Transportation Costs and the Spatial Organization of Economic Activity*

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Abstract

This paper surveys the theoretical and empirical literature on the relationship between the spatial distribution of economic activity and transportation costs. We develop a multi-region model of economic geography that we use to understand the general equilibrium implications of transportation infrastructure improvements within and between locations for wages, population, trade and industry composition. Guided by the predictions of this model, we review the empirical literature on the effects of transportation infrastructure improvements on economic development, paying particular attention to the use of exogenous sources of variation in the construction of transportation infrastructure. We examine evidence from different spatial scales, between and within cities. We outline a variety of areas for further research, including distinguishing reallocation from growth and dynamics.

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1 Introduction

The organization of economic activity in geographic space depends crucially on the transportation of goods and people. Most production involves the movement of inputs such as raw materials, labor and fuel from different locations. Most consumption requires either the conveyance of finished goods or the transfer of people to the points at which goods and services are supplied. The transport sector as a whole typically accounts for around five percent of Gross Domestic Product (GDP), and transport networks comprise some of the largest investments ever made. In the United States (U.S.), the Interstate Construction Program extended to 42,795 miles of highways with an estimated cost of $128.9 billion (1991 U.S. dollars).[1] Multiplying estimates of the cost per interstate lane kilometer found in Duranton and Turner (2012) by the extent of the system, gives much larger values. In China, the National Trunk Highway System (NTHS) involved the construction of around 21,747 miles (35,000 kilometers) of highways over a period of 15 years at an estimated construction cost of around $120 billion (in current price U.S. dollars).[2]

Transportation technologies themselves have undergone large-scale changes over time, which have in turn reshaped the spatial organization of economic activity. For most of human history, the movement of goods and people was limited by the physical capabilities of humans and their animals. The invention of the railroad reduced transport costs and created a hub and spoke transport network that was characterized by substantial fixed costs (e.g. in stations and goods yards) and favored point-to-point travel between the central cities. The development of the internal combustion engine (and hence the automobile and truck) in turn created greater flexibility in transportation, benefiting lower-density locations relative to central cities.[3] Even within existing transport technologies, such as maritime shipping, there have been large-scale changes in the organization of economic activity in the form of containerization and the adoption of new information and communication technologies (ICTs) such as the computer. These innovations have played an important part in the development of integrated logistics networks, which control the movement of a package from its origin to its destination, and integrate packaging, storage, transport, inventories, administration and management. The discovery of entirely new modes of transportation, such as air travel, has further transformed the relative attractiveness of locations for economic activity.

This chapter describes our current understanding of the way that transportation costs and transportation infrastructure affect the organization of economic activity within a country. We first provide some basic facts about transportation costs within and between cities. Next we develop a multi-region model of economic geography as a framework to organize our discussion of the empirical literature. The existing empirical literature on the effects of transportation costs and infrastructure can be usefully divided into two parts. The first of these parts considers the role of transportation costs between cities and is mainly interested in the movement of goods, while the second considers

[1] U.S. Department of Transportation, Federal Highway Administration, interstate cost estimates reported to Congress.
[2] Faber (2014)
[3] See, for example, the discussion in Glaeser and Ponzetto (2013).

the role of transportation costs within cities and is mainly interested in the movement of people. Our model unifies the analysis of within and between city transportation, thereby allowing us to simultaneously consider the two previously disparate strands of the empirical literature. Analysis of our model yields structural equations corresponding to the reduced form estimating equations on which the two parts of the empirical literature are based. The divergence between theoretically founded structural equations and reduced form estimating equations, in turn, provides insight into the inference problems that reduced form estimation must overcome. Finally, with a handful of exceptions, the existing literature provides only an incomplete understanding of general equilibrium effects of transportation infrastructure and little basis for welfare analysis. The model that we develop illustrates a possible direction for research on this issue.

The available empirical literature provides credible, causal estimates of the effect of roads, railroads and subways on outcomes such as population density, land rents and output. In addition to providing particular elasticity estimates, this literature is large enough to suggest three preliminary conclusions. First, that the effects of different types of infrastructure are similar across economies at different stages of development and are not especially sensitive to the spatial scale of the unit of observation. Second, that different modes of transportation are not interchangeable. Railroads affect production more than population and the effects of railroads on the location of production varies systematically with the weight to value ratio of output, while the spatial organization of population is more sensitive to roads and subways than to railroads. Finally, and unsurprisingly, institutions matter. The existing empirical literature suggests that politics plays an important role in the allocation of infrastructure and that these politics vary systematically across countries.

Determining the extent to which the effects of transportation infrastructure reflect growth or reorganization is fundamental to understanding its role in the spatial organization of economic activity. Indeed, this question is at the heart of Fogel's classic study of railroads in the late 19th century United States. While the current empirical literature provides credible causal estimates of the effects of transportation infrastructure, it is impossible for the reduced form regressions conducted by almost all of the empirical papers that we survey to separately identify the effect of transportation infrastructure on the growth and reorganization of economic activity. We suggest two approaches to this problem, one is a simple extension of the existing reduced form literature, and the second is an implementation of our structural model. The handful of papers which shed light on this question suggest that reorganization is often about as important as growth. This is an important area for further research.

The remainder of this chapter is structured as follows. Section 2 reports some descriptive evidence on transportation costs across countries and over time. Section 3 introduces the theoretical framework that we use to organize our discussion of the empirical evidence. Section 4 uses the model to develop a reduced-form framework for examining the impacts of transport infrastructure on the distribution of economic activity between and within cities. Section 5 uses this reduced-form framework to review existing empirical evidence on these impacts. Section 6 discusses the interpretation of this existing evidence. Section 7 summarizes our conclusions.

2 Stylized Facts about Transportation

In this section, we present stylized facts about transportation costs for goods and people, both over a long historical time period and across countries.[4] Key features of the data are as follows. First, there is a secular decline in transportation costs for goods. Second, there is a change in the relative importance of different transport modes over time (e.g. rail versus road versus air) and for value versus weight. Third, transportation costs for people continue to be important. Commuting costs remain substantial, both in terms of the opportunity cost of time and in terms of overall household expenditure.

2.1 Transportation Costs for Goods

To provide a rough indication of the real resources involved in the transportation sector over time, Figure 1 displays the share of the transport sectors in U.S. GDP from the late nineteenth to the early twentieth century.[5] The striking feature of this figure is the long secular decline in the share of the transport sector, which is even more rapid towards the end of the twentieth century if air transport is included. The share of U.S. GDP attributed to transportation[6] has fallen from about 8% in 1929 to about 3% by 1990, of which about one quarter is air transport. While these numbers are striking, they may reflect the increased importance of non-traded services rather than a decrease in the importance of transportation. In addition, while these GDP figures tell us about the resources devoted to moving goods, they do not tell us about the amount and value of the goods being moved.

To provide a more direct measure, Figure 2 displays the transport costs for a given mode of transport (railroads) in the U.S. over a similar time period (measured as costs per ton mile in 2001 dollars). The figure confirms a secular decline in transport costs over time. The price per ton mile of rail freight fell from about 18.5 cents in 1890 to about 2 in 2000. Figure 3 compares the evolution of the cost of truck, rail and pipeline transport costs for the U.S. during the post Second World War period (measured as revenue per ton mile in 2001 dollars). As apparent from the figure, truck transport is substantially more expensive than rail transport, and its real costs have fallen even more rapidly than those of rail transport over this period.[7]

Figure 4 shows the evolution of ton miles of freight over time from the mid-1960s. Rail is relatively more important than trucks when we measure volume shipped than value because of a widely observed selection effect in which more expensive items are disproportionately shipped by the more expensive transport mode.[8] As a share of the value of goods, Glaeser and Kohlhase (2004) find that

[4]For a more detailed analysis of the evolution of transport costs over time in the U.S., see Glaeser and Kohlhase (2004).

[5]Figures 1–4 replicate similar figures that appear in Glaeser and Kohlhase (2004).

[6]Defined as rail, water, pipeline, trucking, warehousing, air transport, transportation services and local and interurban rail transit.

[7]These figures invite the question of why people use trucks at all, the nominally more costly mode. Although trucks have a higher cost per ton mile than rail, the real cost of quality-adjusted transport services also depends on speed, flexibility, reliability and a number of other attributes. The large-scale reallocation of transport expenditure from rail to trucks following the invention of the internal combustion engines suggests that this invention was associated with a substantial reduction in the real cost of quality-adjusted transport services, at least for many types of shipments and journeys.

[8]This is an example of the Alchian-Allen effect from the international trade literature or "Shipping the good apples

for heavy low-value goods traveling by truck, e.g., lumber, the cost of an average shipment distance can be as high as 20% of the value of the good. For more typical sectors this value is of the order of 5%. For goods travelling by rail, the corresponding values range from one tenth to two percent. These findings highlight that the cost of moving freight has dropped dramatically to the point that freight transportation is about 3% of the U.S. economy and that freight charges make up only a small share of the value of final output.

To show that these patterns are not specific to the U.S., Figure 5 describes ton kilometers of domestic trade for seven countries by mode and year. While there are differences between countries, several patterns are clear. First, there is a general trend up in the amount of domestic trade, as expected given a secular increase in the level economic activity over time. Second, trucking is not the dominant mode of travel in any of our countries by this metric. Third, the amount of material being moved is immense.[9]

Table 1 shows the value of international trade by mode for a sample of countries in 2007. In figure 5 we see that the share of ton kilometers that travel by air is negligible. In contrast, in table 1, we see that the share of the value of trade travelling by air is often large. While the two tables are not directly comparable, one measures domestic trade and the other measures international trade, together they strongly suggest that high value goods travel by air and low value goods travel by ship or rail.

Table 2 compares employment in for hire transportation by mode for Canada, Mexico, and the U.S. in 2002 or 2003 (depending on data availability). Transportation is typically smaller as a share of employment than as a share of GDP. The share of employment in transportation is about 3% for the U.S. and Canada, and almost 6% for Mexico. In all three countries, the largest fraction of transportation employment is devoted to trucking. Note that the share of labor devoted to for hire transportation is close to the same as the share devoted to commuting.

A striking feature of international trade in goods is the extent to which the volume of trade in goods declines with distance. Hillberry and Hummels (2008) examines the pattern of shipments between U.S. mining, manufacturing and wholesaling firms and find that three quarters of all shipments, weighted by the value of shipments, begin and end in the same zipcode, a conclusion that does not appear to be driven by shipments from wholesalers to retailers. Hummels (1999) documents the cost of air freight between the 1950s and the 2000s and finds that it decreases by a factor of about 12.5, while the cost of shipping was approximately constant. For comparison, the corresponding decrease for rail, from Glaeser and Kohlhase (2004), is about a factor of 8 for 110 years.[10] Over the same 1955 to 2004 period, Hummels (1999) documents 5-7% increases in the value and weight of international trade and an 11% average annual increase in the share of traded value that travels by air. Limão and Venables (2001) use data describing market price to ship a standard 40 foot container

out."

[9] To get a sense for this, a typical coal train in the U.S. is about 100 cars long, about two kilometers, and each car carries about 100 tons of coal, which implies 10,000 tons per train. If such a train travels 100 kilometers it provides one million ton kilometers of freight service. To carry 5,000 billion ton kilometers of freight per year, a bit less than the current U.S. annual total, we require about 1,200 such trains to operate 24 hours per day 365 days per year at 50 kph.

[10] Note that rail was at its peak in 1890 and airfreight was novel in 1950.

from Baltimore Maryland to one of about 50 countries around the world in the late 1990s.[11] In a regression of total freight charge on a land-locked country indicator, sea distance and land distance to destination, they find that the cost to ship a standard container 1,000km by sea is about 190 dollars while to ship it the same distance over land is about 1,380 dollars. Recalling that a standard container can hold about 30 tons, this gives sea rates of about half a cent per ton mile and land rates of about 5 cents per ton mile, so that overland travel is about 10 times as expensive as sea travel. These rates seem somewhat low compared to the price of U.S. truck and rail rates reported in Glaeser and Kohlhase (2004) (28 cents per ton mile for trucks and 3 cents per ton mile for rail). Finally, Clark *et al.* (2004) find that the cost of shipping all maritime freight to and from the U.S. is equal to about 5.25% of the value of freight and that port efficiency is an important contributor to this cost.

These facts paint a subtle picture. While the real costs of moving goods has fallen to astonishingly low levels and the weight of trade is immense, the fact that not all trade travels by the cheapest mode and that most trade travels very short distances, suggests the decline in the price per ton of moving goods is not leading to the 'death of distance'.

While it is natural to think of time costs as being most important for the movement of people, the rise of air trade suggests that time in transit is an increasingly important part of the cost of transit for goods. A back of the envelope calculation bolsters this idea. The capacity of a typical 40 foot container is about 30 tons. From Duranton *et al.* (2014), the value per ton of an average U.S. domestic shipment of electrical appliances is about six thousand dollars per ton. Thus, a typical container of U.S. electrical appliances can hold about \$200,000 worth of freight. From Glaeser and Kohlhase (2004), shipping this container 1,000 miles by rail will cost about $1,000 \times 30 \times 0.023 = \$700$. At a 5% annual rate, daily interest on a million dollar cargo is $200,000 \times 0.05/365 = \$28$, so that on a five day journey the opportunity cost of travel time is about equal to a fifth of freight charges. An average ton of manufactures is worth less than a tenth of this, while a typical ton of computer equipment is 15 times as valuable. At least for relatively high value to weight products, time in transit is important.

Moreover, the predominance of short haul trade suggests that, not only are transportation costs important, but the geography of production is influenced by transportation costs. For example, the development of 19th century Chicago was heavily influenced by its location relative to its surrounding agricultural hinterland, as discussed in Cronon (1991). This points to an important econometric problem in interpreting the transport costs data presented so far: these data describe equilibrium transport costs. Therefore, they do not isolate the supply-side production function (or cost function) for transportation, but are rather influenced by both demand and supply. Although these data on transport costs are still suggestive, they capture both the cost of transportation (supply) and the endogenous organization of economic activity in space in response to the cost of transportation (demand). This presents important and difficult econometric problems to which we return below.

Another striking feature of micro data on trade and production is Atalay *et al.* (2013)'s finding

[11] To get a sense for the nature of the sample, when the countries are ranked by kilometers of paved road per person, the median country is Kenya. For evidence on the role of containerization in reducing international transport costs, see Bernhofen *et al.* (2013).

that most vertically integrated firms actually ship very little between plants. From the above, we have the puzzling collection of facts: the cost of moving goods is a small fraction of their value, most shipments occur over very small distances, most shipments do not travel by the cheapest mode, and the time cost of freight is probably important. One possible way of rationalizing this combination of findings is that there is something valuable about proximity other than the reduction in transportation costs, i.e., agglomeration effects including knowledge spillovers and idea flows. In this case, trade could decline rapidly with distance even in a world in which transport costs are small, because most economic activity is clustered together for these other reasons and hence most economic interactions are over short distances.

Alternatively, one could question whether the idea that transportation costs are really as small as share of value-added as some of the figures above suggest. Arguably labor used in transportation should be compared to labor used in production and we should take into account the same kinds of costs that we think about for commuting, time costs and scheduling costs.

2.2 Household travel and commuting

While the trade literature has typically focused on the movement of goods, another important source of transport costs in the urban literature is the movement of people. These costs of transporting people remain substantial, both in terms of the opportunity cost of time and in terms of a share of overall household expenditure. Table 3 lists round trip commute times in minutes in a sample of countries and years for which data was easily available. While we should be concerned that differences in commute times across countries reflect sampling error and differences in survey methodology, with this caveat, these data suggest that the country mean round trip commute is about 40 minutes in the 2000-5 window where we have the most observations. These times are fairly closely clustered, with a standard deviation of just less than eight minutes. If the 'work day' consists of eight hours at work and time in commute, then commuting consumes about 7.5% of labor. Alternatively, if we value time in commute at half the wage (as is common in the transportation economics literature, see Small and Verhoef (2007)) and suppose an eight-hour work day, then the value of commute time is about equal to 3.5% of the value of labor. While this is a large number, it understates the cost of household travel by restricting attention to commuters and commute trips.

