameters for the shipment of salt (obtained in Step 1) can be applied to other commodities, as is necessary given the absence of origin-specific product differentiation as was the case of salt, without doing injustice to the data.

Finally, I estimate equation (14) one commodity at a time (for each of the agricultural 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 estimates is 7.80, with a range from -9.60 to 29.21. The estimates for two crops (opium and tea) are in the inadmissible (i.e., negative) range, but neither estimate is statistically significantly different from zero at the 5 percent level. This average estimate is close to 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, though it is somewhat higher than other estimates in the literature such as those from Simonovska and Waugh (2014) or Costinot, Donaldson, and Komunjer (2012) (ranging from 4.5 to 6.5) for the OECD in the 1990s.

As described above, the second goal in estimating equation (14) in this section is to estimate κ, the parameter that relates crop-specific rainfall to (potential) productivity (A_{ot}^{k} in the model). I do this by estimating equation (15) and obtain a value of $\hat{\kappa} = 0.496$ (with a standard error, clustered by exporter-importer pair, of 0.151), implying that a one standard deviation (0.921 across the entire sample) increase in crop-specific rainfall causes a 46 percent increase in agricultural productivity (as defined by A_{ot}^{k} in the model). This suggests that rainfall has a positive and statistically significant effect on productivity, as expected given the importance of water

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[33] As reported in Table 3, the change in the total R^2, that is, that for the full model inclusive of fixed effects, due to the addition of these interaction variables is similarly inconsequential.

in crop production and the paucity of irrigated agriculture in colonial India (as discussed in Section I).

In summary, the results from this section demonstrate that railroads significantly expanded trade in India. This finding is in line with Result 2 and suggests that the expansion of trade brought about by the railroad network could have given rise to welfare gains due to increasingly exploited 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 Step 4.

V. Empirical Step 3: Railroads and Real Income Levels

Steps 1 and 2 have established that Indian railroads significantly reduced trade costs and expanded trade flows, findings which suggest that railroads improved the trading environment in India. I now go on to investigate some of the welfare consequences of railroad expansion in India by estimating the effect of railroads on real income levels.

A. *Empirical Strategy*

Result 3 of the model states that a district's real income will increase when it is connected to the railroad network. This result motivates an estimating equation of the form

$$\ln\left(\frac{r_{ot}}{\tilde{P}_{ot}}\right) = \beta_o + \beta_t + \gamma RAIL_{ot} + \varepsilon_{ot}. \tag{16}$$

In this equation, $r_{ot}/\tilde{P}_{ot}$ represents real agricultural income per acre (the appropriate welfare metric in the model) in district o and year t. There exist no systematic data on land rents or values in this time period, but in the model nominal land rents are equal to nominal output per unit area. As described in Section I, plentiful output data were collected in the agricultural sector (the dominant sector of India's colonial economy), so I use these to measure r_{ot}.[34] Finally, I construct a consumer price index, over agricultural goods, to measure $\tilde{P}_{ot}$.[35]

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[34] Real income per acre is equal to welfare (for a representative agent) in the 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 to railroad expansion in colonial India: in a Malthusian limit, fertility and mortality would adjust to any agricultural productivity improvements (e.g., due to railroads) and hold output per capita constant. However, the potential for endogenous fertility and mortality responses is likely to vary from setting to setting so while knowledge of an effect of railroads on output per acre is transferable to alternative settings, an effect on output per 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 2016 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 (Davis 1951; Rosenzweig and Stark 1989).

[35] In the model this price index is given in equation (9). However, it would be unsurprising if a price index calculated strictly as suggested by a theory fits that theory well. I therefore use a flexible price index (the Törnqvist price index, of which the price index in equation (9) is a special case) as is commonly done when constructing real GDP measures from national income accounts.

The key regressor of interest in equation (16) is $RAIL_{ot}$, a dummy variable that is equal to 1 in all years t in which some part of district o is on the railroad network. I estimate equation (16) 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 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 in which to build railroads.

