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Trade and the Spatial Distribution of Transport Infrastructure*

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Preliminary and incomplete draft, comments welcome

Abstract

This paper endogenizes the spatial distribution of infrastructure investment and transportation costs. Transportation costs between two addresses depend on cumulative infrastructure investment. In a continuous space setting with several independent countries or regions, consumers demand domestic and foreign goods, while central planners care only about welfare of their own constituencies. The equilibrium of the game between countries features under-investment and excessive spatial variation. The distribution of infrastructure is skewed towards central regions, rationalizing the non-linear trade-impeding role of distance in empirical gravity models and the so called border puzzle. We find that the endogenous allocation of infrastructure investment magnifies small discrete border frictions and creates ‘border regions’ within countries. Privatizing infrastructure provision does not solve the problem. French data on transportation costs and an empirical gravity model for trade between US states motivate and corroborate our theory.

JEL Codes: F11, R42, R13

Keywords: Economic Geography, International Trade, Infrastructure Investment, Border Effect Puzzle.

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1 Introduction

Trade costs play a crucial role in the modern empirical and theoretical trade literature, in models of economic geography, or in international macroeconomics. They are responsible for a wide range of results related to the home market bias, the core-periphery pattern, or real exchange rates (see the surveys by Feenstra, 2004; Obstfeld and Rogoff, 2000; Fujita, Krugman, and Venables, 1999). Trade costs come in many guises: they comprise “all transport, border-related, and local distribution costs” (Anderson and van Wincoop, 2004). One major challenge in recent research is to account for the large empirical role of border effects that can only be partially be explained by standard trade policy.

Transport costs are usually related to geographical distance while the border effect is attributed to some lumpy cost that materializes when crossing a border. This dichotomy of variable and fixed costs enjoys empirical support, see Anderson and van Wincoop (2003). The latter authors estimate that the US-Canadian border reduces international trade relative to intranational trade by a factor of 4.7.¹ Explanations for fixed border costs abound. Among other things, they are related to informational costs (Casella and Rauch, 2003), contract enforcement costs (Anderson, 2003), exchange rates (Rose and van Wincoop, 2001). Surprisingly, border effects exist also *within* countries, where the above explanations do not help.² In this paper, we argue that there need not be any explicit cost related to crossing the border for a border effect to appear in empirical trade flow models. The reason is that rational planners find it optimal to underprovide infrastructure investments in geographical areas that are peripheral to their respective legislative territories. This implies that overcoming geographical distance is more costly when a different legislative regions are involved and trade flows cross political borders.

¹Prior to Anderson and van Wincoop (2003), McCallum (1995) compares trade flows within Canada to flows between Canadian provinces and U.S. states, controlling for distance and regional GDPs. Everything else equal, crossing the border reduces trade by a factor as high as 22. For Europe, Nitsch (2000) finds that on average intranational trade is about 10 times higher than international one. Nitsch arrives at his results after controlling for cultural proximity (language), along other conventional gravity covariates. Wei (1996) constructs measures for imports of countries to themselves and compares this with imports from a statistically identical foreign country. He finds that the former magnitude is 2.5 times larger than the latter. Helliwell (1998) offers a comprehensive overview of the pre Anderson and van Wincoop state of the econometric literature. Evans (2003) decomposes cross-country price differences of traded goods into a component due to distortions and a component driven by consumer preferences. She demonstrates that the preferences effect is relatively important quantitatively. Obstfeld and Rogoff (2000) have cited this fact as a major puzzle in international macroeconomics.

²Okubo (2004) shows a border effect for trade between Japanese regions, Wolf (2004) for the US, and Combes et al. (2005) for their sample of French departments.

The reasoning behind this key result is the following. Each region's social planner cares only about utility of domestic agents. However, consumers demand goods from all possible locations. Hence, investment at any location improves the utility of all consumers in the world. Since regional social planners are assumed to behave in a non-cooperative way, they fail to internalize the effect of their infrastructure investment decisions on consumers other than those residing in their political constituency. This behavior leads to global infrastructure *under-investment*. It also biases investment within countries towards central regions since the average domestic consumer benefits more from central than from peripheral investment. The *excessive spatial variation* of infrastructure investment gets further exacerbated by small discrete border frictions which induce a redistribution of spending towards central regions. Our results follow from the fundamental separation between political and economic space, the former being regional, the latter global in scope.

There are only few recent papers that study the effect of transport infrastructure on trade costs and welfare. Limao and Venables (2001) find that up to 60 percent of the cross-country variation in transport costs is due to differences in the quality and quantity of transport infrastructure. Moreover, Venables (2005) argues that infrastructure explains a larger share of spatial income inequality than sheer geography, while the latter certainly is a determinant of the former. Finally, Bröcker (1998) shows that pan-European transport infrastructure projects have important implications for spatial inequality. Those papers have in common that infrastructure is taken as exogenous and that countries (or regions) do not have a geographical extension. The present paper relaxes these assumptions.

Modeling endogenous infrastructure decisions in a spatial world is worthwhile in its own right, since it leads to interesting economic policy issues relating to the efficient provision of transport infrastructure. However, the excessive spatial variation of infrastructure investment that results from the political economy process may help towards an explanation of the border puzzle. Empirically, anecdotal and more rigorous econometric evidence both suggest that trade costs are larger whenever border regions are involved. For example, Combes and Lafourcade (2005) document a strong core-periphery pattern of real trade costs for France. This pattern cannot be explained by variation in topology alone, suggesting systematic core-periphery pattern in the quality and quantity of infrastructure investment.

The present paper is related to literature that jointly considers international and intranational aspects of trade. Courant and Deardorff (1992) emphasize the importance of trade *within* countries for trade patterns across countries. New economic geography models also discuss inter-country dynamics in the context of globalization. An important example of such a paper is

Rossi-Hansberg (2005), who studies the effects of small border costs on the regional distribution of workers within a country. He then assesses the implications of the equilibrium population distribution on intra- versus international trade flows. However, his focus is not on infrastructure investment. Transport economists have a tradition to evaluate the effects of regional transport infrastructure projects in the context of international trade; however, there does not seem much work that both endogenizes the spatial distribution of infrastructure along with its economic implications.

Formally, a close cousin of the present paper is the *racetrack* model of Fujita et al. (2001, ch. 6 and 17).³ In that model, space is continuous, just as in the proposed setup. However, the two approaches differ in focus. The racetrack model endogenizes the distribution of manufacturing labor across space under conditions of increasing economies of scale. It does not say anything on the endogenous spatial distribution of the stock of transport infrastructure, nor does it shed light on how that stock shapes transport costs. In the proposed setup, production technologies exhibit constant returns to scale, and the distribution of workers is exogenous. In turn, transport costs are endogenous. While the proposed model can be generalized to allow for increasing returns to scale and worker mobility, excluding these elements makes the model straightforward to analyze. Essentially, in the conventional economic geography setup it is worker mobility that drives regional differences, in the present framework it is the infrastructure investment decisions of central planners.