Alternatively, Schafer (2000) summarizes 26 national household travel surveys from countries all over the world. Averaging across these surveys, again with the caveat about the comparability of surveys, he finds that daily household travel time is about 73 minutes with a standard deviation of about 12 minutes. If we value this time at half the wage and again suppose an eight-hour work day, then the value of time spent in household travel is about 8% of the value of labor. [12] If we take the

[12] We note that this estimate is problematic for at least two reasons. First, it assigns the time cost of an average worker to an average traveler, when many travellers are likely to have a lower value of time. Second, it assigns the time cost of an average worker to an average commuter, when wages probably vary systematically with commute distance. With this said, on the basis of these surveys, a rough guess would be that the aggregate time cost of household travel is somewhere between 3.5% and 8% of the aggregate value of labor in an economy.

labor share of GDP to be close to the current U.S. level at 0.6, then the time cost of household travel is between 2.4 and 4.8% of GDP.

Table 4 describes household expenditure shares on transportation for 26 countries and several years. Again noting the possibility of different methodologies across countries, the mean expenditure share is about 16.2% for the 2000-2004 window and about 14.6% for the 2005-9 window with standard deviations of 5.4 and 3.7%, respectively. Schafer (2000) investigates these shares using older and somewhat more extensive national accounts data and finds that across countries the average expenditure share for household travel is about 11% with a standard deviation of about 3%. Weighting household transportation share by 0.6, about the share of expenditure in current U.S. GDP, and adding time costs, we have that the total costs of household travel are between 9 and 11.4% of GDP.

Two further points are made in Schafer (2000). First, for country level aggregates, per capita travel time and expenditure share are negatively correlated. Second, for Zambia, only 5% of all trips are longer than 10km while for the U.S. 5% of trips are longer than 50km. To the extent that these findings are driven by differences in transportation technologies, they suggest that the transferral of developed-country transportation technologies to developing countries is likely to lead to substantial changes in the spatial organization of economic activity.

2.3 External costs

We have so far concerned ourselves with private costs of transportation, time and private expense. We now turn attention to two costs of transportation that are rarely priced, carbon emissions and congestion.

Table 5 presents total 2007 Carbon Dioxide Equivalent (CO2e) emissions for the transportation sector for Canada, Mexico, the U.S. and the UK. Total emissions for the U.S. in 2007 were about 7,000 Megatonnes (Mt), so that the transportation sector accounts for about 30% of U.S. emissions. To the extent that these costs of transportation are not priced, the market allocation of resources to the transportation sector will be in general inefficient. With a social cost of about 30$US/ton CO2e, the social cost of CO2e emissions from transportation in the U.S. is about 21 billion $US/year. This is only about one tenth of one percent of U.S. GDP. Thus, while greenhouse gas emissions from transportation are important in an absolute sense, they are small relative the total cost of transportation.

Parry *et al.* (2007) provides a comprehensive survey of the externalities to automobile use, including local air pollution, global air pollution, traffic congestion, traffic accidents and other externalities (such as noise and highway maintenance costs). Couture *et al.* (2012) estimate that a lower bound on the deadweight loss from traffic congestion in the U.S. is of the order of 100 bn $US/year, although we note that these costs are already reflected in transportation expenditure data described above.

3 Theoretical Framework

In this section, we outline a multi-region extension of the Helpman (1998) model that follows Redding and Sturm (2008) and Redding (2012). The model incorporates many locations, goods transportation costs within and between locations, and commuting costs within locations. We use the model to show the effects of improvements in transportation infrastructure on the spatial distribution of wages, land rents, population and trade within and between locations. Although the model does not capture all of the theoretical foundations considered in the regional and urban literatures, it captures many of the standard ingredients, and we use its predictions to structure our review of the empirical evidence below.[13]

3.1 Preferences and Endowments

The economy consists of a set of locations indexed by n or $i \in N$, where n will typically refer to a consuming region and i to a producing region. To refer to a pairwise quantity, such as a distance or a quantity of trade, we use two subscripts with the first indicating the location of consumption and the second the location of production. The economy is populated by a mass of representative consumers, $\bar{L}$, who are mobile across locations and are endowed with a single unit of labor that is supplied inelastically with zero disutility. The effective supply of labor for each location i depends on its population (L_i) and commuting technology (b_i), where commuting costs are assumed to take the iceberg form. For each unit of labor residing in location i, only a fraction b_i is available for production, where $0 < b_i < 1$ and the remaining fraction $1 - b_i$ is lost in commuting. While we treat b_i as a primitive of the model here, it could in principle depend on equilibrium population density (e.g. if higher population density increases congestion costs).

Preferences are defined over a consumption index of tradeable varieties, C_n, and consumption of a non-tradeable amenity, H_n, which can be interpreted as housing. For simplicity, we treat the stock of housing as a primitive of the model, although it could also in principle depend on equilibrium population density (e.g. if a higher population density increases the supply of housing). The upper level utility function is assumed to be Cobb-Douglas:[14]

$$U_n = C_n^{\mu} H_n^{1-\mu}, \qquad 0 < \mu < 1. \tag{1}$$

The tradeables consumption index takes the standard constant elasticity of substitution (CES) form:

$$C_n = \left[\sum_{i \in N} M_i c_{ni}^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}},$$

[13] The model builds on the new economic geography literature synthesized in Fujita *et al.* (1999). While this literature assumes firm product differentiation and monopolistic competition, the model shares many properties with perfectly competitive models such as Eaton and Kortum (2002) (see Redding (2012)) or the Armington model of product differentiation by location (see Allen and Arkolakis (2013)). The organization of economic activity within countries has recently received renewed attention, as in Cosar and Fajgelbaum (2013) and Ramondo *et al.* (2012).

[14] For empirical evidence using U.S. data in support of the constant housing expenditure share implied by the Cobb-Douglas functional form, see Davis and Ortalo-Magne (2011).

where σ is the elasticity of substitution between varieties and we assume that varieties are substitutes ($\sigma > 1$); c_{ni} denotes consumption in country n of a variety produced in country i; we have used the fact that the measure of varieties M_i produced in location i are consumed in location n in the same amount c_{ni}. Varieties are assumed to be subject to iceberg trade costs. In order for one unit of a variety produced in location i to arrive in location n, a quantity $d_{ni} > 1$ must be shipped, so that $d_{ni} - 1$ measures proportional trade costs. The price index dual to the tradeables consumption index C_n is given by:

$$P_n = \left[\sum_{i \in N} M_i p_{ni}^{1-\sigma} \right]^{1/(1-\sigma)}, \tag{2}$$

where we have used the fact that the measure M_i of varieties produced in location i face the same elasticity of demand and charge the same equilibrium price $p_{ni} = d_{ni} p_i$ to consumers in location n.

Applying Shephard's lemma to the tradeables price index, equilibrium demand in location n for a tradeable variety produced in i is:

$$x_{ni} = p_i^{-\sigma} (d_{ni})^{1-\sigma} (\mu v_n L_n) (P_n)^{\sigma-1}, \tag{3}$$

where $v_n L_n$ denotes total income which equals total expenditure and, with Cobb-Douglas utility, consumers spend a constant share of their income, μ, on tradeables.

With constant expenditure shares and an inelastic supply of the non-tradeable amenity, the equilibrium price of this amenity depends solely on the expenditure share, $(1 - \mu)$, total income, $v_n L_n$, and the supply of the non-tradeable amenity, $\bar{H}_n$:

$$r_n = \frac{(1 - \mu) v_n L_n}{\bar{H}_n}. \tag{4}$$

Total income is the sum of labor income and expenditure on the non-tradeable amenity, which is assumed to be redistributed lump-sum to the location's residents:

$$v_n L_n = w_n b_n L_n + (1 - \mu) v_n L_n = \frac{w_n b_n L_n}{\mu}, \tag{5}$$

where we have used the fact that only a fraction b_n of the labor in location i is used in production because of commuting costs. Therefore total labor income equals the wage per effective unit of labor (w_n) times the measure of effective units of labor ($b_n L_n$).

3.2 Production Technology

There is a fixed cost in terms of labor of producing tradeable varieties ($F > 0$) and a constant variable cost that depends on a location's productivity (A_i). Both the fixed cost and the variable cost are the same across all varieties produced within a location. The total amount of labor (l_i) required to produce x_i units of a variety in location i is:

$$l_i = F + \frac{x_i}{A_i}, \tag{6}$$

where we allow productivity (A_i) to vary across locations to capture variation in production fundamentals.

Profit maximization implies that equilibrium prices are a constant markup over marginal cost:

$$p_{ni} = \left(\frac{\sigma}{\sigma - 1}\right) \frac{d_{ni} w_i}{A_i}. \tag{7}$$

Combining profit maximization and zero profits, equilibrium output of each tradeable variety equals the following constant:

$$\bar{x} = x_i = \sum_n x_{ni} = A_i F (\sigma - 1). \tag{8}$$

Labor market clearing for each location implies that labor demand equals the effective labor supply in that location, which is in turn determined by population mobility. Using the constant equilibrium output of each variety (8) and the tradeables production technology (6), the labor market clearing condition can be written as follows:

$$b_i L_i = M_i \bar{l}_i = M_i F \sigma, \tag{9}$$

where $\bar{l}_i$ denotes the constant equilibrium labor demand for each variety. This relationship pins down the measure of tradeable varieties produced in each location as a function of the location's population, the commuting technology, and the parameters of the model.

3.3 Market Access and Wages

Given demand in all markets and trade costs, the free on board price (p_i) charged for a tradeable variety by a firm in each location must be low enough in order to sell the quantity $\bar{x}$ and cover the firm's fixed production costs. We saw above that prices are a constant mark-up over marginal cost. Therefore, given demand in all markets, the equilibrium wage in location i, w_i, must be sufficiently low in order for a firm to sell $\bar{x}$ and cover its fixed production costs. Using demand (3), profit maximization (7) and equilibrium output (8), we obtain the *tradeables wage equation*:

$$\left(\frac{\sigma}{\sigma - 1} \frac{w_i}{A_i}\right)^{\sigma} = \frac{1}{\bar{x}} \sum_{n \in N} \left(w_n b_n L_n\right) \left(P_n\right)^{\sigma - 1} \left(d_{ni}\right)^{1-\sigma}. \tag{10}$$

This relationship pins down the maximum wage that a firm in location i can afford to pay given demand in all markets, trade costs and the production technology. On the right-hand side of the equation, market n demand for tradeables produced in i depends on total expenditure on tradeable varieties, $\mu v_n L_n = w_n b_n L_n$, the tradeables price index, P_n, that summarizes the price of competing varieties, and on bilateral trade costs, d_{ni}. Total demand for tradeables produced in i is the weighted sum of demand in all markets, where the weights are these bilateral trade costs, d_{ni}.

Following Redding and Venables (2004), we define the weighted sum of market demands faced by firms as *firm market access*, fma_i, such that the tradeables wage equation can be written more compactly as:

$$w_i = \xi A_i^{\frac{\sigma-1}{\sigma}} \left[fma_i\right]^{1/\sigma}, \qquad fma_i \equiv \sum_{n \in N} \left(w_n b_n L_n\right) \left(P_n\right)^{\sigma - 1} \left(d_{ni}\right)^{1-\sigma}, \tag{11}$$

where $\xi \equiv (F(\sigma-1))^{-1/\sigma}(\sigma-1)/\sigma$ collects together earlier constants. Therefore wages are increasing in both productivity A_i and firm market access (fma_i). Investments in transportation infrastructure that reduce the costs of transporting goods (d_{ni}) to market demands ($(w_n b_n L_n)(P_n)^{\sigma-1}$) raise market access and wages. Improvements in the commuting technology (b_n) increase the effective supply of labor ($b_n L_n$) and hence total income, which also raises market access and wages.

3.4 Labor Market Equilibrium

With perfect population mobility, workers move across locations to arbitrage away real income differences. Real income in each location depends on per capita income (v_n), the price index for tradeables (P_n), and the price of the non-tradeable amenity (r_n). Therefore population mobility implies:

$$V_n = \frac{v_n}{(P_n)^{\mu}(r_n)^{1-\mu}} = \bar{V}, \tag{12}$$

for all locations that are populated in equilibrium, where we have collected the constants $\mu^{-\mu}$ and $(1-\mu)^{-(1-\mu)}$ into the definition of V_n and $\bar{V}$.

The price index (2) that enters the above expression for real income depends on consumers' access to tradeable varieties, as captured by the measure of varieties and their free on board prices in each location i, together with the trade costs of shipping the varieties from locations i to n. We summarize consumers' access to tradeables using the concept of *consumer market access*, cma_n:

$$P_n = [cma_n]^{1/(1-\sigma)}, \qquad cma_n \equiv \sum_{i\in N} M_i (p_i d_{ni})^{1-\sigma}. \tag{13}$$

Substituting for v_n, P_n and r_n, the labor mobility condition (12) can be re-written to yield an expression linking the equilibrium population of a location (L_n) to its productivity (A_n), its commuting technology (b_n), the supply of the non-traded amenity (H_n), and the two endogenous measures of market access introduced above (one for firms (fma_n) and one for consumers (cma_n)):

$$L_n = \chi b_n^{\frac{\mu}{1-\mu}} A_n^{\frac{\mu(\sigma-1)}{\sigma(1-\mu)}} \bar{H}_n (fma_n)^{\frac{\mu}{\sigma(1-\mu)}} (cma_n)^{\frac{\mu}{(1-\mu)(\sigma-1)}}, \tag{14}$$

where $\chi = \bar{V}^{-1/(1-\mu)} \xi^{\mu/(1-\mu)} \mu^{-\mu/(1-\mu)} (1-\mu)^{-1}$ is a function of the common real income $\bar{V}$.

Therefore equilibrium population (L_n) is increasing in the quality of the commuting technology (b_n), the productivity of the final goods production technology (A_n), and the supply of the non-traded amenity ($\bar{H}_n$). Investments in transportation infrastructure that reduce the costs of transporting goods (d_{ni}) raise both firm and consumer market access (fma_n and cma_n) and hence increase equilibrium population. Improvements in the commuting technology (b_n) also have positive indirect effects on equilibrium population through higher firm and consumer market access.

From land market clearing (4) and total labor income (5), land prices can be written in terms of wages and total population:

$$r_n = \frac{(1-\mu)}{\mu} \frac{w_n b_n L_n}{\bar{H}_n}. \tag{15}$$

Therefore higher firm market access raises (fma_n) land prices through both higher wages (from (10)) and higher population (from (14)), while higher consumer market access (cma_n) raises land prices through a higher population alone (from (14)). Reductions in the cost of transporting goods (d_{ni}) raise land prices through both firm and consumer market access. Improvements in commuting technology (b_n) raise land prices directly and also indirectly through higher wages and population.

3.5 Trade Flows

Using CES demand, the share of location n's expenditure on varieties produced by location i can be expressed as:

$$\pi_{ni} = \frac{M_i p_{ni}^{1-\sigma}}{\sum_{k \in N} M_k p_{nk}^{1-\sigma}}, \tag{16}$$

which, using the equilibrium pricing rule (7) and the labor market clearing condition for each location (9), can be written as:

$$\pi_{ni} = \frac{b_i L_i \left(d_{ni} w_i\right)^{1-\sigma} \left(A_i\right)^{\sigma-1}}{\sum_{k \in N} b_k L_k \left(d_{nk} w_k\right)^{1-\sigma} \left(A_k\right)^{\sigma-1}}. \tag{17}$$

This expression for bilateral trade shares (π_{ni}) corresponds to a "gravity equation," in which bilateral trade between exporter i and importer n depends on both "bilateral resistance" (i.e. the bilateral goods of trading goods between i and n (d_{ni}) in the numerator) and "multilateral resistance" (i.e. the bilateral costs for importer n of sourcing goods from all exporters k (d_{nk}) in the denominator). In this gravity equation specification, bilateral trade depends on characteristics of the exporter i (e.g. the exporter's wage w_i in the numerator), bilateral trade costs (d_{ni}), and characteristics of the importer n (i.e. the importer's access to all sources of supply in the denominator).[15]

Taking the ratio of these expenditure shares, the value of trade between locations (X_{ni}) relative to trade within locations (X_{nn}) is:

$$\frac{X_{ni}}{X_{nn}} = \frac{\pi_{ni}}{\pi_{nn}} = \frac{b_i L_i \left(d_{ni} w_i\right)^{1-\sigma} \left(A_i\right)^{\sigma-1}}{b_n L_n \left(d_{nn} w_n\right)^{1-\sigma} \left(A_n\right)^{\sigma-1}}. \tag{18}$$

Therefore transportation infrastructure improvements that reduce the cost of transporting goods within locations (d_{nn}) by the same proportion as they reduce the cost of transporting goods between locations (d_{ni}) leave the ratio of trade between locations to trade within locations unchanged. One potential example is building roads within cities that make it easier for goods to circulate within the city and to leave the city to connect with long distance highways. Transportation cost improvements that reduce commuting costs for all locations (increase b_n and b_i) also leave the ratio of trade between locations to trade within locations unchanged.