Result 3 states that the coefficient γ on district o's railroad access will be positive. A number of alternative theories (whether stressing the gains from goods trade or otherwise) could make similar predictions about the sign of this coefficient. For this reason, in Step 4 below I go beyond the qualitative test of the model provided by the sign of γ and assess the *quantitative* performance of the model in predicting real income changes due to the expansion of the railroad network.[36]

I begin (in Section VC) by estimating equation (16) using OLS. Unbiased OLS estimates require there to be no correlation between the error term (ε_{ot}) and the regressor ($RAIL_{ot}$), 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, in Section VD I also estimate three different "placebo" specifications in order to assess the potential magnitude of bias in my OLS results due to nonrandom railroad placement.

B. *Data*

I estimate equation (16) using annual data on real agricultural income (per acre of land) in an unbalanced panel of 192 districts, from 1870 to 1930. This variable (calculated as nominal agricultural output calculated from the physical output of each of the 17 principal crops listed in Section IA valued at local retail prices, deflated by a local consumer price index, and then divided by the district's land area)[37] was described briefly in Section I and in more detail in online Appendix A. The variable $RAIL_{ot}$ is a dummy variable for the presence of a railroad line anywhere in district o in year t.

C. *Baseline Results*

Column 1 of Table 4 presents OLS estimates of equation (16). The coefficient estimate is 0.164, implying that in the average district, the arrival of the railroad network is associated with a rise in income of over 16 percent. This OLS estimate

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[36] Similarly, various models, like that in Section II and beyond, could motivate potentially important departures from the simple functional form used in equation (16), a functional form chosen to capture only first-order features of the data, in line with the first-order departures from symmetry motivated by Result 3. In principle, these departures could be explored empirically. Step 4 examines the sufficient statistic of Result 4 that, in contrast to the simple specification in equation (16), describes the precise functional form (one that captures nonlinear, heterogeneous treatment effects and treatment spillovers) suggested by the model in Section II, albeit non-analytically.

[37] This land area denominator is fixed over time and so is irrelevant here given that equation (16) uses the log of real income per acre and conditions on district fixed effects. Note that this measure of land area therefore allows for increases in the cultivation margin due to rail access to be incorporated into the treatment effect γ, as seems desirable given that this is a potentially important response.

Table 4—Railroads and Real Income Levels: Step 3

Dependent variable: log real agricultural income	(1)	(2)	(3)	(4)
Railroad in district	0.164	0.158	0.160	0.167
	(0.049)	(0.048)	(0.050)	(0.050)
Unbuilt railroad in district, abandoned after proposal stage		0.057		
		(0.058)		
Unbuilt railroad in district, abandoned after reconnaissance stage		0.013		
		(0.099)		
Unbuilt railroad in district, abandoned after survey stage		−0.069		
		(0.038)		
(Unbuilt railroad in district, included in Lawrence Plan 1869–1873) × (post-1871 indicator)			0.067	
			(0.104)	
(Unbuilt railroad in district, included in Lawrence Plan 1874–1878) × (post-1874 indicator)			−0.019	
			(0.092)	
(Unbuilt railroad in district, included in Lawrence Plan 1879–1883) × (post-1879 indicator)			0.095	
			(0.084)	
(Unbuilt railroad in district, included in Lawrence Plan 1884–1888) × (post-1884 indicator)			−0.072	
			(0.075)	
(Unbuilt railroad in district, included in Lawrence Plan 1889–1893) × (post-1889 indicator)			0.047	
			(0.049)	
(Unbuilt railroad in district, included in Lawrence Plan 1894–1898) × (post-1894 indicator)			−0.088	
			(0.086)	
(Unbuilt railroad in district, included in Kennedy plan, high-priority) × (year-1848)				−0.0001
				(0.002)
(Unbuilt railroad in district, included in Kennedy plan, low-priority) × (year-1848)				0.001
				(0.003)
Observations	7,086	7,086	7,086	7,086
R^2	0.848	0.848	0.848	0.848

Notes: OLS regressions estimating equation (16) using real income constructed from crop-level data on 17 principal agricultural crops (listed in online Appendix A), from 192 districts in India, annually from 1870 to 1930. All regressions include district fixed effects and year fixed effects. "Railroad in district" is a dummy variable whose value is 1 if any part of the district in question is penetrated by a railroad line. "Unbuilt railroad in district, abandoned after X stage" is a dummy variable whose value is 1 if a line that was abandoned after "X" stage penetrates a district, in all years after the line was first mentioned as reaching stage "X" in official documents. Stages "X" are: "proposal," where the line was mentioned in official documents; "reconnaissance," where the line route was explored by surveyors in rough detail; and "survey," where the exact route of the line and nature of all engineering works were decided on after detailed survey. "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. "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.

is in line with Result 3 and suggests that railroads may have had a large effect on real income in India. In the following subsection I investigate the robustness of this finding to concerns over the nonrandom placement of railroads.