The paper contributes to the literature along three dimensions: First, while maintaining the basic iceberg trade cost assumption, we propose a plausible and tractable formulation of transportation costs as a function of *cumulative* infrastructure investment. This requires modeling regions (or countries) as having some spatial extension themselves.⁴ Second, governments implement their preferred infrastructure allocations across space separately for their specific spatial reach. Hence, transport costs are endogenous. Governments turn out to invest too little in border regions, therefore generating a border effect even in absence of formal and informal trade barriers, and exacerbating it in their presence. Finally, the paper presents tentative supportive evidence based on data for US states.

The structure of the paper is as follows. Section 2 presents some stylized facts on the transportation sector that inform our modeling choices. Section 3 presents and defends our

³The racetrack model is discussed also as the ‘seamless world model’ (Krugman and Venables, 1997).

⁴Much of the economic geography literature (Fujita et al., 1999) and almost all new trade models do not explicitly model the spatial extension of countries. The global economy is assumed to be a collection of countries each modeled as points without spatial extension of their own.

formulation of the mapping between the spatial distribution of infrastructure investment and transport costs. Section 4 sets up the general equilibrium environment which motivates intra- and international trade and analyzes the optimal infrastructure investment schedule in a closed economy. Section 5 moves to a setting of two symmetric open economies and derives our core results on the endogenous emergence of border regions. Section 6 discusses tentative evidence. Finally, section 7 discusses several extensions while section 8 concludes.

2 Stylized facts

This section shows, for the case of France, that the spatial distribution of transportation costs exhibits variation difficult to explain with geographical and demographic determinants. It briefly discusses established stylized facts on the provision of public transport infrastructure and how those can be used in explaining spatial patterns in infrastructure investment.

2.1 The spatial distribution of transport costs

The world is not flat. Geographical obstacles such as mountains, rivers or swamps, affect the ease at which goods and people move across space. Since the most ancient civilizations, states have invested heavily in infrastructure projects to overcome geographical distance more efficiently. While military objectives have often been looming large, interregional exchange of goods always played an important role, too. Hence, there is little doubt that—along obvious geographical factors—government actions have a bearing on the spatial distribution of infrastructure, too.

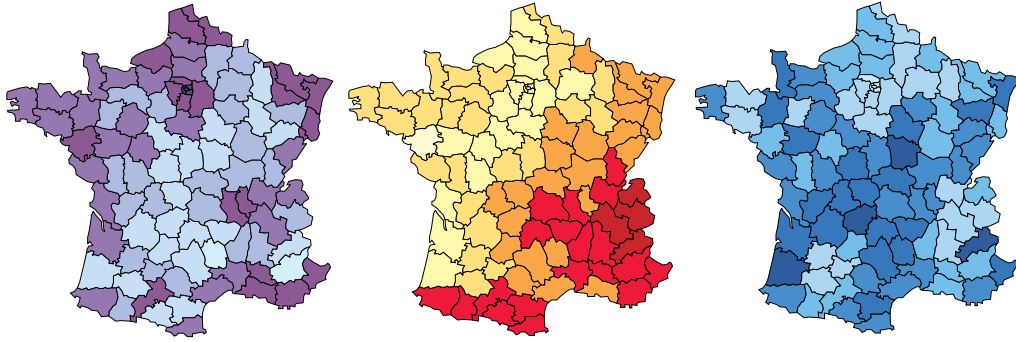
The stock of transport infrastructure investment is very difficult to measure, and there are virtually no data to carry out spatial comparisons. Hence, a more indirect approach is required. For instance, one can see to what extent geographical variables explain variation in variable transportation costs across regions and interpret the residual as shaped by the quality of transport infrastructure investment.

Reliable data on transportation costs is difficult to obtain. However, Combes and Lafourcade (2005) provide estimates of transportation costs across French *départements* for the year of 1998. These data are particularly interesting, because the authors adopt a comprehensive perspective on transportation costs. They report the total cost of transporting a standardized container by standardized truck from one departemental capital to another. They take account of the cost of fuel, truck depreciation, tire use, the wage bill and accommodation costs of the truck driver(s), road tolls, taxes, and insurance costs. For the purpose of the present paper, we look at variable costs, thereby excluding expenses related to the loading and unloading of the truck.

Combes and Lafourcade use their data to calculate measures of average remoteness of regions, i.e., the average cost to reach some place from the rest of France. Not surprisingly, they document a strong core-periphery pattern. In the present context, we are more interested in the spatial gradient of transportation costs. We use the Combes-Lafourcade data data to construct a proxy of the *incremental* trade costs per kilometer of transiting through a département. The Appendix contains the details on the construction of that proxy.

It turns out that the spatial variation in the variable cost of overcoming one unit of distance is not constant over space. Per kilometer costs of overcoming one kilometer of distance are on average 4.79 French Francs. The associated standard deviation is 2.77.

Figure 1: Population density, difficulty of territory, and variable trade costs per km in France



Notes. Source of data is Combes and Lafourcade (2005). Left figure: population density; middle figure: difficulty (ruggedness) of territory; right figure: variable trade costs (transit costs) per km. Shading grows darker as respective values rise

Figure 1 plots the density of population (population per square kilometer), a measure of the geographical difficulty of territory (defined in the Appendix), and average variable transportation costs incurred by transiting a département (also defined in the Appendix). Not surprisingly, population density is highest in the Paris region (about 20,000 inhabitants per square kilometer in Paris intra-muros, and somewhat lower in the closer Parisian neighborhood (Île de France). Regions with strong urban conglomerations, such as the Lille or Lyon regions (départements Nord and Rhône, respectively) have densities of 450. Départements in border regions have above average values, while interior départements have densities below average.⁵ Our measure of difficulty of territory is based on the difference between the highest and the lowest altitude

⁵The average density is about 105 inhabitants per kilometer.

above sea level in a département. This measure is naturally high in départements that in the Alps, the Pyrenees, or the Massif Central. It is low in coastal areas or along large rivers (e.g., the Loire valley).

The rightmost panel of 1 shows transportation costs per kilometer. There is no strong observed association of transportation costs to geographical or demographic features. However, costs tend to be low when the territory is easy or the population density is high. Transportation costs are lowest in the Paris or Lyon region. However, they are also low in the strongly populated North-West.⁶

Table 1 reports the results of simple regressions that attempt to explain the pattern of transportation costs across space. Column (1) shows that the geographical difficulty of territory explains about 15 percent of the variance in transportation costs. Column (2) adds population and land surface to the regression. This effectively accounts for the role of population density. As expected, an increase in density reduces the variable transportation costs. Moreover, the R-squared of the regression surges to 54 percent.

Columns (3) to (6) include different measures of the overall remoteness of geographical units. Depending on the variable included, the R-squared of the regression increases to up to 60 percent. Moreover, regardless of the exact measure of remoteness, transiting more remote regions is significantly more costly, holding geographical and demographic factors constant. *Ceteris paribus*, changing the remoteness measure from its lowest to its highest sample realization increases transport costs by 3.4 to 18.4 percent.

2.2 On the determination of transport costs

Next, we turn to some important stylized facts on the provision of transport services. Unfortunately, data is more easily available for the US than for Europe. Hence, the following draws on US data. When available, European data tends to look comparable.