In this model with a single differentiated sector, all trade takes the form of intra-industry trade, and transport infrastructure improvements affect the volume of this intra-industry trade. More generally, in a setting with multiple differentiated sectors that differ in terms of the magnitude of trade

[15] For an insightful review of the gravity equation in the international trade literature, see Head and Mayer (2013).

costs (e.g. high value to weight versus low value to weight sectors), transport infrastructure improvements also affect the pattern of inter-industry trade and the composition of employment and production across sectors within locations.

3.6 Welfare

We now show how the structure of the model can be used to derive an expression for the welfare effects of transport infrastructure improvements in terms of observables. Using the trade share (16), the price index (2) can be re-written in terms of each location's trade share with itself and parameters:

$$P_n = \frac{\sigma}{\sigma - 1} \left(\frac{b_n L_n}{\sigma F \pi_{nn}} \right)^{\frac{1}{1-\sigma}} \frac{d_{nn} w_n}{A_n}. \tag{19}$$

Using this expression for the price index and land market clearing (15), the population mobility condition (12) implies that the equilibrium population for each location can be written as:

$$L_n = \left[\frac{\left(\frac{1}{\sigma F \pi_{nn}} \right)^{\frac{\mu}{\sigma-1}} \bar{H}_n^{1-\mu} b_n^{\frac{\mu\sigma}{\sigma-1}} A_n^{\mu}}{\mu \left(\frac{1-\mu}{\mu} \right)^{1-\mu} \left(\frac{\sigma}{\sigma-1} \right)^{\mu} \bar{V} d_{nn}^{\mu}}, \right]^{\frac{\sigma-1}{\sigma(1-\mu)-1}}. \tag{20}$$

where terms in wages (w_n) have canceled and labor market clearing for the economy as a whole implies:

$$\sum_{n \in N} L_n = \bar{L}. \tag{21}$$

This expression for equilibrium population (20) has an intuitive interpretation. The population of each location n is decreasing in its domestic trade share (π_{nn}), since locations with low domestic trade shares have good market access to sources of supply of tradables from other locations. The population of each location is also increasing in the efficiency of its commuting technology (b_n), its productivity in production (A_n), its supply of housing ($\bar{H}_n$), and the efficiency of its transport technology (inversely related to d_{nn}). The common level of utility across all locations ($\bar{V}$) is endogenous and determined by the requirement that the labor market clears for the economy as a whole.

Re-arranging the population mobility condition (20), the real income in each location can be written in terms of its population, trade share with itself and parameters.

$$V_n = \frac{\left(\frac{1}{\sigma F \pi_{nn}} \right)^{\frac{\mu}{\sigma-1}} L_n^{-\left(\frac{\sigma(1-\mu)-1}{\sigma-1} \right)} \bar{H}_n^{1-\mu} b_n^{\frac{\mu\sigma}{\sigma-1}} A_n^{\mu}}{\mu \left(\frac{1-\mu}{\mu} \right)^{1-\mu} \left(\frac{\sigma}{\sigma-1} \right)^{\mu} d_{nn}^{\mu}} = \bar{V}. \tag{22}$$

A key implication of this expression for real income is that the change in each location's trade share with itself and the change in its population are sufficient statistics for the welfare effects of improvements in transport technology that reduce the costs of trading goods (see Redding, 2012):

$$\frac{V_n^1}{V_n^0} = \left(\frac{\pi_{nn}^0}{\pi_{nn}^1} \right)^{\frac{\mu}{\sigma-1}} \left(\frac{L_n^0}{L_n^1} \right)^{\left(\frac{\sigma(1-\mu)-1}{\sigma-1} \right)} = \frac{\bar{V}^1}{\bar{V}^0}, \tag{23}$$

where the superscripts 0 and 1 denote the value of variables before and after the improvement in transport technology respectively.

Similar sufficient statistics apply for the welfare effects of improvements in transport technology that reduce commuting costs, although these welfare effects also depend directly on the change in commuting costs (though the resulting increase in the effective supply of labor):

$$\frac{V_n^1}{V_n^0} = \left(\frac{b_n^1}{b_n^0}\right)^{\frac{\mu\sigma}{\sigma-1}} \left(\frac{\pi_{nn}^0}{\pi_{nn}^1}\right)^{\frac{\mu}{\sigma-1}} \left(\frac{L_n^0}{L_n^1}\right)^{\left(\frac{\sigma(1-\mu)-1}{\sigma-1}\right)} = \frac{\bar{V}^1}{\bar{V}^0}. \tag{24}$$

While these improvements in transport infrastructure have uneven effects on wages, land prices, and population, the mobility of workers across locations ensures that they have the same effect on welfare across all populated locations.

To understand the relationship between changes in domestic trade shares and the welfare change from improvements in transport technology that reduce goods trade costs, consider the extreme case where the transport improvement allows goods trade between two previously autarkic locations. For locations closed to goods trade, domestic trade shares must equal to one. Once locations open to trade, they can specialize to exploit gains from trade with other locations, and domestic trade shares fall below one. This fall in the domestic trade shares reflects the increase in specialization and is directly related to increases in real income, our measure of welfare.

To understand the relationship between changes in population and the changes in welfare following improvements in transport technology that reduce goods trade costs, first note that labor mobility requires real wage equalization across populated locations. Therefore, if goods trade is opened between locations, and some locations (e.g. coastal regions) benefit more than other locations (e.g. interior regions) at the initial labor allocation, workers must relocate to arbitrage away real wage differences. Those locations that experience larger welfare gains from trade at the initial labor allocation will experience population inflows, which increases the demand for the immobile factor land, and bids up land prices. In contrast, those locations that experience smaller welfare gains from trade at the initial labor allocation will experience population outflows, which decreases the demand for land, and bids down land prices. This population reallocation continues until real wages are again equalized across all populated locations. Hence these population changes also need to be taken into account in computing the welfare effects of the improvement in transport technology.

Therefore, together, the change in a location's domestic trade share and its population are sufficient statistics for the effects of a transport improvement that reduces the costs of trading goods (d_{ni}). A transport improvement that reduces the commuting costs for a region (b_n) also directly increases the supply of labor for that region, which is taken into account in the welfare formula.

3.7 General Equilibrium

The general equilibrium of the model can be represented by the share of workers in each location ($\lambda_n = L_n/\bar{L}$), the share of each location's expenditure on goods produced by other locations (π_{ni})

and the wage in each location (w_n). Using labor income (5), the trade share (16), population mobility (20) and labor market clearing (21), the equilibrium triple $\{\lambda_n, \pi_{ni}, w_n\}$ solves the following system of equations for all $i, n \in N$ (see Redding, 2012):

$$w_i b_i \lambda_i = \sum_{n \in N} \pi_{ni} w_n b_n \lambda_n, \tag{25}$$

$$\pi_{ni} = \frac{b_i \lambda_i \left(d_{ni} w_i / A_i\right)^{1-\sigma}}{\sum_{k \in N} b_k \lambda_k \left(d_{nk} w_k / A_k\right)^{1-\sigma}}, \tag{26}$$

$$\lambda_n = \frac{\left[\bar{H}_n^{1-\mu} \left(\frac{1}{\pi_{nn}}\right)^{\frac{\mu}{\sigma-1}} b_n^{\frac{\mu\sigma}{\sigma-1}} A_n^{\mu} d_{nn}^{-\mu}\right]^{\frac{\sigma-1}{\sigma(1-\mu)-1}}}{\sum_{k \in N} \left[H_k^{1-\mu} \left(\frac{1}{\pi_{kk}}\right)^{\frac{\mu}{\sigma-1}} b_k^{\frac{\mu\sigma}{\sigma-1}} A_k^{\mu} d_{kk}^{-\mu}\right]^{\frac{\sigma-1}{\sigma(1-\mu)-1}}}. \tag{27}$$

The assumption that $\sigma(1-\mu) > 1$ corresponds to the "no black hole" condition in Krugman (1991) and Helpman (1998). For parameter values satisfying this inequality, the model's agglomeration forces from love of variety, increasing returns to scale and transport costs (which are inversely related to σ) are not too strong relative to its congestion forces from an inelastic supply of land (captured by $1-\mu$). As a result, each location's real income is monotonically decreasing in its population, which ensures the existence of a unique stable non-degenerate distribution of population across locations.

While the existence of a unique equilibrium ensures that the model remains tractable and amenable to counterfactual analysis, often the rationale for transport investments is cast in terms of shifting the distribution of economic activity between multiple equilibria. To the extent that such multiple equilibria exist, their analysis requires either consideration of the range of the parameter space for which the model has multiple equilibria or the use of a richer theoretical framework.[16]

3.8 Counterfactuals

The system of equations for general equilibrium (25)-(27) can be used to undertake model-based counterfactuals in an extension of the trade-based approach of Dekle *et al.* (2007) to incorporate factor mobility across locations. The system of equations for general equilibrium must hold both before and after any counterfactual change in for example transport infrastructure. Denote the value of variables in the counterfactual equilibrium with a prime (x') and the relative value of variables in the counterfactual and initial equilibria by a hat ($\hat{x} = x'/x$). Using this notation, the system of equations for the counterfactual equilibrium (25)-(27) can be re-written as follows:

$$\hat{w}_i \hat{b}_i \hat{\lambda}_i Y_i = \sum_{n \in N} \hat{\pi}_{ni} \pi_{ni} \hat{w}_n \hat{b}_n \hat{\lambda}_n Y_n, \tag{28}$$

[16] An empirical literature has examined whether large and temporary shocks have permanent effects on the location of economic activity and interpreted these permanent effects as either evidence of multiple equilibria or path dependence more broadly. See for example Bleakley and Lin (2012), Davis and Weinstein (2002), Maystadt and Duranton (2014), Redding *et al.* (2011) and Sarvimäki *et al.* (2010).

$$\hat{\pi}_{ni}\pi_{ni} = \frac{\pi_{ni}\hat{\lambda}_i\hat{b}_i\left(\hat{d}_{ni}\hat{w}_i/\hat{A}_i\right)^{1-\sigma}}{\sum_{k\in N}\pi_{nk}\hat{\lambda}_i\hat{b}_i\left(\hat{d}_{nk}\hat{w}_k/\hat{A}_i\right)^{1-\sigma}}, \tag{29}$$

$$\hat{\lambda}_n\lambda_n = \frac{\lambda_n\left[\hat{\bar{H}}^{1-\mu}\hat{\pi}_{nn}^{-\frac{\mu}{\sigma-1}}\hat{b}_n^{\frac{\mu\sigma}{\sigma-1}}\hat{A}_n^{\mu}\hat{d}_{nn}^{-\mu}\right]^{\frac{\sigma-1}{\sigma(1-\mu)-1}}}{\sum_{k\in N}\lambda_k\left[\hat{\bar{H}}_k^{1-\mu}\hat{\pi}_{kk}^{-\frac{\mu}{\sigma-1}}\hat{b}_k^{\frac{\mu\sigma}{\sigma-1}}\hat{A}_k^{\mu}\hat{d}_{kk}^{-\mu}\right]^{\frac{\sigma-1}{\sigma(1-\mu)-1}}}, \tag{30}$$

where $Y_i = w_i b_i L_i$ denotes labor income in the initial equilibrium.

Given an exogenous change in transportation infrastructure that affects the costs of trading goods ($\hat{d}_{ni}$) or the costs of commuting ($\hat{b}_n$), this system of equations (28)-(30) can be solved for the counterfactual changes in wages ($\hat{w}_n$), population shares ($\hat{\lambda}_n$) and trade shares ($\hat{\pi}_{ni}$). Implementing these counterfactuals requires only observed values of GDP, trade shares and population shares $\{Y_n, \pi_{ni}, \lambda_n\}$ for all locations $i, n \in N$ in the initial equilibrium. For parameter values for which the model has a unique stable equilibrium ($\sigma(1-\mu) > 1$), these counterfactuals yield determinate predictions for the impact of the change in transportation costs. From the welfare analysis above, the changes in each location's population and its domestic trade share provide sufficient statistics for the welfare effect of transport improvements that affect the costs of trading goods ($\hat{d}_{ni}$). In contrast, transport improvements that affect the costs of commuting ($\hat{b}_n$) also have direct effects on welfare in addition to their effects through population and domestic trade shares. With perfect population mobility, these welfare effects must be the same across all populated locations.

4 Reduced-form Econometric Framework

4.1 A simple taxonomy

We survey the recent empirical literature investigating the effects of infrastructure on the geographic distribution of economic activity. The preponderance of this literature can be described with a remarkably simple taxonomy.

Let t index time periods, and, preserving the notation from above, let n and $i \in N$ index a set of geographic locations, typically cities or counties. Let L_{it} denote an outcome of interest for location i at time t; employment, population, rent or centralization. Let x_{it} be a vector of location and time specific covariates, and finally, let b_{it} and d_{it} denote the transportation variables of interest. In particular, consistent with notation in our theoretical model, let b_{it} denote a measure of transportation infrastructure that is internal to unit i, and d_{it} a measure of transportation infrastructure external to unit i. For example, b_{it} could count radial highways within a metropolitan area while d_{it} could indicate whether a rural county is connected to a highway network.

With this notation in place, define the 'intracity regression' as

$$L_{it} = C_0 + C_1 b_{it} + C_2 x_{it} + \delta_i + \theta_t + \epsilon_{it}, \tag{31}$$

where δ_i denotes location specific time invariant unobservables, θ_t a common time effect for all locations and ϵ_{it} the time varying location specific residual. The coefficient of interest is C_1, which measures the effect of within-city infrastructure on the city level outcome.[17]

Similarly, define the 'intercity regression' as

$$L_{it} = C_0 + C_1 d_{it} + C_2 x_{it} + \delta_i + \theta_t + \epsilon_{it}, \tag{32}$$

which differs from the intracity regression only in that the explanatory variable of interest describes transportation costs between unit i and other units, rather than within-city infrastructure.

These equations require some discussion before we turn to a description of results. First, both estimating equations are natural reduced form versions of equation (14), or if the outcome of interest is land rent, (15). Thus, they are broadly consistent with the theoretical framework described earlier. Second, comparing the regression equations with their theoretical counterparts immediately suggests four inference problems that estimations of the intracity and intercity regressions should confront.

First, equilibrium employment or land rent depends on the location specific productivity, A_n. This will generally be unobserved, and thus will be reflected in the error terms of our regression equations. It is natural to expect that intracity and intercity infrastructure will depend on location specific productivity, and hence, be endogenous in the two regression equations. Second, equilibrium employment or land rent depends on the level of a location specific amenity, H_n. In our model, this reflects a supply of housing, but in reality, may also reflect unobserved location characteristics that augment or reduce the welfare of residents at a location. We might also be concerned that such amenities, to the extent that they are unobserved, affect infrastructure allocation and give rise to an endogeneity problem. More generally, the intercity and intracity regressions do not by themselves distinguish between the demand for and supply of transportation.

Third, equations (14) and (15) involve expressions for market access not present explicitly in the estimating equations. To the extent that market access depends on transportation costs between cities, the treatment of market access in these estimations deserves careful attention. Fourth, to the extent that there are general equilibrium effects of transport infrastructure on all locations, these are not captured by C_1. Instead they are captured in the time effects θ_t and cannot be separated from other time-varying factors that are common to all locations without further assumptions. More generally, in general equilibrium, transport investments between a pair of regions i and j can have effects on third regions k, which are not captured by the transportation variables for regions i and j.