D. *Three "Placebo" Checks*

In this subsection I explore the plausibility of concerns about bias due to endogenous railroad placement by estimating the effects of "placebo" railroad lines: over 40,000 km of railroad lines that came close to being constructed but, for three separate reasons, were never actually built. I group these placebo lines into three categories as follows.

Four-Stage Planning Hierarchy.—From 1870–1900, India's Railways Department used one constant system for the evaluation of new railroad projects. 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).[38] 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 would have to pass.

Column 2 of Table 4 presents an estimate of equation (16) that additionally includes regressors for railroad lines abandoned at the first three of these planning stages, with separate coefficients on each.[39] If line placement decisions were driven by unobservable determinants of changes in agricultural income then 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 with district fixed effects. Further, it is likely that 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). However, the coefficients on unbuilt lines reported in column 2 are never statistically significantly different from zero, or of a similar magnitude as that corresponding to 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. These findings 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 (16).

Lawrence's Proposal.—In 1868, Viceroy John Lawrence (head of the Government of India) proposed and had surveyed a 30-year railroad expansion plan, broken into 5-year segments, that would begin where Dalhousie's trunk lines (described in Section IC) left off.[40] Lawrence consulted widely about the optimal routes for this railroad expansion, and drew upon his 26 years of experience as an administrator in India. Upon his retirement 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 a newcomer to administration in India and a fiscal conservative, and he wasted no time in criticizing the high costs of railroad

[38] 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 the standard engineer's textbook of the day, Wellington (1877), make clear, surveying was much more detailed. The goal of a survey was to identify the exact position of the intended lines and to provide a precise statement of all engineering works (down to the estimated number of bricks required to build each bridge).

[39] The fourth stage, sanctioning, appears to have never been reached by an unbuilt line. A previous version of this paper (Donaldson 2010) estimated a coefficient for this category on the basis of one line in Madras but I have subsequently discovered that the line was in fact eventually built.

[40] 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.

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 (16), it was likely to be Lawrence.

To check for this, I estimate equation (16) 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.[41] 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.

Column 3 of Table 4 presents estimates of coefficients on the lines that were identified in Lawrence's proposal. The coefficients on these lines are never statistically significantly different from zero (and substantially smaller than that on unbuilt lines). Further, the estimated coefficients on Lawrence's early proposals are no larger on average than those on his later proposals. This is in contrast to what one would expect if Lawrence were attempting to allocate railroads to districts he expected to grow, but where his ability to forecast growth was weaker at more distant forecast horizons.

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.[42]

Kennedy's 1848 proposal is useful for my identification strategy because it singles out districts with low perceived 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 (16) would erroneously attribute unobserved trends to railroad construction. I therefore estimate equation (16) while including a variable that is

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[41] One exception concerns the first period (1869–1873) which I allow to take effect with a three-year lag, as seems plausible given typical construction periods and as is necessary to distinguish this regressor from the main effect of $RAIL_{ot}$. These estimates vary only slightly if this regressor is omitted instead.

[42] 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 pessimistic construction cost estimates were, if anything, underestimates. Indeed, high construction costs were a major factor in Mayo's decision to abort Lawrence's plan, as described above when introducing my second placebo variable.

an interaction between an indicator variable that captures districts that would have been penetrated by Kennedy's proposed network and a time trend. 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 subdivided his proposal into high and low priority lines, I also look for differential trends across these designations.

Column 4 of Table 4 presents these results, which examine the extent to which locations identified in Major Kennedy's proposal (inexpensive districts in which to construct a vast railroad network) 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. This is reassuring, as it suggests that controlling for the (time-varying effects of the) unobserved geographical features that India's chief engineer thought were important for building railroads cheaply has little bearing on the results estimated above.