Fact 1: Infrastructure investment explains transport costs well. Limao and Venables (2001) run regression analyses on several data sets to explain measured trade costs as a function of infrastructure investment and other determinants. They find that about 60% of the variation in transportation costs can be explained by cross-country differences in the quantity and quality of infrastructure. They conclude that transport infrastructure is quantitatively more important in explaining transportation costs than sheer geography.⁷

Fact 2: Intracontinental trade flows are mostly land-borne. Since the border puzzle appears

⁶Note that there is no transportation data for Paris intra-muros.

⁷See also Venables (2005).

Table 1: Different remoteness measures and average transit costs

Dep. var.: Ln variable transport costs per km for transits through a département						
	(1)	(2)	(3)	(4)	(5)	(6)
			Ln distance (km) to Paris	ln GTC to Paris	ln GTC remoteness	ln weighted GTC remoteness
Remoteness			0.175*** (0.064)	0.491*** (0.014)	0.485* (0.025)	0.983** (0.043)
Ln population		-0.040*** (0.012)	-0.034*** (0.012)	-0.027** (0.011)	-0.042*** (0.013)	-0.040*** (0.012)
Ln area (km ²)		0.094*** (0.011)	0.084*** (0.011)	0.065*** (0.012)	0.092*** (0.011)	0.088*** (0.011)
Ln geography	0.410*** (0.130)	0.210** (0.077)	0.096 (0.099)	0.105 (0.092)	0.040 (0.090)	0.029 (0.095)
Constant	1.590*** (0.22)	1.363*** (0.22)	1.253*** (0.20)	1.119*** (0.18)	0.939** (0.46)	1.295*** (0.21)
N	94	94	94	94	94	94
$adj.R^2$	0.15	0.54	0.57	0.60	0.54	0.56
$F - stat.$	10.06	44.45	44.65	61.82	35.42	41.06
RMSE	0.097	0.072	0.069	0.067	0.072	0.070
Robust standard errors in parentheses, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.						

in trade within the European Union, NAFTA, or Japan, it is natural to take a brief look at the relative prevalence of intercontinental transport modes. Table 2 reports data for within NAFTA trade in 2001. It appears that two thirds of the value of total trade flows between NAFTA member states is transacted by means of trucks. Total land-borne traffic amounts to about 83 percent of the total value of trade. Hence, while the share of air-borne traffic is certainly increasing, it is not prevalent. Not surprisingly, in terms of quantities, water-borne traffic appears relatively important, reflecting the low unit-value of bulky goods transported by that mode.⁸

Fact 3: The public input into the provision of transportation services is important. According to the Bureau of Economic Analysis, in the US, public gross investment plus government consumption spending on transportation goods amount to about 9.4 percent of total government spending (across all levels of government) or 1.8 percent of GDP in 2004. Private gross fixed investment in transport equipment (this excludes cars used for private use) is 1.3 percent of GDP.⁹ Hence, albeit the fact that private and public investments into transportation goods

⁸Combes and Lafourcade (2006) note that, "in Europe, around 72% of trade volumes are shipped through the road network (against around 15% for rail, 8% for pipers and 5% for rivers)" (p. 324), which roughly corresponds to the North American pattern.

⁹NIPA tables 1.15 and 3.155.

Table 2: US trade with NAFTA countries by mode

Percent of total merchandise trade, 2001		
	Value	Quantity
Truck	67.3	36.6
Rail	15.8	19.7
Air	6.3	0.1
Water	5.0	43.4
Other	5.6	0.2
Pipeline transport excluded.		
Source: Bureau of Transportation Statistics.		

differ dramatically in terms of their nature, they are both quantitatively significant and comparable in size.

Whether publicly provided transport infrastructure is financed through taxes or through user fees such as the road tolls does not matter for the present argument as long as planners have discretion on where to invest toll receipts; see below. Data collected by the Bureau of Transport Statistics indicates that toll revenue finances only a small fraction of total public transport infrastructure spending in the US.

Fact 4: Regional governments influence interregional infrastructure projects substantially. All levels of government contribute towards spending on transport infrastructure and equipment. However, in the US, spending falls predominantly on the local or state level. Table 1 shows that state and local government command about 99 percent of total spending on highways and about 3 percent on transit and railroad projects. Federal involvement is higher for air and water transportation, so that the lower levels of government account for about 86 percent of total spending on infrastructure. These data are only indicative; the federal government influences local and state infrastructure decisions indirectly, e.g., through sales of federal land.

In Europe, the allocation of infrastructure spending on different levels of government is usually less skewed than in the US. However, in Germany, all interregional highways are planned, financed and maintained by state governments. In France, the interregional network of highways is managed centrally, but even in this case, regional entities have considerable influence over total infrastructure spending. Local governments are involved in the planning of interregional infrastructure projects in all larger OECD countries.

Table 3: US infrastructure spending on different levels of government

USD bn, 2004			
	Federal	Local/State	Total
Highways	1.6	153.0	154.6
Transit and Railroad	0.5	14.0	14.5
Air	17.3	9.0	26.3
Water	10.3	3.2	13.5
All	29.7	179.2	208.9

Source: BEA-NIPA Table 3.1505

3 Modeling transportation costs

Economic geography models, pioneered amongst others by Krugman (1991), bring together monopolistic competition with Samuelson’s (1952) iceberg trade costs assumption.¹⁰ The iceberg assumption has proved convenient, because it makes the introduction of a specific transportation sector redundant: during transportation, a distance-dependent share of the output shipped from the location of production gets lost, i.e. melts away. The implicit transportation sector production function uses the good being transported as the only input. Formally, assume that economic space S is unidimensional and continuous (e.g., the real line, or the circumference of a circle). For two arbitrary addresses x and z in S , a Krugman-type transportation costs specification would be

$$T(x, z) = e^{a|x-z|} \geq 1, \quad (1)$$

where the coefficient $a > 0$ is the iceberg decay parameter. $T(x, z)$ models the cost of delivering a good over the distance $|x - z|$ as an *ad-valorem* tax equivalent, where the tax income is lost in transit. In order to receive one unit of the good at x , $T(x, z)$ units of that good have to leave the factory at z . A share $1 - T(x, z)^{-1}$ of the good ‘melts’ in transport; the share $T(x, z)^{-1}$ arrives at x when one unit of the good is shipped at z .

The iceberg formulation amounts to introducing a shadow transport sector which uses the share $1 - T(x, z)^{-1}$ of a good to be shipped from z to x as an input. The transport service is produced at the location of the producer, using the same input mix than the good to be shipped. Given the continuous space nature of our setup, one could more generally posit that transportation services are produced in some sub-interval in $[x, z]$. In the specific economic

¹⁰Note that much of the new trade theory literature that discusses trade in differentiated goods under increasing returns to scale and monopolistic competition uses an essentially discrete formalization of trade costs. Associated empirical papers using the gravity equation do, however, resort to Krugman’s specification. For a model of trade in continuous space see Krugman and Venables (1997).

environment proposed below, these differences do not matter, as f.o.b. prices in any location are independent of demand for the variety produced at those locations.