4.2 Identification of causal effects

As discussed above, perhaps the biggest empirical challenge in estimating the intercity and intracity regressions is constructing the appropriate counterfactual for the absence of the transport improve-

[17]Pioneering studies of the role of automobiles and highways in reorganizing the distributions of population and economic activity within metropolitan areas are Moses (1958) and Moses and Williamson (1963).

ment. In particular, ordinary least squares (OLS) regressions comparing treated and untreated locations are unlikely to consistently estimate the causal effect of the transport improvement, because the selection of locations into the treatment group is non-random. The main empirical approach to addressing this challenge has been to develop instruments for the assignment of transport improvements that plausibly satisfy the exclusion restriction of only affecting the economic outcome of interest through the transport improvement.[18] More formally, this approach to identifying the causal effects posits an additional first-stage regression that determines the assignment of transport infrastructure:

$$\mathbb{I}_{it} = D_0 + D_1 x_{it} + D_2 z_{it} + \eta_i + \gamma_t + u_{it}, \tag{33}$$

where $\mathbb{I}_{it} \in \{b_{it}, d_{it}\}$ is the transportation variables of interest (depending on whether the specification is intracity or intercity); x_{it} are the location and time-varying controls from the second-stage regression ((31) or (32)); η_i are location specific time invariant unobservables; γ_t are time indicators; u_{it} is a time varying location specific residual; and z_{it} are the instruments or excluded exogenous variables.

Combining the second-stage equation ((31) or (32)) with the first-stage equation (33), the impact of transport infrastructure on the economic outcomes of interest (C_1) can be estimated using two-stage least squares. Credible identification of the causal impact of transport infrastructure requires that two conditions are satisfied: (i) the instruments have power in the first-stage regression ($D_2 \neq 0$) and (ii) the instruments satisfy the exclusion restriction of only affecting the economic outcomes of interest through transport infrastructure conditional on the controls x_{it}, that is, $\text{cov}(\epsilon_{it}, u_{it}) = 0$.

The existing literature has followed three main instrumental variables strategies. The first, the *planned route IV*, is an instrumental variables strategy which relies on planning maps and documents as a source of quasi-random variation in the observed infrastructure. The second, the *historical route IV*, relies on very old transportation routes as a source of quasi-random variation in observed infrastructure. The third, the *inconsequential place approach*, relies on choosing a sample that is inconsequential in the sense that unobservable attributes do not affect the placement of infrastructure. The plausibility of these identification strategies depends sensitively on the details of their implementation and is sometimes contentious. With this said, we here briefly describe these identification strategies and the rationale for their use. We avoid discussion of the validity of these strategies in particular contexts. Broadly, the strategies we describe are the best approaches currently available for estimating the causal effects of transport infrastructure on the organization of economic activity.

4.2.1 Planned Route IV

Baum-Snow (2007) pioneers the planned route IV by using a circa 1947 plan for the interstate highway network as a source of quasi-random variation in the way the actual network was developed.

[18] While the program evaluation literature suggests other complementary approaches, such as conducting randomized experiments with transport improvements or the use of matching estimators, these have been less widely applied in this empirical literature.

In the specific context of Baum-Snow (2007), this means counting the number of planned radial highways entering a metropolitan area and using this variable to predict the actual number of interstate highway rays. Since the network plan was developed under a mandate to serve military purposes, the validity of this instrument hinges on the extent to which military purposes are orthogonal to the needs of post war commuters. Several other empirical investigations into the effects of the U.S. road and highway network exploit instruments based on the 1947 highway plan, while Hsu and Zhang (2012) develop a similar instrument for Japan. Michaels *et al.* (2012) uses an even earlier plan of the U.S. highway network, the 'Pershing plan', as a source of quasi-random variation in the U.S. highway network. Although Donaldson (2013) stops short of using hypothetical planned networks as instruments for realized networks, he does compare the development of districts without railroads and without planned railroads to those without railroads but with planned railroads. That these sets of districts develop in the same way suggests that the planning process did not pick out districts on the basis of different unobservable characteristics.

4.2.2 Historical Route IV

Duranton and Turner (2012) develop the historical route IV approach. In regressions predicting MSA level economic outcomes they rely on maps of historical transportation networks, the U.S. railroad network circa 1898 and the routes of major expeditions of exploration of the U.S. between 1535 and 1850 as sources of quasi-random variation in the U.S. interstate highway network at the end of the 20th century. The validity of these instruments requires that, conditional on controls, factors that do not directly affect economic activity in U.S. metropolitan areas at the end of the 20th century determine the configuration of these historical networks. A series of papers, Duranton and Turner (2011), Duranton and Turner (2012) and Duranton *et al.* (2014), use the two historical route instruments and the 1947 highway plan as sources of quasi-random variation in regressions predicting metropolitan total vehicle kilometers traveled, changes in metropolitan employment, and trade flows between cities as functions of the interstate highway network.

One distinctive feature of Duranton and Turner (2011), Duranton and Turner (2012), and Duranton *et al.* (2014) is the use of multiple instruments based on different sources of variation. With more instruments than endogenous variables, the specification can be estimated with either all or subsets to the instruments, and over-identification tests can be used as a check on the identifying assumptions. Conditional on one of the instruments being valid, these over identification tests check the validity of the other instruments. Given that the instruments exploit quite different sources of variation in the data, if a specification passes the over-identification test, this implies that either all of the instruments are valid or that an improbable relationship exists between the instruments and the errors of the first and second-stage regressions.

Several other authors develop historical transportation networks as a source of quasi-random variation in modern transportation networks in other regions. Baum-Snow *et al.* (2012) rely on Chinese road and rail networks from 1962 as a source of quasi-random variation in road and rail networks after 2000. Garcia-Lopez *et al.* (2013) use 18th century postal routes and Roman roads for Spain. Hsu and Zhang (2012) relies on historical Japanese railroad networks. Martincus *et al.* (2012) uses the Inca roads for Peru. Duranton and Turner (2012) provides a more detailed discussion of the validity of these instruments.

4.2.3 Inconsequential Units Approach

To estimate the intercity regression, researchers often rely on the inconsequential units approach to identification, sometimes in conjunction with one or both of the instrumental variables strategies described above. If we consider economically small units lying between large cities, then we expect that intercity links will traverse these units only when they lie along a convenient route between the two large cities. That is, we expect that the unobserved characteristics of units between large cities are inconsequential to the choice of route, and therefore that the connection status of these units will not depend on the extent to which these units are affected by the road. Chandra and Thompson (2000) pioneer this strategy in their analysis of the effect of access to the interstate highway system on rural counties in the U.S.. By restricting attention to rural highways they hope to restrict attention to counties that received interstates 'accidentally', by virtue of lying between larger cities. While it is difficult to assess the validity of this approach, some of the regressions reported in Michaels (2008) are quite similar to those in Chandra and Thompson (2000) but rely on the 1947 planned highway network for identification. That the two methods arrive at similar estimates is reassuring. Banerjee *et al.* (2012) also use the inconsequential units strategy in their analysis of the effects of Chinese transportation networks. In particular, they construct a hypothetical transportation network connecting historical treaty ports to major interior trading centers. Counties near these predicted networks are there accidentally in the same sense that rural counties may be accidentally near interstates in the U.S. Similarly, and also for China, Faber (2014) constructs a hypothetical least cost network connecting major Chinese cities and examines the impact of proximity to this network on outcomes in nearby rural counties.

These three econometric responses to the probable endogeneity of transportation infrastructure are widely used. Other approaches to this problem typically exploit natural experiments that, while they may provide credible quasi-random variation in infrastructure, are not easily extended to other applications.

4.3 Distinguishing growth from reorganization

As Fogel observes in his classic analysis of the role of railroad construction in the economic development of the 19th century U.S. (Fogel, 1964), an assessment of the economic impacts of transportation infrastructure depends fundamentally on whether changes in transportation costs change the amount of economic activity or reorganize existing economic activity. For example, the welfare implications of a road or light rail line that attracts pre-existing firms are quite different than those of one that leads to the creation of new firms. Importantly, this issue is distinct from the endogeneity problem discussed above. The problem of endogeneity follows from non-random assignment of transportation infrastructure to 'treated' observations. The problem of distinguishing between growth and reorganization persists even when transportation is assigned to observations at random. Even in the case in which a region experiences an exogenous change in transport infrastructure, the observed effects on economic activity in the region can either reflect reorganization or growth. This same issue of distinguishing growth and reorganization appears in the literature evaluating place-based policies, as discussed in Neumark and Simpson (2014) in this volume.[19]

Figure 6 illustrates a simple hypothetical data set with the same structure as those typically used to estimate the intercity and intracity estimating equations. Figure 6 describes a sample consisting of three regions: a region that is 'treated' in some way that affects transportation costs in this region, e.g., a new road; an untreated region which is typically near the treated region but is not subject to a change in transportation infrastructure; and third, everyplace else. The outcome variable of interest is y and the new road creates a units of this outcome in the treated region and displaces d units from the untreated to the treated region.

Fundamentally, the intercity and intracity regressions estimate the effect of treatment on the difference between treated regions and untreated comparison regions. As the figure makes clear, the difference in the outcome between treated and untreated regions is $2d + a$, the compound effect of reorganization and growth. At its core, the problem of distinguishing between reorganization and growth requires us to identify two quantities. Without further assumptions, these two quantities cannot be separately identified if we estimate only a single equation, regardless of whether it is the intercity or intracity estimating equation. To identify both the growth and reorganization effect, we must estimate two linearly independent equations.

In the context of the sample described in figure 6 these two equations could involve a comparison of any two of the three possible pairs of regions, i.e., treated and untreated, untreated and residual, treated and residual. Alternatively, with panel data, one could estimate the change in the treated region following a change in transportation costs and also the change in the untreated region following the change in the treated region. While the literature has carefully addressed the possibility that transportation costs and infrastructure are not assigned to regions at random, few authors conduct estimations allowing the separate identification of growth and reorganization.

While figure 6 suggests simple methods for distinguishing between growth and reorganization, this reflects implicit simplifying assumptions. In particular, the new road in the treated district does not lead to migration of economic activity from the residual to the untreated or the treated region and does not cause growth in the untreated or residual district. If we allow these effects, then the effect of a new road in the treated region is characterized by six parameters rather than two. Identifying all of these parameters will generally require estimating six linearly independent equations and will not generally be possible with cross-sectional data. In the context of 'real data', with a more complex ge-

[19]For approaches to distinguishing growth and reorganization in this literature on place-based policies, see Criscuolo *et al.* (2012) and Thierry Mayer and Py (2013).

ography and many regions subject to treatment, distinguishing between growth and reorganization requires a priori restrictions on the nature of these effects.

The literature has, as yet, devoted little attention to what these identifying assumptions should be. As suggested by figure 6, this problem can be resolved with transparent but ad hoc assumptions. Alternatively, the theoretical model described in section 3 provides a theoretically founded basis for distinguishing between growth and reorganization which derives from the iceberg structure of transportation costs and increasing returns to scale in cities. Importantly, if the new road in the treated region affects the level of economic activity in all three regions, then no cross-sectional estimate can recover this effect. This requires time series data or cross-sectional data describing 'replications' of figure 6. More generally, for a penetration road or single transport project, it may be possible to construct plausible definitions of treated, untreated and residual regions, as in Figure 6. However, for an evaluation of a national highway system, there may be no plausible residual regions, in which case we are necessarily in a general equilibrium world.

5 Reduced-form empirical results

5.1 Intracity infrastructure and the geographic organization of economic activity

5.1.1 Infrastructure and decentralization

Baum-Snow (2007) partitions a sample of U.S. metropolitan areas into an 'old central business district', the central business district circa 1950, and the residual suburbs. He then estimates a version of the intracity regression, equation (31), in first differences, where the unit of observation is a U.S. MSA, the measure of infrastructure is the count of radial interstate highways, and the instrument is a measure of rays based on the 1947 highway plan discussed above. He finds that each radial segment of the interstate highway network causes about a 9% decrease in central city population. Since one standard deviation in the number of rays in an MSA is 1.5, this means that a one standard deviation increase in the number of rays causes about a 14% decrease in central city population. To get a sense for the magnitude of this effect, U.S. population grew by 64% during his study period, MSA population by 72% and constant boundary central city population declined by 17%. Thus, the interstate highway system can account for almost the entire decline in old central city population densities. Note that, since Baum-Snow (2007) estimates the share of population in the treated area, he avoids the problem of distinguishing between growth and reorganization. The share of population in the central city reflects changes in the level of central city and suburb and migration between the two.

This result has been extended to two other contexts. Baum-Snow *et al.* (2012) conduct essentially the same regression using data describing Chinese prefectures between 1990 and 2010. They first partition each prefecture into the constant boundary administrative central city and the residual prefecture, and then examine the effect of several measures of infrastructure on the decentralization of population and employment. They rely on a historical routes (from 1962) as a source of quasi-random variation in city level infrastructure. They find that each major highway ray causes about a

5% decrease in central city population. No other measure of infrastructure; kilometers of highways, ring road capacity, kilometers of railroads, ring rail capacity or radial rail capacity, has a measurable effect on the organization of population in Chinese prefectures. Baum-Snow *et al.* (2012) also examine the effect of infrastructure on the organization of production. They find that radial railroads and highway ring capacity both have dramatic effects on the organization of production. In particular, each radial railroad causes about 26% of central city manufacturing to migrate to the periphery while ring roads also have a dramatic effect. This effect varies by industry. Industries with relatively low weight to value ratios are more affected. None of the other infrastructure measures they investigate affect the organization of production.

Finally, Garcia-Lopez *et al.* (2013) consider the effect of limited access highways on the organization of population in Spanish cities between 1991 and 2011. Their unit of observation is one of 123 Spanish metropolitan regions. They conduct a version of the intracity regression in first differences to explain the change in central city population between 1991 and 2011 as a function of changes in the highway network over the same period. They rely on three historical road networks to instrument for changes in the modern network: the Roman road network; a network of postal roads, circa 1760; and a network of 19th century main roads. They find that each radial highway causes about a 5% decrease in central city population, and that kilometers of central city or suburban highways have no measurable effect. Using a similar instrumentation strategy, Àngel Garcia-López (2012) examines the impact of transport improvements on the location of population within the city of Barcelona. Consistent with some of the findings discussed above, improvements to the highway and railroad systems are found to foster population growth in suburban areas, whereas the expansion of the transit system is found to affect the location of population inside the central business district (CBD).[20]

Where the decentralization papers above investigate the effect on central cities of infrastructure improvements which reduce the cost of accessing peripheral land, the Ahlfeldt *et al.* (2012) considers the effect of changes in transportation cost between two adjacent parts of the same central city. Specifically, Ahlfeldt *et al.* (2012) consider the effect of the construction and destruction of the Berlin wall, which bisected the historical central business district, on the organization of population, employment and land values in 1936, before the partition of the city, 1986, shortly before reunification, and 2006, 15 years after reunification. That is, when the cost of commuting from the West to the East was, low, prohibitively high, and low again.

Methodologically, Ahlfeldt *et al.* (2012) differs dramatically from the centralization papers above. Their sample consists of approximately 16,000 'statistical blocks' comprising metropolitan Berlin, each with a population of about 250 people in 2005. Loosely, for each block, Ahlfeldt *et al.* (2012) record location, population, land rent and employment in the three years of their study. They use these data to estimate a first differences variant of the intercity regression, equation (32). The reduced form results in Ahlfeldt *et al.* (2012) show that the construction of the Berlin Wall caused the central

[20]One issue that has received relatively little attention in the intracity literature is the role of transport infrastructure in segregating cities and leaving some neighborhoods "on the wrong side of the tracks."

business district to migrate so that it was more nearly central in the territory of West Berlin, and that the removal of the Berlin Wall approximately reversed this process. The identifying assumption underlying this natural experiment is that change in access to economic activity following from division and reunification is uncorrelated with other changes in the way the city was organized, except through its effect on access to economic activity. In addition to these reduced form results, Ahlfeldt *et al.* (2012) also conduct structural estimations, which we discuss later.