E. *Summary and Relation to "Social Savings" Methodology*

The three sets of "placebo" results in Table 4 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 Indian career, or India's chief engineer), or their motivation in doing so (lines attractive to the government for many potential reasons, commercially attractive lines, or low costs of construction), unbuilt lines that these experts wanted to build are not statistically significantly correlated 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. This is perhaps unsurprising given the strong military motivations for building railroads in India outlined in Section I, the difficulty in forecasting the attractiveness of competing railroad plans (as evidenced by the stark disagreements among top-level Indian administrators described in Section VD), and the challenges of targeting precisely a highly networked infrastructure such as railroads.

Taken together, the results in Table 4 suggest that my key estimate in column 1, that railroads caused a large (16 percent) increase in real agricultural income in India, can be interpreted as a plausibly unbiased estimate of the effect of railroads on real agricultural income in India. This finding is also plausible when considered in the context of the large "social savings" literature on railroads. A social savings calculation in my context estimates the benefits of railroads to be equal to 11.2 percent of agricultural income, which is lower than (but still within the 95 percent confidence interval of) the estimate in Table 4.[43] However, because numerous

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[43] 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

authors have pointed out that the social savings methodology suffers from both positive bias (due, for example, to the typical assumption of elastic transport demand) and negative bias (due, for example, to a neglect of returns to scale as in David 1969), estimates of the benefits of railroads from conventional econometric methodologies that compare exposed to unexposed regions, like that I pursue here, are of additional value.

The final step of my empirical analysis explores whether the benefits due to railroads estimated in this section (a 16 percent rise in real income) are plausible in the context of the model in Section III. That is, I explore whether it is plausible that the reduction in trade costs due to railroads (estimated in Step 1), when introduced into the environment of heterogeneous technologies that existed in colonial India (estimated in Step 2), could have raised living standards by the estimated 16 percent.

VI. Empirical Step 4: A Sufficient Statistic for Railroad Impact

Steps 1 and 2 of this paper have argued that railroads significantly improved the ability to move goods cheaply within India. Step 3 demonstrated that railroads also substantially raised the level of real agricultural income. These two sets of results are qualitatively consistent with each other, in the context of the model in Section II: that is, when trade costs fall (and trade flows expand) there should be gains from trade, and these gains will show up as a rise in real income. In this section I explore whether these two sets of results are also *quantitatively* consistent with each other in the context of the model. Because the reduced-form impact estimated in Step 3 could arise 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 the model.

A. *Empirical Strategy*

In order to compare the reduced-form impact of the railroad network on each district's real agricultural income (estimated in Step 3) to the impact that is predicted by the model, I exploit Result 4. This result is equation (11), restated here for convenience:

$$\ln\left(\frac{r_{ot}}{\tilde{P}_{ot}}\right) = \Omega + \sum_{k}\frac{\mu_k}{\theta_k}\ln A_{ot}^{k} - \sum_{k}\frac{\mu_k}{\theta_k}\ln \pi_{oot}^{k}. \tag{17}$$

Result 4 thus states that real agricultural income ($r_{ot}/\tilde{P}_{ot}$) is, up to a constant, a function of only two terms: technology (A_{ot}^{k}) and the "trade share" (π_{oot}^{k}, the share of district o's expenditure that it buys from itself), each appropriately summed over all commodities k. The former term is taken to be exogenous (and driven by rainfall),

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been employed in their next-best substitute (Fishlow 2000 reviews this literature). The calculation reported here is simply that due to Hurd (1983) expressed as a share of agricultural income. It is not straightforward to compare the reduction in transport prices used by Hurd (1983) in this calculation with those estimated for salt in Table 2 because the constant elasticity of distance functional form in equation (12), chosen here for its similarity to that used prominently in the international and interregional trade literatures, is different from that implicitly used in the social savings approach.

while the latter term is endogenous and captures all of the (heterogeneous, general equilibrium) effects that railroads could generate in this model.