In this paper, transportation costs are modeled as a function of *cumulative* infrastructure investment. Public infrastructure investment refers to the process of investing some resource at specific locations $s \in S$ with the aim of reducing transportation costs.¹¹ We assume that the set of geographic locations, S , is given by an interval, $[0, \bar{s}]$, where \bar{s} characterizes the geographical size of the economy. Note that an alternative way to formulate the geographic space in the economy is to assume that S is a circle. However, in contrast to the linear case, the circle geography does not exhibit a natural periphery, implying that the geography does not affect the infrastructure investment. Indeed, if all the locations on a unit circle are symmetric (in terms of endowments, available technologies, etc.), the infrastructure investment is also symmetric across the locations, implying the symmetric transportation infrastructure. In contrast, in the below analysis we show that, in the case of a linear space, the symmetry of locations does not imply the symmetry of investment decisions and, therefore, the symmetry of the transport infrastructure: i.e. geography matters.

We model the effectively available stock of infrastructure over some interval $[x, z] \in S$ as a constant elasticity of substitution aggregator function

$$I(x, z) = \left[\int_x^z i(s)^{1-\delta} ds \right]^{\frac{1}{1-\delta}}, \delta > 1, x \leq z, \quad (2)$$

where $i(s)$ is the level/stock of infrastructure at location $s \in [x, z]$ and $\delta > 1$ is a constant technological parameter (which will have a precise economic interpretation later). $I(x, z)$ increases in distance. This formulation has the natural implication that spreading a constant investment budget B over increasing distance $z - x$ lowers the available stock of $I(x, z)$. Note also that if $i(s)$ is equal to zero on some subset (with a positive measure) of $[x, z]$, then the available stock of infrastructure over the whole interval $[x, z]$ is zero.

The costs of transportation a product from z to x , where $x \leq z$, are linked with the infrastructure stock as follows:¹²

$$T(x, z) = \left(1 + \frac{1}{\delta - 1} I(x, z)^{1-\delta} \right)^\gamma, \delta > 1, \gamma > 0, x \leq z. \quad (3)$$

¹¹Since the model proposed is static, we use the term infrastructure investment and stock of infrastructure interchangeably.

¹²In Section 4.5, we discuss the robustness of the results in the paper to changes in the functional form of the transportation costs.

A more general definition, where x and z are not ordered, implies that

$$\begin{aligned} T(x, z) &= \left(1 + \frac{1}{\delta - 1} |I(x, z)^{1-\delta}| \right)^\gamma \\ &= \left(1 + \frac{1}{\delta - 1} \left| \int_x^z i(s)^{1-\delta} ds \right| \right)^\gamma, \end{aligned}$$

where $|\cdot|$ means the absolute value. As can be seen, the transportation costs are symmetric in the sense that delivering a product from x to z costs the same as delivering a product from z to x . Here, parameter γ represents the effect of the total stock of infrastructure on the transportation costs, while δ stands for the elasticity of substitution between infrastructure investments at different locations (see the Lemma below). Note that for any locations x , y , and z , the triangle inequality holds: $T(x, y)T(y, z) \geq T(x, z)$ (the strict inequality holds, if x , y , and z represent different locations).¹³ That is, it is cheaper to transport products directly to a destination address, rather than through some intermediate address.

The choice of functional forms (2) and (3) proofs convenient as the problem of optimally allocating $i(s)$ over space resembles the problem of optimally allocating consumption spending over time. Moreover, the formulation (3) has properties long discussed (but rarely modelled) by transport economists (Winston, 1985, and Gramlich, 1994).

Lemma 1 *Generalized iceberg trade costs $T(x, z)$ have the following properties:*

- (i) $T(x, z) \geq 1$ with $T(x, x) = 1$ and $T(x, y)T(y, z) \geq T(x, z)$.
- (ii) $T(x, z) = (1 + a|z - x|)^\gamma$, if $i(s)$ is a constant \bar{i} over the interval $[x, z]$, and $a = \bar{i}^{1-\delta}/(\delta - 1)$.
- (iii) $T(x, z) = \infty$, if $i(s) = 0$ on some subset (with a positive measure) of $[x, z]$.
- (iv) $T(x, z)$ is increasing in distance: i.e. for fixed x a more distant location z results in higher transportation costs. Moreover, if $i(s)$ is a differentiable function on S , $T(x, z)$ is convex in distance if the distance-induced increment to $T_z(x, z)$ in trade costs is not outweighed by

¹³Indeed, it is straightforward to see that for three different locations x , y , and z such that $x < y < z$,

$$\begin{aligned} T(x, y)T(y, z) &= \left(1 + \frac{1}{\delta - 1} \int_x^y i(s)^{1-\delta} ds \right)^\gamma \left(1 + \frac{1}{\delta - 1} \int_y^z i(s)^{1-\delta} ds \right)^\gamma \\ &= \left(1 + \frac{1}{\delta - 1} \int_x^y i(s)^{1-\delta} ds + \frac{1}{\delta - 1} \int_y^z i(s)^{1-\delta} ds + \frac{1}{(\delta - 1)^2} \int_x^y i(s)^{1-\delta} ds \int_y^z i(s)^{1-\delta} ds \right)^\gamma \\ &> \left(1 + \frac{1}{\delta - 1} \int_x^y i(s)^{1-\delta} ds + \frac{1}{\delta - 1} \int_y^z i(s)^{1-\delta} ds \right)^\gamma \\ &= \left(1 + \frac{1}{\delta - 1} \int_x^z i(s)^{1-\delta} ds \right)^\gamma = T(x, z). \end{aligned}$$

an improvement in infrastructure. That is, if $(\gamma - 1) [a(z)]^2 / (T(x, z))^{1/\gamma} > i'(z) i(z)^{-\delta}$ where $a(z) = i(z)^{1-\delta} / (\delta - 1)$.

- (v) *The (interregional) elasticity of substitution between infrastructure investment at different locations is $0 < 1/\delta < 1$, so that investments at different places are gross complements.*
- (vi) *Investment smoothing property: if investment costs do not vary across locations, then the cost-efficient way to achieve some exogenous target level of transportation costs involves a flat spatial investment profile*

$$i(s) = \left\{ (z - x) / \left[(\delta - 1) \left(\bar{T}^{1/\gamma} - 1 \right) \right] \right\}^{1/(\delta-1)}.$$

where $\bar{T} > 1$ is the target level of iceberg transportation costs.

Proof The first three properties directly follow from the definition of the trade costs in (3). The last three properties are proved in the Appendix.

One of the critiques of the Krugman specification of transportation costs (see McCann, 2005) is that, according to (1), the delivered price of a good transported from a producer to a consumer over some distance is convex with respect to distance, which is at least partly counterfactual. In the present framework, iceberg transportation costs are convex in distance, as long as the component of $dT(x, z)/dz$ driven by variation in infrastructure investment does not outweigh the pure distance component of $dT(x, z)/dz$ (see property (iv) in the above lemma). Hence, in general, whether $T(x, z)$ is convex in distance depends on the spatial allocation of infrastructure investment. Moreover, if γ is assumed to be less than or equal to one, the transportation cost function is concave in distance.