5.1.2 Infrastructure and miscellaneous city level outcomes

Beyond the literature investigating infrastructure and decentralization, a series of papers by Duranton and Turner investigates the relationship between roads and employment growth, intercity trade and driving.

Duranton and Turner (2012) investigate the relationship between employment growth in U.S. MSAs between 1984 and 2004. Their principle regression is a variant of the intracity regression for which the outcome is employment growth between 1984 and 2004, and their measure of transportation is kilometers of interstate highways within city boundaries. They rely on the 1947 highway plan, a map of the 1898 railroad network and maps of historical routes of exploration as sources of exogenous variation in the interstate highway network. Their main finding is that a 10% increase in kilometers of interstate highways causes about a 1.5% increase in employment over 20 years. Alternatively, a one standard deviation in initial roads causes a change in employment growth of about 15% over 20 years. This is a bit under two thirds of the sample average growth rate.

Duranton and Turner (2012) also estimate a second equation in which they examine the effect on employment growth of changes in the stock of roads in the nearest large city. In the context of figure 6, this corresponds to looking for an effect in the treated region from changes in the residual region. They find no effect. This regression, together with their main intracity regression, provides a tentative basis for concluding that roads cause employment growth in cities rather than simply rearranging employment across cities.

In a second exercise, Duranton *et al.* (2014) investigate the relationship between intercity trade flows in 2007 and the interstate highway network. Their unit of analysis is a U.S. 'commodity flow survey area': a reporting unit somewhat larger than an MSA. They record the weight and value of pairwise trade flows between 69 such units and also aggregate flows in and out of each area by sector. On the basis of a methodology pioneered in Redding and Venables (2004) and Anderson and van Wincoop (2003) they develop two estimating equations. The first is a variant of the intercity regression and explains pairwise trade flows of weight and value as a function of pairwise interstate distance. The second is a variant of the intracity regression and predicts aggregate flows in and out of each city, by weight and value (irrespective of destination). In each case they use the 1947 highway plan and the 1898 railroad network to derive instrumental variables. For the intracity regression, they also use instruments derived from routes of major explorations between 1530 and 1850. They arrive at three main findings. First, a one percent decrease in pairwise travel distance causes about a 1.4% increase in the value of pairwise trade and a 1.7% increase in its weight. Second, within-city highways affect the weight of exports, but not their value. Specifically, a 1% increase in the lane kilometers of within commodity flow survey area interstate highways causes about a 0.5% increase in the weight of exports but has no measurable effect on the value of exports. A 50 year panel of employment data confirms this result. Cities with more highways employ more people to make heavy manufactured goods, and conversely.

Finally, Duranton and Turner (2011) investigate the effect of the supply of roads and highways on the amount of driving in a city. More specifically, they conduct a version of the intracity regression. The outcome variable of interest is a measure of the total vehicle kilometers driven in a U.S. MSA on particular road networks in a year and the explanatory variables of interest measure the extent of road networks. They conduct this regression in levels, first differences and second differences. They also rely on maps of the 1947 highway plan, the 1898 railroad network and of routes of major expeditions of exploration between 1530 and 1850 as sources of exogenous variation in MSA roads. They establish a "fundamental law of road congestion," according to which driving increases by about 1% for each 1% increase in the stock of roadways, a finding that is robust across all of their specifications. They provide a rough decomposition of the sources of the marginal induced driving. About half comes from changes in individual behavior. Increases in commercial driving are less important. Migration in response to new roads and diversion of traffic from other networks appears to be least important. Hsu and Zhang (2012) replicate the analysis of Duranton and Turner (2011) using Japanese data. They arrive at the same conclusion. Driving in Japanese cities increases about 1% for each 1% increase in the extent of the road network.

While the above papers are concerned with the relationship between overall traffic volumes and lane kilometers of roads, Couture *et al.* (2012) examine the determinants of driving speed in large U.S. cities. Remarkably, their paper is the first to estimate an econometric framework in which the supply and demand for travel are both explicitly modeled. The estimation results are used to construct a city-level index of driving speed and to undertake a welfare analysis of counterfactual changes in driving speed. Cities differ substantially in terms of driving speed and the welfare gains from improvements in driving speed in the slowest cities are found to be large. Taken together, these results are consistent with substantial deadweight losses from congestion.

Although most of the intracity literature is based on one of the three instrumental variables estimation strategies discussed above, Gonzalez-Navarro and Quintana-Domeque (2013) is noteworthy for its use of a randomized experiment research design to examine the effects of road paving in Mexico. Homes in treatment streets that were paved experienced an increase in value of between 15-17% relative to those in control streets. The estimated rate of return to road pavement is 2% without taking into account externalities, but rises to 55% after incorporating externalities.

5.1.3 Subways and the internal organization of cities, and related other results

A large literature examines the effect of subways on the internal organization of cities. These papers typically consider a unit of analysis that is small relative to the city, e.g., a census tract or zip code. The explanatory variable of interest is typically the distance to the subway. The outcome of interest is typically population or employment density, land prices or ridership rates. That is, these papers perform a version of the intercity regression (here inaptly named), equation (32), at a subcity scale of analysis. As we discuss in sections 4.2 and 4.3, such regressions must overcome two problems, endogeneity and distinguishing between growth and reorganization.

The literature on subways is too large to survey exhaustively. We focus on three papers which provide, in our opinion, the best resolution to the endogeniety problem; Gibbons and Machin (2005), Billings (2011) and Ahlfeldt *et al.* (2012), on two papers showing that within-city roads are associated with qualitatively similar density gradients as subways; Baum-Snow (2007) and Garcia-Lopez *et al.* (2013), and finally, on two others which provide cross-city evidence of the effects of subways; Baum-Snow and Kahn (2005) and Gordon and Willson (1984). Gibbons and Machin (2005) and Billings (2011), in particular, provide more extensive surveys.

Gibbons and Machin (2005) conduct a difference in differences estimate of the intercity estimation equation in order to evaluate the effect on London residential real estate prices of subway extension in the late 1990s. Their unit of observation is a 'postcode unit', an administrative unit containing 10-15 households. They observe real estate transactions by postcode unit before and after the Docklands light rail extension in South London. As a consequence of this extension, parts of their sample experience a decrease in distance to a subway station. This makes a difference in differences estimate possible: they compare the change in real estate prices in postcodes that experienced changes in subway access to the change in postcodes that did not.

They find that, for properties within 2km of a station, a 1km reduction in station distance causes about a 2% increase in real estate prices. Usefully, Gibbons and Machin (2005) compare their difference in differences estimate with a more conventional cross-sectional estimate. They find that estimates based on cross-sectional variation alone are three times as large as difference in difference estimates. This suggests that, as we might hope, subway station locations are not selected at random and more valuable land is more likely to receive subway service.

Billings (2011) and Ahlfeldt *et al.* (2012) also conduct difference in differences estimates of the effects of subways. For a newly opened light rail line in Charlotte, North Carolina, Billings (2011) finds that residential real estate prices within one mile of a station increase by about 4% for single family homes, by about 11% for condominiums and that light rail access has no effect on commercial property prices. Ahlfeldt *et al.* (2012) find that properties further than 250m from a 1936 subway line experienced about a 40% smaller decrease in value as a consequence of the division of Berlin than did those within 250m. Glaeser *et al.* (2008) look at the effects of the New York city subway and find evidence that poor people move to be closer to subway stations.

Each of these three papers investigates the rate at which land rent declines with distance from a subway or light rail line. Baum-Snow (2007) and Garcia-Lopez *et al.* (2013) investigate how population density varies with distance to a highway. The unit of observation in Baum-Snow (2007) is a census tract. For each U.S. census tract in a 1990 MSA, he observes population density in 1970 and 1990 and distance to an interstate highway. This allows him to estimate a variant of the intercity estimating equation for two cross-sections and in first differences. He finds that a 10% decrease in the distance to a highway is associated with about a 0.13% increase in population density in 1970 and a slightly smaller increase in 1990. First difference estimates are similar. Garcia-Lopez *et al.* (2013) arrives at similar estimates using Spanish data.

While each of these papers attempts to resolve the problem of endogenous placement of infrastructure, they do not provide a basis for determining whether subways cause growth or reorganization of nearby economic outcomes. In particular, they are unable to measure whether a change in a city's subway network affects city level variables. In the context of figure 6 this would correspond to asking whether a change in treated unit infrastructure affects the level of an outcome in all three regions. This question, which is of obvious public policy interest, requires cross-city data describing subways and city level outcomes, i.e., data which allows the estimation of the intracity regression, equation (31). Since subways are relatively rare, this sort of data is difficult to assemble and we know of only two such efforts to date. The first, Gordon and Willson (1984) constructs a single cross-section of 52 cities that describes population density, subway passenger kilometers per year and a handful of city level control variables. In a simple cross-sectional estimate of ridership on density they find a strong positive relationship. Baum-Snow and Kahn (2005) construct disaggregated panel data describing a panel of 16 U.S. metropolitan areas with subways. In addition to describing the extent of each city's subway network, their data describe ridership commute times. Overall they find little evidence that U.S. subway expansions elicit large increases in ridership.

5.2 Intercity infrastructure and the geographic organization of economic activity

We now turn attention to the effect of infrastructure that connects a unit of observation, typically a county, to the rest of the world. This most often involves estimating a version of the intercity regression. We first describe results for high income countries and then turn to results for low income countries and historical data.

5.2.1 High income countries

Chandra and Thompson (2000) considers the effect of the interstate highway system on a sample of 185 non-metropolitan U.S. counties that received a highway after 1969, and 391 neighboring non-metropolitan counties that did not. By restricting attention to non-metropolitan counties, Chandra and Thompson (2000) hope to restrict attention to counties that were treated with highways 'accidentally', and in particular, without regard for effect of highways on the treated counties. This is the pioneering use of the inconsequential place approach to identification. Their outcome measures are aggregate annual earnings by county, year and one digit SIC code, for all years between 1969 and

1993, inclusive.

Chandra and Thompson (2000) estimate a distributed lag version of the intercity regression with county fixed effects. In particular, they include 24 dummies for the age of the highway connection in each year as explanatory variables. Their results are striking. They find that a marginally positive 24 year effect of a highway connection on earnings in: Finance, Insurance, Real Estate; Transportation and Public Utilities; and, Retail and Services. They find that the effect on earnings in manufacturing and farming is marginally negative. Overall, the 24 year effect on earnings of a highway connection of a non-metropolitan county is a 6-8% increase. The effect on untreated neighboring counties is approximately opposite. Overall, untreated neighbor counties see a decrease in total earnings of between 1 and 3%. Note that Chandra and Thompson (2000) estimate two distinct equations. In the context of figure 6, the first predicts the effect of changes in infrastructure on the treated area, the second the effect of changes in infrastructure on neighboring untreated regions. Together, these two regressions are exactly what is required to distinguish between growth and reorganization. Importantly, Chandra and Thompson (2000) cannot reject the hypothesis that aggregate changes in earnings caused by a highway connection sum to zero across the whole sample of treated and neighbor counties.

Michaels (2008) considers a sample of 2000 counties in the U.S. that are more than 50% rural and have no highways in 1950, i.e., the inconsequential place approach. He then identifies a subset of the interstate network constructed between 1959 and 1975 to serve intercity travel. His explanatory variable of interest is an indicator of whether a county is connected to this network at the end of the study period. He also relies on a planned route IV based on the 1947 highway plan. He considers a number of outcome variables, in particular, per capita earnings in trucking and retail sales, and in the relative wages of skilled and unskilled workers. He finds that rural counties receiving highway connections experience about the same increase in trucking and retail earnings as Chandra and Thompson (2000) observe, the only two outcome variables common to the two papers. This is reassuring given the quite different identification strategies. He also finds that highways cause a small increase in the wage of skilled relative to unskilled workers.

In two related, but methodologically quite different papers, Redding and Sturm (2008) consider the effect of the post-war partition of Germany on the organization of economic activity. They find that the population of German cities near the East-West border grew more slowly than those far from the border. That is, in response to an increase in the cost of travel between East and West Germany, economic activity migrates away from the border region. Duranton *et al.* (2014) examine the effect of pairwise distance on pairwise trade of manufactured goods between U.S. cities in 2007. They find that trade responds to highway distance rather than straight line distance, that the effect of distance on trade is large, and that it is larger on the weight of goods than on their value. Unsurprisingly, Duranton *et al.* (2014) also find that trade by rail is less sensitive to distance than is trade by road. Curiously, Duranton (2014) replicates Duranton *et al.* (2014) using data describing trade in Columbia rather than the U.S. He reaches somewhat different conclusions: trade is less sensitive to distance, the value and weight of trade are about equally sensitive to infrastructure, and the value of trade responds to infrastructure.

While most of the intercity literature has focused on roads, Sheard (2014) estimates the effects of airport infrastructure on relative sectoral employment at the metropolitan-area level, using data from the United States. To address the potential endogeneity in the determination of airport sizes, the 1944 National Airport Plan is used to instrument for the current distribution of airports. Airport size is found to have a positive effect on the employment share of tradable services, controlling for overall local employment, but no measurable effect on manufacturing or most non-tradable sectors. The effect of airport size on overall local employment is practically zero, suggesting that airports lead to specialization but not growth at the metropolitan-area level. The implied elasticity of tradable-service employment with respect to airport size is approximately 0.22.

5.2.2 Low income countries

Donaldson (2013) considers the effect of railroads on a sample of 235 'districts' covering the preponderance of India during the period from 1870 to 1930. He uses these data to estimate the intercity regression with district and year fixed effects. His outcome variable is the aggregate annual value of 17 agricultural crops per unit of district area. During this study period, agriculture accounted for about two thirds of Indian GDP, and the 17 crops Donaldson considers accounted for 93% of the value of agricultural output. To investigate the probable endogeneity of railroads, Donaldson gathers data describing hypothetical planned railroad networks that were competitors to the realized network. He finds no difference in output between districts treated with planned networks and those not treated. This suggests that the realized network did not target the most productive districts.

Donaldson finds that districts with access to the railroad report about 17% higher real agricultural income per unit of district area than districts without railroads. Because Donaldson's regression equation contains year and district effects, this means that a district treated with a railroad connection sees income increase by 17% relative to untreated districts. This is a large effect. Over the course of the 1870-1930 study period, India's real agricultural income increased by only about 22%, so that a rail connection was equivalent to more than 40 years of economic growth.

In a related paper, Donaldson and Hornbeck (2013), consider a sample of about 2200 counties in the continental U.S. between 1870 and 1890, a period of rapid rail expansion. Donaldson and Hornbeck (2013) also perform a variant of the intercity regression, this time with county fixed effects, state-year fixed effects, and a cubic polynomial in latitude and longitude. The outcome variable of interest is the total value of a county's agricultural land.

Donaldson and Hornbeck (2013) find that counties treated with rail access in a year experience a 34% increase in aggregate agricultural land rent relative to others in the same state and year. If the share of agricultural land in production stays approximately constant during their study period then this implies the same effect on output, nominally larger than the corresponding estimate for India. With this said, the rate of growth in the U.S. was much higher during this period, so a rail link was equivalent to only about 7.5 years of economic growth, as opposed to more than 40 years for Indian districts.

Beyond the inclusion of county fixed effects and other controls, Donaldson and Hornbeck (2013) do not have a strategy to deal with the endogeniety of rail access in the specification discussed above. Instead, they conduct an alternative regression where the explanatory variable of interest is a measure of market access. Their measure of market access results from a model similar to the one we describe in section 3, and is well approximated by a 'gravity' measure of population, i.e., an inverse travel time weighted sum of county populations. They find that the effects of this measure are similar to those of the connection indicator. They also find that the effects of a restricted gravity measure, which excludes nearby counties, has a similar effect. That the two gravity measures have similar effects suggests that the effect of rail access on a county depends equally on rail access to places near and far.