To estimate this equation, I substitute in estimates for the unobserved productivity terms A^k_{ot}, the unknown parameters θ_k and μ_k, and the unobserved trade share term π^k_{oot}.[44] I discuss these in turn. First, the goal of Step 2 was to estimate the parameter κ in the modeled relationship $\ln A^k_{ot} = \kappa RAIN^k_{ot}$ as well as the parameters θ_k; I use the estimates obtained in Step 2 (in conjunction with the data on $RAIN^K_{ot}$) here.[45] Second, the parameters μ_k are simply consumer expenditure shares and I estimate these as such.[46] Finally, I obtain a measure of predicted π^k_{oot} by solving for this variable in the model equilibrium (i.e., by solving equation (6)) conditional on all estimated parameters ($\hat{\Theta} \doteq (\hat{\boldsymbol{\theta}}, \hat{\boldsymbol{\mu}}, \hat{\boldsymbol{\alpha}}, \hat{\delta}, \hat{\kappa})$) and the value of all exogenous variables (all districts' rainfall series, denoted by the vector $\mathbf{RAIN}_t$, the entire transportation network, $\mathbf{R}_t$, and all districts' land sizes, $\mathbf{L}$).[47] I refer to the estimated trade share term as $\pi^k_{oot}(\hat{\Theta}, \mathbf{RAIN}_t, \mathbf{R}_t, \mathbf{L})$ to denote its dependence on both estimated parameters and all exogenous variables. It is important to note that there are multiple reasons to expect this estimated trade share to be unequal to the (unobserved) data equivalent; what matters for the procedure below is an estimate that correlates well (in logs, and conditional on the fixed effects used below) with the data equivalent. This contrasts to the approach pioneered by Dekle, Eaton, and Kortum (2008), feasible in richer data settings, that calibrates all model parameters to match ex ante data exactly.

Result 4 (i.e., equation (17)) states that, once rainfall (through the relationship, $\ln A^k_{ot} = \kappa RAIN^k_{ot}$, estimated in Step 2) is controlled for (and weighted over commodities k in the manner suggested by this equation), the trade share (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 explore Result 4 empirically I estimate equation (16) from Step 3 but additionally include the sufficient statistic variable, the trade share (π^k_{oot}), and adjust for rainfall:

$$\text{(18)} \quad \ln\left(\frac{r_{ot}}{\tilde{P}_{ot}}\right) - \left[\sum_k \frac{\hat{\mu}_k}{\hat{\theta}_k}\,\hat{\kappa}\,RAIN^k_{ot}\right]$$
$$= \beta_o + \beta_t + \gamma RAIL_{ot} + \psi\left[\sum_k \frac{\hat{\mu}_k}{\hat{\theta}_k} \ln \pi^k_{oot}(\hat{\Theta}, \mathbf{RAIN}_t, \mathbf{R}_t, \mathbf{L})\right] + \varepsilon_{ot}.$$

If the trade share (i.e., π^k_{oot}) is truly a sufficient statistic for the impact of railroads, as predicted by the model, then when the trade share is included in equation (18) all other railroad variables should lose predictive power. That is, Result 4 states that the

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[44] The term π^k_{oot} is unobserved because I do not observe the trade of a district with itself (intra-trade block rail shipments were never, to my knowledge, recorded).

[45] One exception concerns the estimated values of A^k_{ot} I use for the four main port cities (Bombay, Calcutta, Karachi, and Madras) in India, whose exports to inland Indian destinations include all sea trade imported from foreign countries (in which I do not observe rainfall). Online Appendix C discusses my method for obtaining estimates of A^k_{ot}, as well as of L_o, for these regions. Another exception concerns the values of θ_k for the grain crops that are missing or aggregated (all of which I set equal to the estimated value corresponding to the aggregate crop group of bajra and jowar, given the similarities among these grain crops) or whose estimates are negative (which I set equal to the lowest positive estimated value of θ_k).

[46] I estimate these Cobb-Douglas weights as the average (over trade blocks and years in which these are available) expenditure share for commodity k, where expenditure is calculated as output plus net imports.

[47] For the fixed land size L_o of each district I use the average total cultivated area across all years.

Table 5—A Sufficient Statistic for Railroad Impact: Step 4

log real ag. income, corrected for rainfall:	(1)	(2)
Railroad in district	0.258 (0.050)	0.124 (0.050)
"Trade share," as computed in model		-1.587 (0.177)
Observations	7,086	7,086
R^2	0.835	0.844

Notes: OLS Regressions estimating equation (18) using real income constructed from crop-level data on 17 principal agricultural crops (listed in online Appendix A), from 192 districts in India, annually from 1870 to 1930. Dependent variable is log real income, corrected for crop-specific rainfall of each of 17 crops, weighted across crops as in equation (18). Regressions include district fixed effects and year fixed effects. "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. "Trade share" is the share of a district's expenditure that it buys from itself; this variable 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. Heteroskedasticity-robust standard errors corrected for clustering at the district level are reported in parentheses.