Properties (v) and (vi) exploit the isomorphism between (3) and the usual representation of utility in an optimal growth model. The parameter δ measures the ease with which infrastructure investment at some address can substitute for investment at another place. The restriction $\delta > 1$ ensures that investments at different places are gross complements: investment at some address makes investment at some other place more worthwhile, which seems realistic.¹⁴

4 Infrastructure investment in a closed economy

This section embeds the transport technology described in (3) into a specific model of inter and intra-regional trade. The model is static and features a single factor of production, labor. The

¹⁴We do not allow for incremental transport costs incurred at address s to depend on the volume of traffic transiting through s . Actually, in equilibrium, the contrary will hold: more traffic at s will encourage the planner to invest more in infrastructure, thereby driving down the gradient of T . This lowers the incremental trade costs at s for all units of goods that transit through s .

economic environment combines spatial product differentiation with constant returns to scale production functions and perfect competition.¹⁵

4.1 Geographical space and goods space

As discussed above, the geographic space S that constitutes the economy is understood as a continuum of locations (or: addresses) $s \in S$ organized along an interval, $[0, \bar{s}]$. At each location s there is a representative household who inelastically supplies $m(s)$ units of labor. Households are immobile across space, so $m(s)$ is exogenous. We can leave the form of $m(s)$ open as long as $m(s) > 0$ for all $s \in S$ (no inhabited locations). The total endowment of labor in the economy is then equal to $\int_{s \in S} m(s) ds$, which we define as L .

At each location, a homogeneous agricultural and a spatially differentiated industrial good can be produced. Consumers consume both types, perceiving industrial goods produced at specific locations as imperfect substitutes. There are no costs of transporting the agricultural good. Moreover, the agricultural good serves as an input into infrastructure provision. Each location s is home of consumers and producers. We denote addresses of consumers by x and addresses of producers by z .

We assume that locations may differ with respect to the topological circumstances. In other words, we have a distribution of productivities $q(s)$ which gives the rate at which resources are transformed into infrastructure investment goods. Specifically, infrastructure at address s is produced according to a linear production function $i(s) = b(s)/q(s)$, where $b(s)$ denotes the input of the agricultural good used for infrastructure investment, and $1/q(s) > 0$ measures the rate at which that resource is transformed into infrastructure. We restrict $q(s)$ to be continuously differentiable. Feasibility of an investment policy $i(s)$ implies that

$$\int_{s \in S} q(s) i(s) \leq B, \quad (4)$$

where B is the amount of agricultural good invested in the economy infrastructure and will be endogenously determined by government policy.

The assumption that the agricultural good can be transported freely across space can be relaxed only at the price of considerable complication. It is similar to the assumption of a costlessly tradable agricultural good in much of the economic geography literature and delivers factor price equalization across space (in nominal terms) as long as all locations produce both types of goods (which we assume). Moreover, the existence of the agricultural good as an input

¹⁵It is, therefore of the Armington (1969) type; see also Anderson and van Wincoop (2003).

in infrastructure production makes thinking about a transportation technology for transferring infrastructure production inputs from one region to the other redundant.¹⁶

4.2 Consumption

The utility function of a representative household at location x is a monotone transformation of a Cobb-Douglas aggregate over the homogeneous agricultural good and a Dixit-Stiglitz aggregate over industrial goods:

$$U(x) = [c^A(x)]^{\alpha\rho/((1-\alpha)(1-\rho))} [u(x)]^{\rho/(1-\rho)}, \alpha \in (0, 1), 0 < \rho < 1, \quad (5)$$

where $c^A(x)$ denotes the total quantity of the agricultural good consumed at address x and $u(x)$ is the subutility index attributable to spatially differentiated goods. Specifically,

$$u(x) = \left(\int_{z \in S} c^I(x, z)^\rho dz \right)^{1/\rho}, \quad (6)$$

where $c^I(x, z)$ is the quantity of an industrial variety produced at address z and consumed at x .¹⁷

Let $Y^n(x)$ denote household x 's net income in terms of a numeraire to be defined below. Then, the budget constraint of household x is

$$Y^n(x) = c^A(x) p^A(x) + \int_{z \in S} c^I(x, z) p^I(x, z) dz, \quad (7)$$

where $p^A(x)$ is the price of the agricultural good at location x and $p^I(x, z)$ is the price of a variety imported from location z and consumed at x .

The utility maximization problem implies that the demand functions for the agricultural good and a certain variety of the industrial good are respectively

$$c^A(x) = \frac{\alpha Y^n(x)}{p^A(x)} \text{ and } c^I(x, z) = (1 - \alpha) Y^n(x) \frac{p^I(x, z)^{-\sigma}}{P^I(x)^{1-\sigma}}, \quad (8)$$

where $\sigma = 1/(1 - \rho)$ and

$$P^I(x) = \left[\int_{z \in S} p^I(x, z)^{1-\sigma} dz \right]^{\frac{1}{1-\sigma}} \quad (9)$$

is the price index for industrial goods at location x .

¹⁶An alternative/equivalent way to model infrastructure provision is to assume that the only input into infrastructure is labor, which in turn is perfectly mobile between locations (within an economy). But consumption takes place at the place of origin. This will equalize wages across locations (which is in the present model done by the presence of the homogenous agricultural good) making the presence of the agricultural good redundant.

¹⁷Notice that $U(x)$ is a positive monotonic transformation $U(x) = [\tilde{U}(x)]^{\rho/((1-\alpha)(1-\rho))}$ of the usual Cobb-Douglas formulation $\tilde{U}(x) = [c^A(x)]^\alpha [u(x)]^{1-\alpha}$. The transformation makes the theoretical analysis of the model more tractable (without qualitatively changing the main conclusions).

The indirect utility attainable at prices $p^A(x)$, $p^I(x, z)$ and income $Y^n(x)$ can be written as

$$V(x) = \left(\alpha^{\alpha/(1-\alpha)} (1-\alpha) \right)^{\rho/(1-\rho)} [p^A(x)]^{-\alpha\rho/((1-\alpha)(1-\rho))} [P^I(x)]^{1-\sigma} (Y^n(x))^{\rho/((1-\alpha)(1-\rho))}. \quad (10)$$

4.3 Production

At each location $z \in S$, the agricultural and the industrial good are produced under conditions of perfect competition. The only input of production is labor. Production functions for the two types of goods are linear $y^A(z) = bl^A(z)$ where $y^I(z) = l^I(z)$, where $b > 0$ is a productivity parameter common for all locations. Output quantities are denoted by $y^A(z)$ and $y^I(z)$, and labor inputs by $l^A(z)$ and $l^I(z)$, respectively.

We assume that workers are perfectly mobile across agricultural and industrial firms. This in turn implies that $p^A(z) = w(z)/b$ and $p^I(z) = w(z)$, where $w(z)$ is the wage rate (expressed in units of numeraire) at address z .

4.4 Equilibrium

Industrial goods bear transportation costs. We assume that there are no trade costs other than transportation costs.¹⁸ Hence, the c.i.f. prices faced by consumers differ from the f.o.b. (ex-factory) prices. In particular, a household at x faces the price

$$p^I(x, z) = p^I(z) T(x, z)$$

for a variety of the industrial good imported from location z . In contrast, the agricultural good can be transported freely. In the paper, we impose a *non-full-specialization* (NFS) assumption: there is always a strictly positive quantity of agricultural production at each location. The NFS assumption introduces factor price equalization in terms of the agricultural good.¹⁹ We may therefore choose the agricultural good as the *numeraire* and set $p^A(z) = 1$ for all $z \in S$. Since $p^A(z) = 1$ for any z , we drop the superscripts A and I in the following.