Haines and Margo (2008) conduct a similar analysis to Donaldson and Hornbeck (2013). They consider a sample of 655 counties in 12 U.S. states and estimate the intercity regression in first differences. Their study period runs from 1850-1860, just before the 1870-1890 period that Donaldson and Hornbeck consider. They primarily consider the following outcome measures; share of urban population, agricultural wage, agricultural output per acre and improved acreage share. Their measure of rail access is an indicator variable describing whether or not a rail line passes through a county in a year. They find that rail access is associated with a 10% increase in the share of a county's improved acreage, a 3% increase in farm wages, no effect on output per improved acre, a small increase in service sector employment and a 4% decrease in agricultural employment. In spite of the fact that Haines and Margo (2008) consider many of the same counties as Donaldson and Hornbeck (2013), and that the two study periods are adjacent, these results are much smaller than those obtained by Donaldson and Hornbeck (2013).

Bogart (2009) uses a sample of about 3000 English parishes and townships between 1692 and 1798 to estimate the intercity regression in first differences. His dependent variable is land rent per acre. His measure of transportation is an indicator of whether a parish or township is close to a turnpike, an improved road maintained by tolls. He also conducts an instrumental variables variant of the first differences intercity regression, where he uses proximity to a major trade route as an instrument for the presence of a turnpike. This is a variant of the inconsequential places approach developed in Chandra and Thompson (2000). Bogart (2009) finds that a turnpike increases parish or township land rent by about 11% in first difference estimates and by about 30% in IV estimates.

Banerjee *et al.* (2012) use county level Chinese data to estimate the intercity regression with provincial and year fixed effects, and county level controls. They consider a sample of 310 Chinese counties for which they observe per capita GDP annually from 1986 until 2006, a period when Chinese road and rail infrastructure expanded dramatically. They also consider a census of firms for a larger set of counties in a smaller number of years. To measure infrastructure, Banerjee *et al.* (2012) construct a hypothetical network constructing 'treaty ports' to interior trading centers and use this network as an instrument. Again, this is a variant of the inconsequential places approach. Their measure of infrastructure is the distance from a county to a line in this hypothetical network, which predicts proximity to both railroads and major highways.

Since Banerjee *et al.* (2012) have one instrument and two endogenous dependent variables, proximity to railroads and highways, they cannot separately identify the effects of roads and railroads. Instead, they present the results of an intercity regression in which the measure of transportation access is distance to the hypothetical line. Therefore, as the authors acknowledge, these results are somewhat difficult to interpret. With this said, Banerjee *et al.* (2012) arrive at robust and interesting results. In particular, a 10% increase in distance to a 'line' causes about a 6% decrease in county GDP, and has no effect on the growth of income. They find that the gradient for the density of firms is slightly steeper and that proximity to a line has no effect, or possibly a small negative effect, on the growth rate of firm density.

Storeygard (2012) uses a sample of 287 small cities in sub-Saharan Africa between 1992 and 2008 to estimate a first differences variant of the intercity regression. This paper is innovative in two regards. First, it uses 'lights at night data' as a proxy measure for city GDP in small developing countries where data availability is limited.[21] Second, to generate time series variance in transportation costs he interacts constant network distances with a measure of the price of oil on international markets. As the author observes, the validity of this approach hinges on the claim that, conditional on controls, oil prices do not affect city lights except through transportation costs. Thus, more specifically, for a sample of 287 small cities, Storeygard (2012) estimates a variant of the intercity regression where the outcome of interest is a measure of average annual light intensity for constant boundary cities, the measure of transportation costs is the interaction of network distance with annual average oil prices, city fixed effects and variables to control for other possible channels through which oil prices might affect light intensity. Storeygard (2012) estimates that doubling the distance between a sample city and the primate port city causes about a 6% reduction in GDP, and that this is close to the effect of a quadrupling of fuel costs.

Jedwab and Moradi (2013) provide evidence on the intercity regression using rail construction in colonial Sub-Saharan Africa, where over 90% of African railroad lines were built before independence. Colonial railroads are found to have strong effects on commercial agriculture and urban growth before independence. A number of identification strategies are used to provide evidence that these effects are causal, including placebo lines that were planned but not built and a version of the inconsequential units approach. Furthermore, using the fact that African railroads fell largely out of use post-independence, due to mismanagement and lack of maintenance, the paper shows that colonial railroads had a persistent impact on cities. While colonial sunk investments (e.g., schools, hospitals and roads) partly contributed to urban path dependence, the evidence suggests that railroad cities persisted because their early emergence served as a mechanism to coordinate contemporary

[21] Henderson *et al.* (2012) pioneers the use of these data and show that they are highly correlated with national level GDP, a result that Storeygard (2012) confirms at the sub-national level.

investments for each subsequent period.

Faber (2014) also estimates a version of our intercity regression using a sample of about 1,300 rural Chinese counties that are more than 50km from a major city and that he observes in 1990, 1997 and 2006. For each county/year he observes county level GDP in three sectors; agriculture, industrial and services, as well as government expenditure. He also observes a rich set of county level controls. His measure of infrastructure is the distance from the county centroid to the nearest segment of the trunk highway network, the limited access highway network that was substantially constructed during Faber's study period. To resolve the probable endogeneity of the network placement he relies on two hypothetical networks, the first resembles the hypothetical network developed by Banerjee *et al.* (2012). The second describes the cost minimizing network to connect a set of major cities targeted by plans for the realized network. Faber (2014) finds that industrial GDP, total GDP and government revenue all *decrease* with proximity to the network. This result, which appears robust, is without precedent in the literature. Every other implementation of this research design we survey arrives at the opposite conclusion, that is, that transportation infrastructure attracts (or creates) economic activity.

Ghani *et al.* (2013) use the inconsequential units approach to estimate the intercity regression for "The Golden Quadrilateral project", which upgraded the quality and width of 5,846 km of roads in India. A difference-in-differences specification is used to compare non-nodal districts based on their distance from the highway system. Positive treatment effects are found for non-nodal districts located 0-10 km from the Golden Quadrilateral that are not present in districts 10-50 km away, most notably for higher entry rates and increases in plant productivity.

6 Discussion

6.1 Growth versus reorganization

Determining the extent to which the observed effects of infrastructure reflect changes in the level of economic activity versus a reorganization of existing activity is fundamental to understanding the effects of infrastructure and to policy analysis. The existing reduced form literature generally does not provide a basis for separately identifying the two effects. In spite of this, we can suggest some tentative conclusions about the contributions of growth and reorganization to the observed effects of infrastructure. These conclusions are based on comparisons between four sets of estimation results.

First, Duranton *et al.* (2014) examine the effect of within-city highways on the composition and value of intercity trade for U.S. cities. They find that an increase in within-city highways causes cities to become more specialized in the production of heavy goods, but has at most small effects on the total value of trade. Here, the primary effect of within city highways is to reorganize economic activity, not to create it.

Second, using the result in Baum-Snow (2007), Garcia-Lopez *et al.* (2013) and Baum-Snow *et al.* (2012), respectively, the effects of a one standard deviation increase in the number of radial highways causes central city population to decrease by 14%, 5%, and 17% where secular rates of city population growth were 72%, 30% and 55%. Thus, the transportation network causes reorganizations of cities that are large compared to forces affecting them. On the other hand, Duranton and Turner (2012) find that a one standard deviation increase in within city lane kilometers of interstate highways causes about a 15% increase in population over 20 years. Happily, the sample of cities and years considered by Baum-Snow (2007) and Duranton and Turner (2012) substantially overlaps. While the comparison is somewhat strained, it suggests that growth and reorganization are about equally important.

Third, Banerjee *et al.* (2012) conduct intercity regressions where the outcome variable is the level of GDP, and where it is the growth of GDP. They find that transportation infrastructure (really, their hypothetical network connecting treaty ports and interior trading centers) has important effects on the level of output, but not on its growth.

Fourth, and finally, Chandra and Thompson (2000) find that interstate highways increase firm earnings in U.S. counties treated with interstate highways at the expense of their untreated neighbors. Summing over the treated and untreated counties, they cannot reject the hypothesis of no change.

While our evidence here is fragmentary, it suggests two conclusions. First, within large cities, relocation of economic activity in response to transportation infrastructure is at least as important as the creation of economic activity. This conclusion is broadly consistent with current estimates of agglomeration effects: if output increases by 2% with each doubling of city size, then even if infrastructure can double population size, we will see only small increases in productivity. Second, for non-urban counties, the primary effect of treatment with highways or railroads is to attract economic activity at the expense of more remote areas, with some variation by industry.

6.2 The effects of transportation infrastructure on economic activity

6.2.1 Invariance across economies

Quite different data underlie the three decentralization papers. Baum-Snow (2007) considers a 40 year study period and a U.S. unit of observation with mean population around 160,000. Garcia-Lopez *et al.* (2013) considers a 20 year study period and a Spanish unit of observation with mean population around 120,000. Baum-Snow *et al.* (2012) consider a 20 year study period and a Chinese unit of observation with population near 4 million. In spite of this, the three studies find remarkably similar effects of highways on the decentralization of population from central cities to suburbs; 5% per ray in Spanish cities, 9% per ray for U.S. cities and 5% for Chinese cities. That the effect of radial highways on population decentralization is so nearly the same in such different contexts suggests that the effects of infrastructure are not sensitive to the scale of analysis or the details of the economies where the cities are located.[22]

Other comparisons bolster this proposition. First, Duranton and Turner (2011) and Hsu and

[22] It also suggests that the changes caused by radial highways may occur more rapidly than these 20 or 40 year study periods considered by extant research.

Zhang (2012) find, respectively, that a 1% increase in limited access highways in a metropolitan area increases driving by 1% in U.S. and Japanese metropolitan regions. Second, the effect of subways on land rent gradients appears to be about the same in suburban London as in Charlotte, North Carolina, while the effect of highway access on population density gradients appears similar in the U.S. and Spain.

Finally, with a few exceptions, there is broad agreement among the many papers that estimate the intercity regression: Chandra and Thompson (2000) find a 6-8% increase in firm earnings in counties adjacent on the interstate highway network; Michaels (2008) confirms Chandra and Thompson (2000) in the two industries where they overlap; Donaldson (2013) finds 17% higher real agricultural income for Indian districts with rail access; Haines and Margo (2008) find a 3% increase in farm wages for counties served by a railroad; Bogart (2009) finds an 11-30% increase in land rent for parishes served by a turnpike; Banerjee *et al.* (2012) find a 6% decrease in per capita income from doubling the distance to a hypothetical trade route and Storeygard (2012) finds a 6% decrease in city light intensity from doubling travel cost the primate city. Donaldson and Hornbeck (2013) and Faber (2014) are outliers, predicting a 34% increase in agricultural land rent for counties served by a railroad and a decrease in output for counties closer to highway.

Excluding Faber (2014), and ignoring the problem of comparing the gradient estimates of Banerjee *et al.* (2012) and Storeygard (2012) with discrete treatment effects in the others, these estimates are all within one order of magnitude.[23] Given the differences in the underlying economies that are the subject of these studies, this seems remarkable.

In sum, the literature suggests that transportation infrastructure has similar effects on the organization of economic activity across a range of countries and levels of development. More specifically: highways cause the decentralization of economic activity and an increase in its level in cities; highways cause a dramatic increase in driving; highways and railroads cause an increase in economic activity in rural areas near highways. This conclusion is subject to four caveats. First, there is some disagreement among papers estimating the intercity regression. Second, although the methods and data used in these papers are similar, they are not identical, so comparisons between them need to be regarded with caution. Third, as we note above, we do not have much basis for distinguishing growth from reorganization. Fourth, and finally, Duranton *et al.* (2014) and Duranton (2014) examine the effects of roads on trade in the U.S. and Columbia and find different effects.

6.2.2 Variability across activities and modes

While the literature surveyed above suggests a number of general results, it also provides suggestive evidence that different activities respond differently to changes in infrastructure. The three decentral-

[23] Banerjee *et al.* (2012) consider the effect of distance to a line, rather than an indicator for whether a line crosses a county. Therefore their results cannot be compared directly to results based on treatment indicators. However, an average county in their sample is approximately 2,000km^2, the area of a square about 45km on a side. Given this, doubling or quadrupling the distance from a county center to a line should usually be enough to remove an intersecting segment. This suggests that the effect of an indicator variable for line presence should be in the neighborhood of 6-12%.

ization studies, Baum-Snow (2007), Baum-Snow *et al.* (2012) and Garcia-Lopez *et al.* (2013) find that decreasing transportation costs leads population to migrate to the lower density periphery. Here, reductions in transportation costs reduce central city population density. Baum-Snow *et al.* (2012) finds that manufacturing decentralizes along with population.

Empirical results from the literature conducting intercity regressions also suggest heterogenous responses by industries. Chandra and Thompson (2000) finds different responses to the interstate highway access in rural counties by different sectors, a result confirmed in Michaels (2008). Haines and Margo (2008) finds a shift of land into agriculture and of employment into services with rail access in 19th century U.S. counties. Duranton *et al.* (2014) find that U.S. cities with more highways specialize in the production of heavier goods.

Finally, the gradient estimates in Banerjee *et al.* (2012) can be directly compared to within-city regressions estimating the effects of population density or land rent on proximity to a road, e.g., Baum-Snow (2007) and Garcia-Lopez *et al.* (2013). This comparison suggests a much steeper gradient for economic activity near rural highways than near urban highways.

Broadly, these studies support the claim that the weight per unit value of output, land share of production, and sensitivity to agglomeration are all economically important determinants of how a firm or industry responds to changes in transportation infrastructure. The literature is as yet too incomplete to provide much insight into the relative importance of these different factors. More speculatively still, highways may have larger effects on the organization of economic activity in rural areas than in cities.

6.2.3 Political economy of infrastructure allocation

As discussed above, a central issue in evaluating the effects of transport improvements is that these improvements are not randomly assigned. Implicit evidence on the process through which transport investments are assigned can be obtained by comparing the OLS coefficients for the inter and intracity regressions (which capture the impact of transport investments assigned through the existing political process) with the IV coefficients (which capture the impact of transport investments assigned through quasi-experimental variation). In Baum-Snow (2007) and Duranton and Turner (2012), IV estimates are larger in magnitude than OLS. This suggests that the equilibrium allocation process assigns roads to places growing more slowly than a randomly selected city. Baum-Snow *et al.* (2012) and Garcia-Lopez *et al.* (2013) find contrary results for China and Spain. Thus, conditional on the validity of their respective identification strategies, these papers point to implicit differences in the political economy of infrastructure funding across countries.

Further research is needed explicitly examining the political economy of transport infrastructure investments. Knight (2002) examines the U.S. Federal Aid Highway Program, over which the House Committee on Transportation and Infrastructure and the Senate Environment and Public Works Committee have jurisdiction. The paper finds evidence that measures of the political power of state delegations affect the allocation of funds, including a state's proportion of members serving on the transportation authorization committee, the proportion of a state's representatives in the majority party, and the average tenure of a state's representatives. Federal highway grants are found to crowd out state highway spending, leading to little or no increase in net spending.

6.3 General equilibrium effects

Generally, studies of the effect of infrastructure on the internal organization of cities do not consider the role of market access. This occurs despite the fact that market access is a component of the theoretical precursor of both the intercity and intracity regression equations. This appears to rest on the assumption, usually implicit, that cities are small open units and that we can examine changes in their internal structure and level of economic activity without reference to other cities. In fact, Duranton and Turner (2012) make this small open city assumption explicitly and attempt to test it by examining the effect on a target city of a change in roads in the nearest large city. While this is not a particularly satisfying test, that they find no effect suggests that ignoring interactions between cities while studying the effect of transportation infrastructure on their internal workings is reasonable.

The problem of market access merits two further comments. First, for the purpose of examining pairwise trade flows, Redding and Venables (2004) develop a framework which allows the explicit estimation of market access and variants of estimating equations (32) and (31) based on a two step estimation procedure. It is this framework that Duranton *et al.* (2014) apply to their investigation of the effect of the interstate highway system on pairwise trade flows between U.S. cities. Second, the extant empirical literature can be usefully divided into two classes. The first follows a long tradition of conducting city level regressions that assume implicitly (or explicitly in the case of Duranton and Turner (2012)) that cities can be regarded as independent units. In this framework, what happens in each city is pinned down by the utility level in a residual rural sector. This implies that what happens in one city does not affect what happens in others. The second follows the trade or new economic geography literature, e.g., Redding and Sturm (2008), and supposes that the interactions between cities are important. An interesting area for further research is reconciling these two different approaches.