coefficient γ should be zero in this regression while it was statistically significantly different from zero in Step 3. Further, taking the model equation (17) literally, Result 4 also states that the coefficient ψ will equal -1.[48]

B. *Results*

The results from this section are presented in Table 5. As a benchmark, column 1 estimates equation (18) while omitting the "trade share" variable (i.e., $\pi^k_{oot}(\hat{\Theta}, \mathbf{RAIN}_t, \mathbf{R}_t, \mathbf{L})$). The coefficient on the railroad access dummy (i.e., $RAIL_{ot}$) is large and statistically significant. This estimate is larger than that in column 1 of Table 4 but still within its 95 percent confidence interval. While the reduced-form result in column 1 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 (18), column 2 of Table 5 adds the trade share variable (i.e., $\pi^k_{oot}(\hat{\Theta}, \mathbf{RAIN}_t, \mathbf{R}_t, \mathbf{L})$) to the regression in column 1. Consistent with Result 4 of the model, the coefficient γ on the railroad access dummy variable, which was statistically and economically significant in column 1, falls considerably by a factor of more than two (though its 95 percent confidence interval does not include zero). This is consistent with the notion that a substantial share of the impact of railroads on real agricultural income is working through the sufficient statistic predicted by the model.

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[48] The computed trade share term, $\pi^k_{oot}(\hat{\Theta}, \mathbf{RAIN}_t, \mathbf{R}_t, \mathbf{L})$, is a generated regressor, so conventional standard errors obtained when using it will be incorrect. This is of little consequence here, however, because the empirical procedure in this section is concerned primarily with the magnitude of point estimates rather than statistical inference about these estimates.

In further agreement with Result 4, the coefficient on the trade share term is negative and statistically significant, implying that the trade share, when measured in a model-consistent manner, is a strong determinant of real agricultural income. Notably, the model parameters that enter the trade share term were not estimated using data that enter the current estimating equation, so the impressive fit of the trade share term was not preordained. However, it is noteworthy that the model's prediction of a coefficient of -1 on the trade share is rejected at the 5 percent level.

Finally, taking the point estimate of 0.124 on railroad access $(RAIL_{ot})$ in column 2 seriously implies that a little over one-half (i.e., $1 - \frac{0.124}{0.258} = 0.52$) of the total impact of the railroads estimated in column 1 can be explained by the mechanism of enhanced opportunities to trade according to comparative advantage, represented in the model.

The results in Table 5 establish a quantitative connection between the earlier results in this paper, that railroads improved the ability to trade within India (Steps 1 and 2) and that railroads raised real incomes (Step 3). These results suggest that the important welfare gains that railroads brought about can be well, but by no means fully, accounted for by the specific mechanism (and parameterization) of Ricardian comparative advantage-based gains from trade modeled here.

VII. Conclusion

This paper has aimed to make 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 colonial India's railroad network. Using a new panel of 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, and increased trade volumes.

My second contribution is to estimate the effect of India's railroads on a proxy for economic welfare in colonial India. I find that when the railroad network was extended to the average district, real agricultural income in that district rose by approximately 16 percent. While it is possible that railroads were deliberately allocated to districts on the basis of time-varying characteristics unobservable to researchers today, I find little evidence for this potential source of bias to my results in three separate placebo 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 an estimable, 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 real income, which, when estimated and computed according to the model's equilibrium, is a strong predictor of the evolution of real income in Indian districts over time and accounts empirically for more than one-half of the observed real income effect of railroads. This is consistent with a mechanism in which railroads raised real income in India because they reduced the cost of trading, and enabled India's heterogeneous districts to enjoy previously unexploited gains from trade due to Ricardian comparative advantage. But these results imply substantial scope for other channels of influence from railroads to growth as well.

While the findings in this paper argue that railroads caused an increase in the level of real incomes in India, a component of economic welfare about which this paper has been silent concerns the *volatility* of real incomes over time. As in much of the developing world today, colonial India's precarious monsoon rains and its rain-fed agricultural technologies made real income volatility extremely high. Famines were a perennial concern. One potentially important question for future research concerns the extent to which transportation infrastructure systems, like India's railroad network, can help regions to smooth away the effects of local weather extremes on local well-being.

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