As the price of the agricultural good is normalized to unity, the wage rate at location z , $w(z)$, is equal to b . The gross income at location x in terms of the numeraire is then $Y(x) = bm(x)$. Finally, from our assumption on technology, the c.i.f. prices of industrial goods are

$$p(x, z) = bT(x, z). \quad (11)$$

¹⁸In section 5.3, when we consider international trade, we will introduce a discrete trade friction at the border.

¹⁹Relaxing the NFS assumption would allow to study the interaction between infrastructure investment policies and regional specialization patterns. This is an interesting issue that raises additional complications. It is therefore left to future research.

The government imposes a lump-sum tax t , which is assumed identical across addresses $s \in S$. Thus, the net income at location x , $Y^n(x)$, is $(1-t)bm(x)$. The total tax income is

$$B = bt \int_{s \in S^c} m(s) ds = btL.$$

Substituting the expressions for the net household income and the price index and taking into account that the price of the agricultural good is one, we can now rewrite the indirect utility function in (10) as follows:

$$V(x) = \Omega((1-t)m(x))^{(\sigma-1)/(1-\alpha)} \left[\int_{z \in S} T(x, z)^{1-\sigma} dz \right], \quad (12)$$

where $\Omega \equiv (\alpha^{\alpha/(1-\alpha)} b^{\alpha/(1-\alpha)} (1-\alpha))^{(\sigma-1)}$ is a function of exogenous parameters only. The latter can be rewritten as follows:

$$V(x) = \Omega(1-t)^{(\sigma-1)/(1-\alpha)} \tilde{m}(x) \left[\int_{z \in S} T(x, z)^{1-\sigma} dz \right], \quad (13)$$

where

$$\tilde{m}(x) = (m(x))^{(\sigma-1)/(1-\alpha)}.$$

Equation (13) shows that the measure of economic activity at a location, $\tilde{m}(x)$, is exactly proportional to indirect utility (defined over the entire household located at x). Hence, in per capita terms (with respect to $\tilde{m}(x)$), indirect welfare is independent from $\tilde{m}(x)$: Higher endowment at a location does not trigger a negative terms of trade effect as in the standard Armington model due to the presence of a linear outside sector that absorbs any variation in labor endowments across locations.

4.5 The choice of infrastructure investment

In this section, we characterize optimal policies $\{i^a(s), t^a\}_{s \in S}$ in a closed economy. The social planner chooses the infrastructure investment and the tax rate to maximize the total welfare in the economy. Specifically, the planner's objective function is an aggregate of the indirect utilities achieved at every address. Accordingly, ignoring the irrelevant constant, the planner problem is

$$\{i^a(x), t^a\}_{x \in S} = \arg \max \left\{ (1-t)^{(\sigma-1)/(1-\alpha)} \int_{x \in S} \tilde{m}(x) v(x) dx \left| \int_{x \in S} q(x) i(x) dx \leq btL \right. \right\}, \quad (14)$$

where

$$v(x) = \int_{z \in S} T(x, z)^{1-\sigma} dz. \quad (15)$$

Note that the household size at location x , represented by $(m(x))^{(\sigma-1)/(1-\alpha)}$, plays a role of the weight attached to the consumption utility $v(x)$. Hence, from the social planner's problem, we may expect larger infrastructure investments in more densely populated regions.

The above optimization problem can be equivalently written as follows:

$$\{i^a(x), t^a\}_{x \in S} = \arg \max \left\{ (1-t) \left(\int_{x \in S} \tilde{m}(x) v(x) dx \right)^{\frac{1-\alpha}{\sigma-1}} \mid \int_{x \in S} q(x) i(x) dx \leq bL \right\}. \quad (16)$$

To guarantee the concavity of the objective function in (14), we assume that

$$\gamma(\sigma-1)(\delta-1) < 1, \text{ and} \quad (17)$$

$$\frac{1-\alpha}{\sigma-1} < 1. \quad (18)$$

The first inequality means that $T(x, z)^{1-\sigma}$ is concave with respect to infrastructure investments, implying that the consumption utility, $v(x)$, is concave in infrastructure investments as well.²⁰ The second inequality, which would be always met if $\sigma > 2$, implies that the objective function is concave in $v(x)$. As a result, the objective function is concave with respect to infrastructure investments.²¹ Note that the results derived in the paper are qualitatively robust to changes in the functional form of the transportation costs as soon as $T(x, z)^{1-\sigma}$ is concave in $i(s)$, $s \in [x, z]$, and has an unbounded derivative at $i(s) = 0$.

Next, we characterize the solution of the planner's problem. Note that we find the solution among continuous functions on $[0, \bar{s}]$. That is, the social welfare is maximized with respect to $i^a(x)$, where $i^a(x)$ is continuous. This limitation also holds in the subsequent analysis (see Section 5). The following proposition holds.

Proposition 1 *The optimal allocation of infrastructure spending across space and the optimal tax rate chosen by a social planner under autarky are implicitly determined by the following system of equations:*

$$i^a(x)^\delta = \frac{b\gamma(1-\alpha)(1-t^a)L}{q(x)} (\phi^L(x) + \phi^R(x)), \quad (19)$$

$$t^a = \frac{\int_{s \in S} q(s) i^a(s) ds}{bL}, \quad (20)$$

²⁰In brief, the idea behind is that the function, $\left(1 + \frac{1}{\delta-1}x^{1-\delta}\right)^{\gamma(1-\sigma)}$ is strictly concave if and only if $\gamma(\sigma-1)(\delta-1) < 1$. This in turn implies that $T(x, z)^{1-\sigma}$ is concave with respect to infrastructure investments.

²¹In fact, in the Appendix we show that the objective function is strictly concave in infrastructure investments.

where

$$\begin{aligned}\phi^L(x) &= \frac{\int_0^x \tilde{m}(s) \left(\int_x^{\bar{s}} \left(1 + \frac{1}{\delta-1} \int_s^t i^a(r)^{1-\delta} dr \right)^{\gamma(1-\sigma)-1} dt \right) ds}{\int_{s \in S} \tilde{m}(s) v(s) ds}, \\ \phi^R(x) &= \frac{\int_x^{\bar{s}} \tilde{m}(s) \left(\int_0^x \left(1 + \frac{1}{\delta-1} \int_t^s i^a(r)^{1-\delta} dr \right)^{\gamma(1-\sigma)-1} dt \right) ds}{\int_{s \in S} \tilde{m}(s) v(s) ds}.\end{aligned}$$

Proof In the Appendix.

The terms $\phi^L(x)$ and $\phi^R(x)$ represent the aggregate marginal welfare gains (from a rise in $i^a(x)$) to the left and the right of location x , respectively. The investment at location x is higher, the larger the sum $\phi^L(x) + \phi^R(x)$ or the lower the cost of infrastructure at the location, $q(x)$. In the next proposition, we summarize some additional properties of the optimal infrastructure investment function, $i^a(x)$, and the consumption utility, $v(x)$.