6.4 Structural estimation, general equilibrium and welfare

The recent reduced form literature has made important strides in identifying causal effects of infrastructure on economic activity in rural regions. Specifically, this literature estimates changes in economic activity by industry and changes in population for cities and rural regions. We are just beginning to investigate whether different modes of transportation have different effects. With this said, the existing literature provides at most suggestive evidence on the extent to which the observed effects of infrastructure reflect the reorganization or creation of economic activity. Progress on this issue appears to, fundamentally require an econometric framework which is capable of dealing with general equilibrium effects such as the possibility that infrastructure moves activity from one unit to another.

In the remainder of this section, we discuss a number of studies that have used structural approaches to estimate intercity or intracity effects of transport infrastructure. These studies highlight four main advantages of a structural approach. First, as discussed above, this approach enables general equilibrium effects to be captured. Second, a structural approach allows for the estimation or testing of specific economic mechanisms. Third, the estimated model can be used to quantify aggregate welfare effects (as for example in Section 3.6). Fourth, the estimated model can be used to undertake counterfactuals and generate *ex ante* predictions for the effects of policies that have not yet been implemented (see for example Section 3.8).

We begin with intercity studies. Redding and Sturm (2008) use the division of Germany after the Second World War and the reunification of East and West Germany in 1990 as a natural experiment to provide evidence in support of a quantitative model of economic geography. As discussed above, in the aftermath of division, cities in West Germany close to the East-West German border experienced a substantial decline in population growth relative to other West German cities, and the estimated treatment effect is larger for small than for large cities. In a multi-region extension of the Helpman (1998) model, the treatment effect of division on border cities depends on two parameter combinations that capture (a) the strength of agglomeration and dispersion forces and (b) the elasticity of trade with respect to distance. For plausible values of these parameter combinations, the model can account quantitatively for both the average treatment effect of division and the larger treatment effect for small than for large cities. Smaller cities are more adversely affected by division, because they are disproportionately dependent on markets in other cities.

Donaldson (2013) combines a general equilibrium trade model with archival data from colonial India to investigate the impact of India's vast railroad network. The empirical analysis is structured around an extension of Eaton and Kortum (2002) to incorporate multiple agricultural commodities that shares some features with the theoretical framework developed in Section 3 above. This model delivers four key theoretical predictions that are taken to the data. First, for goods that are traded between regions, price differences between those regions can be used to measure bilateral trade costs. Second, the model yields a gravity equation for bilateral trade flows that can be used to estimate the response of trade flows to trade costs. Third, railroads increase real income levels, as measured by the real value of land income per unit area. Fourth, as in the theoretical framework developed above, each location's trade share with itself is a sufficient statistic for welfare. Consistent with these predictions of the model, there is a strong and statistically significant estimated effect of railroads on real income levels, but this effect becomes statistically insignificant after controlling for the model's sufficient statistic of a region's own trade share. These results provide evidence that the estimated effects of railroads are capturing the goods trade mechanism emphasized in the model.[24]

To quantity the intercity effects of road construction, Duranton and Turner (2012) develop a system of cities model that they use to derive a system of equations for employment and roadway

[24]Transport infrastructure may not only promote internal trade within countries (as considered here) but may also enable the interior regions of countries to participate in external (international) trade, as examined in Fajgelbaum and Redding (2013) using the natural experiment of Argentina's integration into the world economy in the late nineteenth century.

growth that can be estimated empirically. Utility in each city depends on the quality of amenities, consumption of a numeraire composite good, distance travelled and consumption of land. Productivity in producing the composite good is increasing in city employment through a standard agglomeration economy. The cost of travel per unit of distance is decreasing in the length of roadway and increasing in aggregate vehicle traffic through a standard congestion effect. Population mobility implies that utility in each city is equalized with utility in the outside alternative of a rural area. Equilibrium city size is determined by the willingness of residents to drive to the city center. Using equalization of utility between cities and rural areas, together with equilibrium in land and travel markets, equilibrium city employment can be expressed as a power function of the length of roadways. Specifying a partial adjustment process, according to which city employment growth is a function of the distance between a city's actual population and its equilibrium population, the model delivers the following equation for city employment growth:

$$n_{it+1} - n_{it} = A_1 + a r_{it} + \lambda n_{it} + c_1 x_i + \epsilon_{1it}, \tag{34}$$

where n_{it} is log employment in city i at time t; r_{it} is log roadway; x_i are controls for city characteristics; and ϵ_{1it} is a stochastic error. Specifying a similar partial adjustment process for road construction, we obtain an analogous equation for the city roadway growth:

$$r_{it+1} - r_{it} = A_2 + \theta r_{it} + \eta n_{it} + c_2 x_i + \epsilon_{2it}, \tag{35}$$

where ϵ_{2it} is a stochastic error. Equilibrium log roadway length is assumed to depend on log city population, the city characteristics controls, x_i, and instruments, z_i that satisfy the exclusion restriction of only affecting city population through roadways:

$$r_{it} = A_3 + c_3 n_{it} + c_4 x_i + c_5 z_i + \epsilon_{3it}, \tag{36}$$

where ϵ_{3it} is a stochastic error. The identification assumptions for instrument validity are:

$$c_5 \neq 0, \tag{37}$$

$$\mathrm{Cov}(z, \epsilon_1) = 0, \tag{38}$$

$$\mathrm{Cov}(z, \epsilon_2) = 0. \tag{39}$$

As discussed above, the instrumental variables estimates imply that a 10 percent increase in a city's stock of interstate highways causes about a 1.5 percent increase in its employment growth over 20 years. These instrumental variables estimates are somewhat larger than the OLS estimates. Therefore an additional kilometre of highway allocated to a city at random is associated with a larger increase in employment or population than for a road assigned to a city by the prevailing political process. These results are consistent with the view that the existing political process tends to assign highways to more slowly growing cities.

The intercity study of Desmet and Rossi-Hansberg (2013) highlights the way in which a general equilibrium model can be used to quantify the relative importance of different mechanisms and evaluate welfare effects. The paper develops a system of cities model that incorporates heterogeneity in productivity, amenities and congestion costs as determinants of city sizes. Congestion costs are modelled as depending on city-specific transport infrastructure. Data on U.S. metropolitan statistical areas (MSAs) are used to estimate these city characteristics and decompose the variation in city sizes into their contributions. All three characteristics are important for explaining the observed city size distribution. Eliminating differences across cities in any one characteristic leads to large population reallocations but has small welfare effects (population reallocations of as large as 40 percent can have welfare gains of as small as 2 percent). This pattern of results is consistent with the idea that welfare is approximately equalized across cities in the initial equilibrium, in which case the envelope theorem implies small welfare effects from population reallocations. In contrast, when the same methodology is applied to Chinese cities, eliminating differences across cities in any one characteristic leads to both large population reallocations and large changes in welfare. These contrasting results between the two countries are consistent with urban policies in China playing an important role in determining relative city sizes and aggregate welfare.

The intercity study of Allen and Arkolakis (2013) also uses a structural approach to quantify alternative economic mechanisms and evaluate welfare effects. The paper develops an Armington model of trade and factor mobility that incorporates both an economic and geographic component. The economic component combines the gravity structure of trade in goods with labor mobility to determine the equilibrium distribution of economic activity on a space with any continuous topography of exogenous productivity and amenity differences and any continuous bilateral trade costs. To incorporate the possibility of agglomeration and dispersion forces, the overall productivity and amenity in a location can endogenously depend on its population. The paper provides general conditions for the existence, uniqueness and stability of the spatial economic equilibrium. The geographic component of the model provides a micro foundations for bilateral trade costs as the accumulation of instantaneous trade costs along the least-cost route between locations. Combining these economic and geographic components, the model is used to estimate the topography of trade costs, productivities and amenities in the United States. Geographical location is found to account for at least twenty percent of the spatial variation in U.S. income. The construction of the U.S. interstate highway system is estimated to increase welfare by 1.1-1.4 percent, which is substantially larger than its cost.

We now turn to intracity studies. Until recently, theoretical models of internal city structure were highly stylized, which limited their usefulness for empirical research. Much of the theoretical literature has focused on the monocentric city model, in which firms are assumed to locate in a Central Business District (CBD) and workers decide how close to live to this CBD.[25] Lucas and Rossi-Hansberg (2002) were the first to develop a model of a two-dimensional city, in which equi-

[25] The classic urban agglomeration models of Alonso (1964), Mills (1967) and Muth (1969) impose a monocentric city structure. While Fujita and Ogawa (1982) and Fujita and Krugman (1995) allow for non-monocentricity, they model one-dimensional cities on the real line.

librium patterns of economic activity can be nonmonocentric.[26] In their model, space is continuous and the city is assumed to be symmetric, so that distance from the center is a summary statistic for the organization of economic activity within the city. Empirically, however, cities are not perfectly symmetric because of variation in locational fundamentals, and most data on cities are reported for discrete spatial units such as blocks.[27]

To address these challenges, Ahlfeldt *et al.* (2012) develop a quantitative theoretical model of internal city structure that allows for a large number of discrete locations within the city that can differ in their natural advantages for production, residential amenities, land supply and transport infrastructure. The model remains tractable and amenable to empirical analysis because of the stochastic formulation of workers' commuting decisions that follows Eaton and Kortum (2002) and McFadden (1974). The city is populated by an endogenous measure of $\bar{H}$ workers, who are perfectly mobile within the city and larger economy. Workers experience idiosyncratic shocks to the utility they derive from each possible pair of residence and employment locations within the city. Workers choose their residence and employment locations and consumption of residential land and a tradable final good to maximize their utility. This idiosyncratic formulation of utility yields a gravity equation for bilateral commuting flows:

$$\pi_{ij} = \frac{T_{ij}\left(d_{ij}Q_i^{1-\beta}\right)^{-\epsilon}\left(B_i w_j\right)^{\epsilon}}{\sum_{r=1}^{S}\sum_{s=1}^{S} T_{rs}\left(d_{rs}Q_r^{1-\beta}\right)^{-\epsilon}\left(B_r w_s\right)^{\epsilon}}, \tag{40}$$

where T_{ij} is a Fréchet scale parameter that determines the average attractiveness of the bilateral commute from residence location i to employment location j; d_{ij} is the iceberg cost in terms of utility of commuting between i and j; Q_i is land prices; B_i denotes amenities at residential location i; and w_j denotes wages at employment location j.

In this setting, transport technology influences the organization of economic activity within the city through the matrix of bilateral commuting costs d_{ij}. Both residential amenities (B_i) and final goods productivity (A_j which determines w_j) are characterized by agglomeration economies and hence depend on the transport technology through the endogenous employment distribution. Ahlfeldt *et al.* (2012) use the division and reunification of Berlin as an exogenous shock to structurally estimate the strength of the model's agglomeration and dispersion forces and to show that the model can account quantitatively for the observed changes in city structure. The model also provides a framework that can be used to analyze the effects of other public policy interventions, such as transport infrastructure investments that reduce commuting costs d_{ij} between pairs of locations.

Another structural intracity approach is Combes *et al.* (2012), which develops a methodology for estimating congestion costs (which depend on transport technology) using land transactions data. The key insight behind this methodology is that residential mobility implies that urban (dis)amenities and commuting costs are ultimately reflected in land prices. A system of cities model is developed,

[26] For an analysis of optimal urban land use policies in such a setting, see Rossi-Hansberg (2004).

[27] For empirical evidence on the extent to which the organization of economic activity within cities is indeed symmetric, see Brinkman (2013).

in which each city is monocentric and workers face costs of commuting to the Central Business District (CBD). The model highlights that the elasticity of urban costs with respect to city population is the product of three quantities: the elasticity of unit land prices at the city centre with respect to population, the share of land in housing, and the share of housing in consumption expenditure. Implementing this methodology, the paper's preferred estimates for these three elasticities are 0.72, 0.25 and 0.23 respectively. Taking the product of these three parameters, the preferred elasticity of urban costs with respect to city population is 0.041, which is close to existing estimates of agglomeration economies in the form of the elasticity of city productivity with respect to city population. This finding that cities operate near aggregate constant returns to scale suggests that the fundamental trade-off of spatial economics – between agglomeration economies and congestion costs – may play only a limited role in explaining the observed distribution of city sizes. This prediction is in turn consistent with the observation that cities of vastly different sizes exist and prosper.

7 Conclusion

To determine the causal effect of infrastructure on the spatial organization of economic activity, the central inference problem that researchers must overcome is that infrastructure is not assigned to locations at random, but rather on the basis of many of the same unobserved location characteristics that affect economic activity. The recent empirical literature is organized around three main approaches to this problem, planned routes IV, historical routes IV and the inconsequential places approach. While these approaches remain open to criticism and refinement, they are about as good as can be hoped for in an environment where experiments seem implausible.

This literature suggests a number of tentative conclusions about the effects of infrastructure. Most studies estimate that population or employment density falls between 6 and 15% with a doubling of the distance to a highway or railroad (where railroads are the primary mode of transportation). Highways decentralize urban populations, and with less certainty, manufacturing activity. They may also lead to a complementary concentration of services. Different sectors appear to respond differently to different modes of transportation and people respond differently than firms. The effects of infrastructure seem similar across countries at different stages of development.

While much effort has been directed to unraveling the problem of non-random assignment of infrastructure to places, much less has been directed to distinguishing between growth and reorganization. This distinction is clearly central to any understanding of the role of infrastructure and transportation costs in an economy. We suggest two approaches to resolving this problem. The first is a two equation generalization of the current single equation reduced form models. The second relies on our structural model to resolve this problem. With this said, the literature does suggest that much of the estimated effect of transportation costs and infrastructure on the spatial organization of economic activity is probably due to reorganization rather than growth. Refining our understanding of this issue seems an obvious place for further research.

In addition to the largely reduced-form literature currently available, structural models of transportation costs and the spatial organization of economic activity are beginning to appear. Structural models have the important advantage of allowing for estimates of general equilibrium effects, such as the migration of economic activity in response to changes in transportation costs, on the basis of theoretically founded estimating equations. They also have obvious advantages for welfare and counterfactual analysis: available results suggest the importance of the 'share of trade with self' as an indicator of welfare. With this said, there is disagreement in the literature on fundamental assumptions underlying these models. In particular, whether we should think of cities as drawing people from the countryside or as competing with cities other for residents. Resolving this issue appears to be an important prerequisite for further progress.

Finally, the existing literature has devoted little attention, empirical or theoretical, to the dynamics of how transportation infrastructure affects economic development. In particular, there are few panel data studies conducting impulse response estimates. This seems to be an important, though difficult area for further research.