Proposition 2 *The optimal infrastructure investment function, $i^a(x)$, and the consumption utility, $v(x)$, have the following properties:*

- (i) *The infrastructure investments are zero at the borders of the region: $i^a(\bar{s}) = i^a(0)$.*
- (ii) *If $q(x)$ is continuously differentiable, $i^a(x)$ is increasing in the neighborhood of zero and decreasing in the neighborhood of one: specifically, $(i^a(x))'_{x=0} = \infty$ and $(i^a(x))'_{x=\bar{s}} = -\infty$.*
- (iii) *If there is no variation in the cost of infrastructure investment and the household size across the locations: $q(x) = q$ and $m(x) = m$ for any $x \in S$, then $v(x)$ and $i^a(x)$ are symmetric around $x = \bar{s}/2$ and have a hump shape with maximum at $x = \bar{s}/2$.*

Proof The first property immediately follows from the definitions of $\phi^L(x)$ and $\phi^R(x)$. Specifically, we have that $\phi^L(\bar{s}) = \phi^L(0) = \phi^R(\bar{s}) = \phi^R(0) = 0$. The last two properties are proved in the Appendix.

According to the proposition, if there is no variation in the cost of infrastructure and the household size, the optimal infrastructure is symmetric around the middle point of the $[0, \bar{s}]$ -interval. That is, to maximize the social welfare, the social planner concentrates the infrastructure around the middle point. As a result, households located closer to the middle point have higher indirect utility.

4.6 Comparative Statics

In this section, we explore how the parameters in the model affect the infrastructure profile chosen by the social planner. Note that the optimal infrastructure investments at location x can be written as follows:

$$i^a(x) = \left(\frac{\gamma(1-\alpha)(bL - \int_{s \in S} q(s) i^a(s) ds)}{q(x)} (\phi^L(x) + \phi^R(x)) \right)^{1/\delta}, \quad (21)$$

where $\phi^L(x)$ and $\phi^R(x)$ depend on the investments at all locations $x \in [0, \bar{s}]$ (see *Proposition 1*). In other words, the infrastructure investments at location x depend on that particular location, the infrastructure profile in the whole economy, and the set of parameters in the model. That is,

$$i^a(x) = i^a(x, I^a, \epsilon),$$

where I^a represents the infrastructure profile in the economy and ϵ is the set of parameters in the model. Thus, the changes in $i^a(x)$ due to changes in ϵ are implicitly determined from

$$\frac{\partial i^a(x)}{\partial \epsilon} = \frac{\partial i^a(x, I^a, \epsilon)}{\partial \epsilon} + \frac{\partial i^a(x, I^a, \epsilon)}{\partial I^a} \frac{\partial I^a}{\partial \epsilon}. \quad (22)$$

The first term in the right-hand side of (22) captures the direct effect of ϵ on $i^a(x)$, while the second term stands for the indirect effects. Unfortunately, the rigorous analysis of the overall effect (the direct effect plus the indirect effect) on the infrastructure profile is quite complex. Therefore, in the paper we only focus on the direct effect, as we believe that the indirect effect is of the second order. In addition, in Section 6 we provide the results of numerical experiments (where we consider the overall effects) that look mainly consistent with the direct effect playing a major role.

It is straightforward to see that, all else equal, a rise in the share of the total income spent on the agricultural product, α , decreases the right-hand side of (21). As a result, the infrastructure investments fall at all locations. Moreover, as the tax rate is equal to $(\int_{s \in S} q(s) i^a(s) ds) / bL$, the tax rate falls as well. Indeed, rise in α makes the differentiated product less valuable in consumption. As a result, there is no need to invest that much in the infrastructure (remember that the transportation of the agricultural product is costless).

As can be seen, a rise in b increases the right-hand side of (21) resulting in the positive direct effect of b on $i^a(x)$. In words, there are more investments in the infrastructure in more productive (richer) economies. The impact on the tax rate is not so straightforward. On the one hand, larger investments in the infrastructure require a higher tax to be financed. On the other hand, a rise in income increases the tax base, reducing the necessary tax rate. In the Appendix,

we show that the latter effect is stronger than the former. As a result, a rise in b has a negative direct impact on the tax rate. Notice that in this exercise we ignore changes in $\phi^L(x)$ and $\phi^R(x)$ caused by a rise in b and, therefore, focus on the direct impact of b on t^a . However, numerical experiments we conduct show that the overall effect on the tax rate is negative, which confirms our belief that the indirect effects are of the second order.

Recall that the size of the economy, L , is given by $\int_0^{\bar{s}} m(s)ds$ and, therefore, depends on the geographical size, \bar{s} , and the population density, $m(x)$. To examine the impact of L on the infrastructure profile, we assume that $m(x) = m$ for all $x \in [0, \bar{s}]$. In this case, L is equal to $m\bar{s}$. Note that if $m(x)$ is the same at all locations, $\phi^L(x)$ and $\phi^R(x)$ do not directly depend on m , as it is canceled out (see *Proposition 1*). Hence, the direct impact of m on $i^a(x)$ is exactly the same as that of b : that is, a rise in m increases $i^a(x)$ for all x and decreases the tax rate.

The analysis of the impact of the geographical size, \bar{s} , is more complicated, as $\phi^L(x)$, $\phi^R(x)$, and $\int_{s \in S} q(s) i^a(s) ds$ directly depend on \bar{s} . It is possible to show that a rise in \bar{s} (from \bar{s}' to \bar{s}'') increases $i^a(x)$ for x from some left neighborhood of \bar{s}' . Indeed, when \bar{s} rises from \bar{s}' to \bar{s}'' , \bar{s}' becomes an internal location of the new geography and, therefore, has some positive infrastructure investments. This means that $i^a(\bar{s}')$ increases (as before the changes \bar{s}' was the border location with zero infrastructure). By continuity, the infrastructure investments increase in some left neighborhood of \bar{s}' as well. In addition, we find that if the cost of infrastructure is uniform ($q(x) = q$ for all x), then $i^a(x)$ rises in all locations $x \in S$. The results of numerical experiments suggest that if we take into account the indirect effects as well, then depending on the parameters $i^a(x)$ can decrease for x sufficiently close to the left border (even if the cost of infrastructure is uniform). This implies that while the direct effects are of the first order, the indirect effects should not be completely ignored in the analysis.

Finally, it is straightforward to see that a rise in the cost of infrastructure investments, $q(x)$, in some neighborhood of x reduces the investments in that neighborhood. In particular, if we assume that $q(x) = q$ for all x , then the impact of q on $i^a(x)$ and t^a is exactly opposite to that of b : that is, a rise in q decreases $i^a(x)$ and increases the tax rate, t^a . The next proposition summarizes the above considerations.