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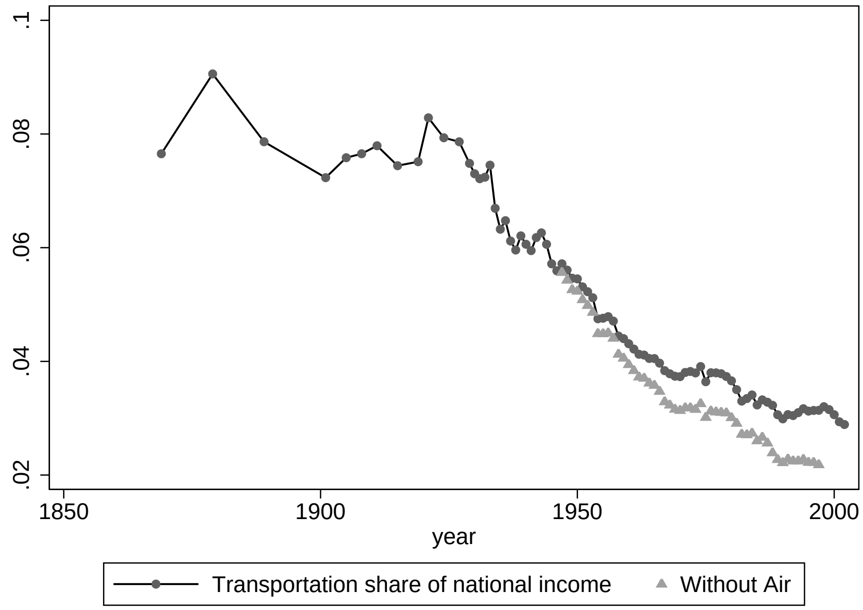


Figure 1: Share of Transport Sector in U.S. GDP. *Notes: Source is Department of Commerce (since 1929), and Historical Statistics of the U.S. (Martin Series) before then.*

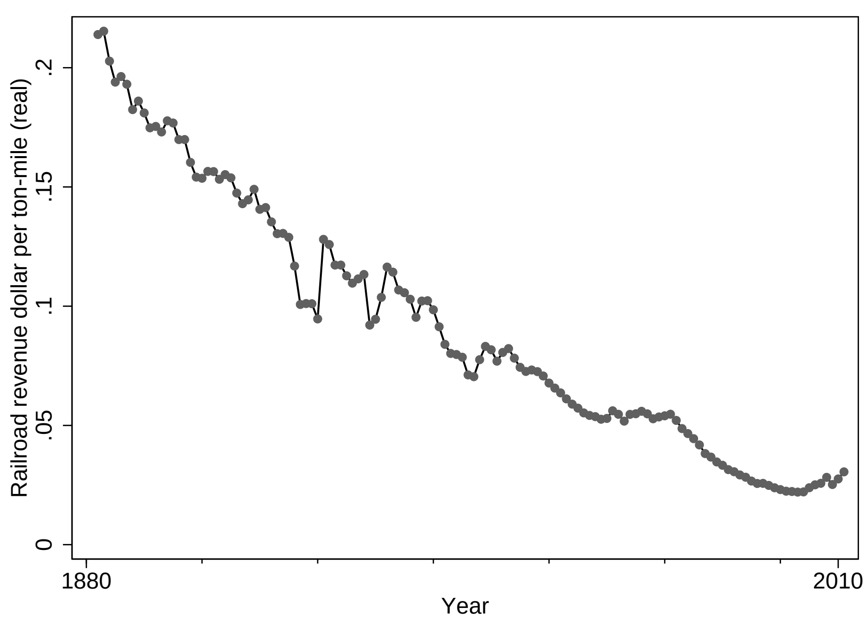


Figure 2: The Costs of Railroad Transportation over Time. *Notes: Source is Historical Statistics of the* U.S. *(until 1970), 1994, Bureau of Transportation Statistics Annual Reports 1994 and 2002.*

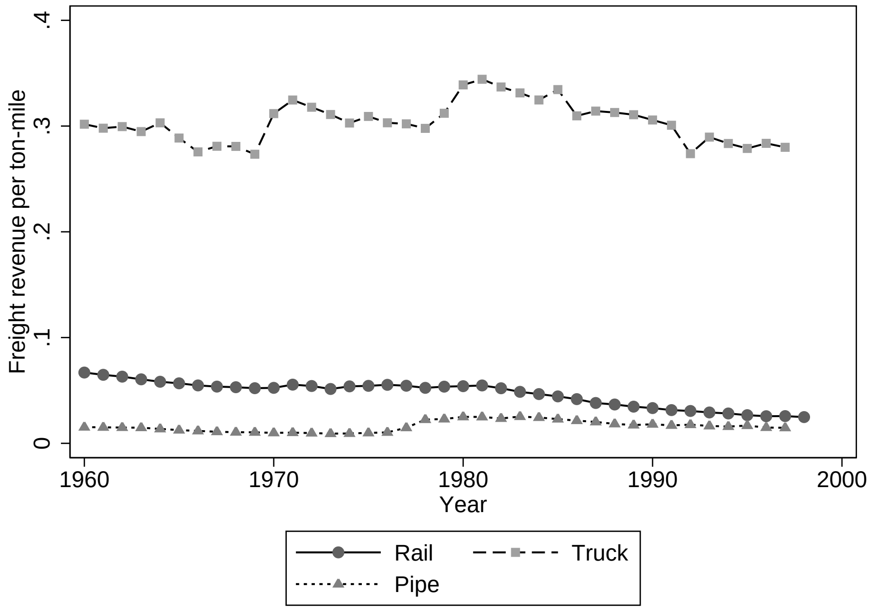


Figure 3: Revenue per Ton Mile (All Modes). *Notes: Source is Bureau of Transportation Statistics Annual Reports.*

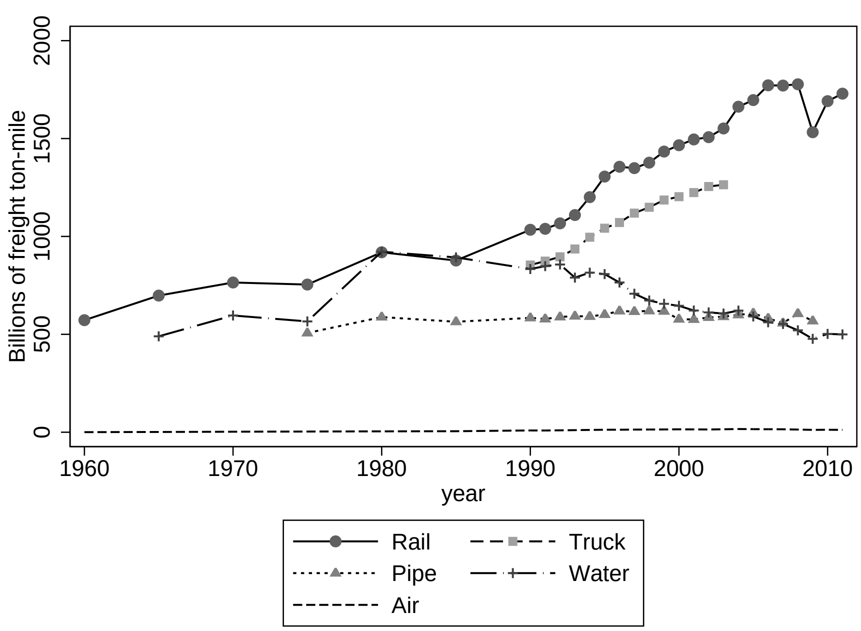
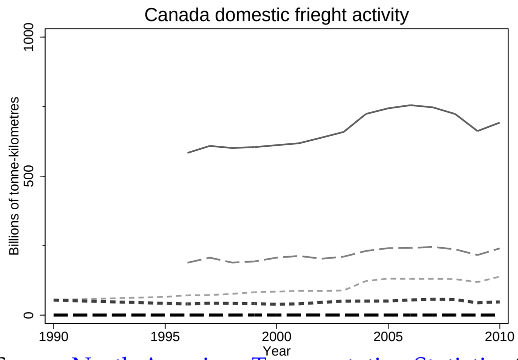
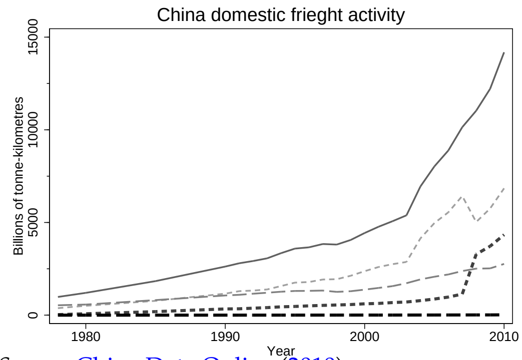


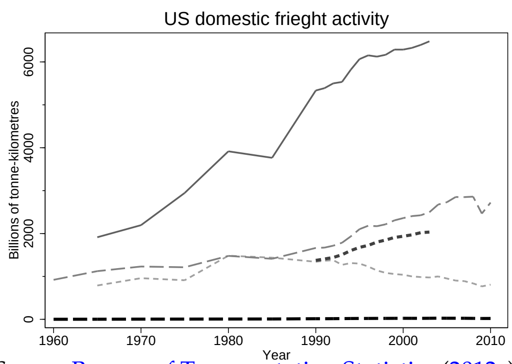
Figure 4: Ton Miles of Freight over Time. *Notes: Source is Bureau of Transportation Statistics Annual Reports*



Source: North American Transportation Statistics (2012*a*)



Source: China Data Online (2010)



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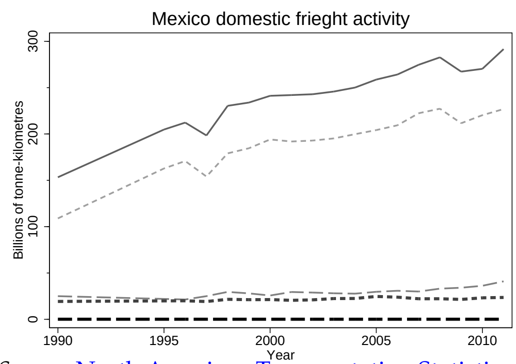

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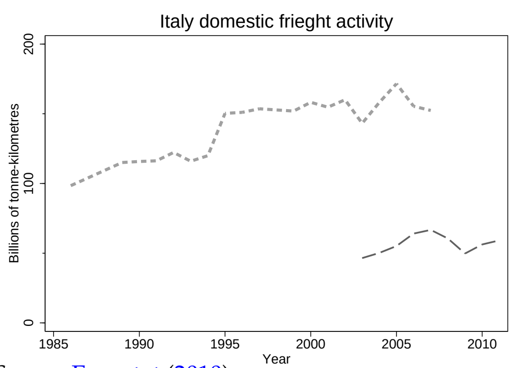
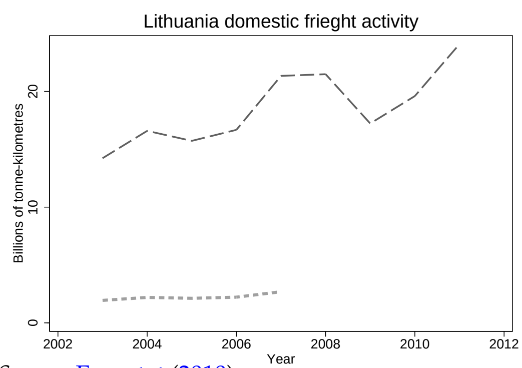


Source: Eurostat (2010)



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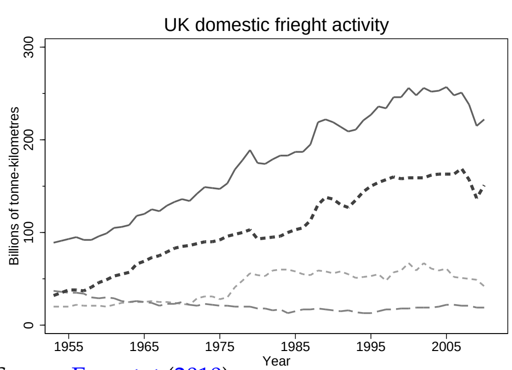

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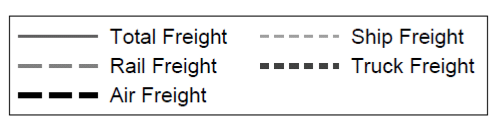
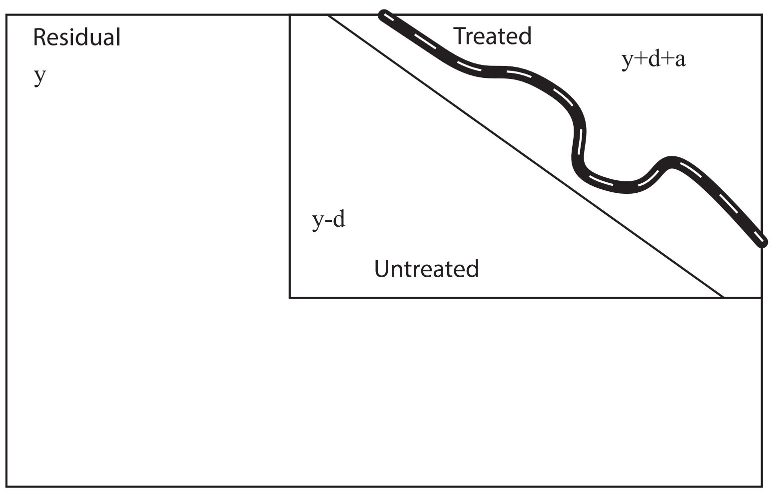


Figure 5: Ton km of freight by year and mode for several countries.

Figure 6: A simple hypothetical sample.



	Total	Ship %	Air %	Truck %	Rail %
Austria	279	13	8	70	7
Belgium	750	26	14	44	2
Bulgaria	48	38	4	50	7
Canada	798	19	11	47	12
Cyprus	10	83	16	0	
Czechrepublic	194	2	5	82	9
Denmark	186	24	8	11	0
Estonia	24	34	4	34	10
EU27	10261	29	12	32	2
Finland	169	69	15	12	4
France	1105	25	11	9	0
Germany	2231	27	14	37	3
Greece	106	57	7	33	1
Hungary	164	1	10	75	9
Ireland	198	45	31	11	0
Italy	1003	40	9	36	3
Latvia	21	18	3	45	14
Lithuania	38	29	3	56	12
Mexico	554	24	6	56	8
Netherlands	995	27	9	39	1
Poland	259	17	3	55	9
Portugal	119	37	7	52	0
Romania	101	25	2	13	3
Slovakia	96	13	4	60	12
Slovenia	56	16	3	64	4
Spain	615	45	7	44	2
Sweden	313	25	10	15	1
UK					
US	3116	45	25	18	4

Table 1: Shares of total international trade by country and mode. Total trade for European countries are in Billions of Euros, the others are in Billions of $US. Sources: North American Transportation Statistics (2012*b*), Eurostat (2012).

Country	Year	Total emp.	All Trans %	Air %	Rail %	Truck %	Ship %
Canada	2002	13	3.56	.44	.28	1.29	.09
Mexico	2003	35	5.75	.06	.04	2.75	.03
US	2003	130	3.22	.41	.17	1.02	.04

Table 2: Employment in for hire transport as share of total employment. Total employment is in million of people, all others are percentage of total. Sources: North American Transportation Statistics (2012*c*), Bureau of Transportation Statistics (2012*b*).

	1980-4	1990-4	2005-9	2010-2	
Austria			35		
Belgium			41		
Canada		54	59	63	52
Denmark			38		
Finland			41		
France			36		
Germany			42		
Greece			32		
Ireland			36		
Italy			30		
Luxembourg			35		
Netherlands			47		
Portugal			29		
Spain			38		
Sweden			38		
UK			37	53	
US	43	45	51		50

Table 3: Roundtrip commute times in minutes, by country and year. Sources: Statistics Canada (2010), Turcotte (2005), Eurofound (2000), Office of National Statistics (2009), Census Bureau (2009).

	1990-4	1995-9	2000-4	2005-9	2010-2
Austria		15	14	16	
Belgium	10	10	13	12	
Bulgaria			23	12	
Canada				15	14
China(rural)	1	3	6	10	10
China(urban)	1	5	9		14
Croatia				13	
Cyprus			23	16	
Czechrepublic			26	19	
Denmark		12	11	10	
Estonia			13	16	
Finland		12	14	13	
France	15	13	13	13	
Germany	11	13	12	13	
Greece	12	12	14	12	
Hungary			25	23	
Ireland		14	14	9	
Italy	14	15	15	12	
Latvia			15	19	
Lithuania			17	15	
Luxembourg	12	14	15	16	
Macedonia				16	
Malta			19	25	
Mexico					21
Netherlands	9	9	11	11	
Norway				13	
Poland			19	13	
Portugal	27	23	21	15	
Romania			17	12	
Slovakia			24	15	
Slovenia			26	21	
Spain	14	14	15	12	
Sweden		11	10	12	
Turkey				16	
EU27				13	
UK					14
US				18	16

Table 4: Percentage of household expenditure on all modes of transportation by year and country. Sources:Statistics Canada (2012), China Data Online (2011), Eurostat (2009), OECD Stat Extracts (2012), Bureau of Labour Statistics (2012).

Country	Total Mt CO2e	Transport %	Rail %	Truck %	Ship %	Air %
Canada	561	32	1.32	24.34	1.69	3.14
Mexico	456	35	.42	32.53	.57	1.43
UK	529	29	.87	25.81	2.38	7.24
US	5829	33	.89	27.72	.95	2.96

Table 5: 2007 Carbon dioxide emissions from transportation and shares by mode. Sources: Natural Resources Canada (2012), North American Transportation Statistics (2012*d*), Department for Transport (2012).