Proposition 3 *Changes in the parameters in the model have the following direct effects on the optimal infrastructure profile in a closed economy:*

- (i) *A decrease in α increases t^a and $i^a(x)$ for all x .*
- (ii) *A rise in b decreases t^a and increases $i^a(x)$ for all x .*

- (iii) *Assuming that $m(x) = m$ for all x , a rise in m decreases t^a and increases $i^a(x)$ for all x .*
- (iv) *Assuming that $m(x) = m$ for all x , a rise in \bar{s} increases $i^a(x)$ for x close to the right border and has an ambiguous impact on the investments at the other locations. If in addition $q(x) = q$ for all x , then a rise in \bar{s} increases $i^a(x)$ for all $x \in S$.*
- (v) *A rise in $q(x)$ in some neighborhood of x reduces $i^a(x)$ in that neighborhood. Assuming that $q(x) = q$ for all x , a rise in q increases t^a and decreases $i^a(x)$ for all x .*

Proof In the Appendix.

The analysis of the direct effects of γ , δ , and σ on the infrastructure profile is quite complex, as these parameters are included into the expressions for $\phi^L(x)$ and $\phi^R(x)$ in the non-trivial way. At the same time, the intuition, which is behind the effects, seems straightforward. A rise in γ makes the dependence of the transportation costs on infrastructure investments stronger. As a result, $i^a(x)$ rises at all locations. A rise in σ makes the varieties of the differentiated product more substitutable, shifting the consumption towards local varieties. As a result, the gains from infrastructure investments fall and, therefore, $i^a(x)$ falls as well for all x . Finally, a rise in δ makes infrastructure investments in different locations less substitutable (as $1/\delta$ falls), which in turn results in higher optimal investments at all locations. We run a number of numerical experiments that appear to be consistent with the above intuition.

5 Infrastructure investment in an open economy

In this section, we present the key results of the paper. We assume that the world economy consists of two independent countries, each with its own government that decides on infrastructure investment in a non-cooperative way. However, consumers demand goods produced all over the world. Thus, we have a situation with ‘globalized markets, regional politics’. As in the previous section, the world geography is linear. To simplify the analysis, we assume that countries are symmetric. In particular, the world geography is described by the $[0, 2\bar{s}]$ -interval, where locations from $[0, \bar{s}]$ and $(\bar{s}, 2\bar{s}]$ represent the home and foreign country, respectively. Alternatively, one may think of the $[0, 2\bar{s}]$ -interval as a closed country, with segments representing autonomous regions within that country. As before, the homogenous good is assumed to be produced at all locations in both countries, resulting in the same wage rates (equal to b). We also assume away any variation in the costs of infrastructure and the household sizes across locations: i.e.,

$q(x) = q$ and $m(x) = m$ for all $x \in [0, 2\bar{s}]$. The idea behind this assumption is to isolate a pure border effect on the equilibrium infrastructure profile.²²

In the following analysis, the rationale behind many results is the discrepancy between the political and the economic reach of countries: while infrastructure investment decisions are limited to domestic locations, consumers demand imports from both countries and, therefore, from all locations. Since countries decide in a non-cooperative way, they do not internalize the positive externality that their investment decisions exert on consumers in other countries. This leads to global underprovision of infrastructure.

In the following, we first examine the world planner problem. Then, we formulate and solve the game between the two countries when infrastructure decisions are undertaken independently. Finally, we compare the obtained outcomes of the game to the world-planner solution.

5.1 World planner problem

The world planner chooses the world infrastructure profile to maximize the indirect utility of the entire world population. In this case, the space which individuals trade across and the space which infrastructure decisions are made over coincide. In other words, we have one market and one jurisdiction (that decides over infrastructure investments). Thus, the world planner problem can be written as follows:

$$\{i^w(x), t^w\}_{x \in [0, 2\bar{s}]} = \arg \max_{i(x), t} \left\{ (1-t) \left(\int_0^{2\bar{s}} v(x) dx \right)^{\frac{1-\alpha}{\sigma-1}} \left| q \int_0^{2\bar{s}} i(x) dx \leq 2bLt \right. \right\}, \quad (23)$$

where $v(x)$ is the consumption utility at address x and L is the population size in each country.²³ As can be seen, the world planner problem looks very similar to the social planner problem in the case of a closed economy. The only difference is that the geographical space is now given by the $[0, 2\bar{s}]$ -interval rather than by the $[0, \bar{s}]$ -interval. Hence, we can formulate the following proposition.²⁴

Proposition 4 *The optimal allocation of infrastructure spending across the world geography and the optimal tax rate chosen by the world planner are implicitly determined by the following*

²²The framework can be easily extended to the case when $q(x)$ and $m(x)$ are symmetric around $x = \bar{s}$.

²³Notice that the constraint in the maximization problem is

$$q \int_0^{2\bar{s}} i(x) dx \leq bt \int_0^{2\bar{s}} m(x) dx = 2b\bar{s}m = 2bL,$$

where L is the size of the countries.

²⁴As in the previous section, we assume that the optimal infrastructure profile is chosen among continuous functions.

system of equations:

$$i^w(x)^\delta = \frac{2bL\gamma(1-\alpha)(1-t^w)}{q} (\phi^{L,w}(x) + \phi^{R,w}(x)), \quad (24)$$

$$t^w = \frac{q \int_0^{2\bar{s}} i^w(s) ds}{2bL}, \quad (25)$$

where $\phi^{L,w}(x)$ and $\phi^{R,w}(x)$ are defined in analogy to their counterparts in Proposition 1 with the right border equal to $2\bar{s}$ and $v(s) = \int_0^{2\bar{s}} T(x, z)^{1-\sigma} dz$. The properties of the world planner solution are the same as those for the autarky planner case; see Proposition 2.

Proof The proof is exactly the same as that for Proposition 1.

Similar to the infrastructure profile in the case of a closed economy, $i^w(x)$ is symmetric around $x = \bar{s}$ and has a hump shape, implying that the maximum of the function is achieved at $x = \bar{s}$ (this is due to the absence of variation in the costs of infrastructure and household sizes). Thus, the first-best allocation involves the highest levels of infrastructure investment around the border between the countries. Indeed, as the world planner cares about the entire world population, she finds it optimal to invest more at locations closer to the “core” of the world (as the social marginal gains at these locations are higher), which is the border. In the next section, we explore the case when infrastructure decisions are undertaken independently by each country.

5.2 Global economics, regional politics

In this section, we find the solution of a game between two countries that choose the infrastructure investments simultaneously and independently from each other. The game is defined as $\Gamma = (I, U_i, \Theta_i)$, where $I = \{H, F\}$ represents the set of countries, Θ_i is the i th country’s strategy set ($i \in I$), and U_i is the i th country’s payoff functional defined on $\Theta_1 \times \Theta_2$.

In the context of the present framework, the set of strategies of the home country, Θ_H , is given by $\{i^H(x), t^H\}_{x \in [0,1]}$, where $i^H(x) \geq 0$, $\int_0^{\bar{s}} i^H(x) dx \leq bLt^H/q$, and $t^H \in [0, 1]$. Similarly, Θ_F is the set of $\{i^F(x), t^F\}_{x \in [1,2]}$, where $i^F(x) \geq 0$, $\int_{\bar{s}}^{2\bar{s}} i^F(x) dx \leq bLt^F/q$, and $t^F \in [0, 1]$. Here, $i^H(x)$ and $i^F(x)$ are continuous on $[0, \bar{s}]$ and $[\bar{s}, 2\bar{s}]$, respectively. Finally, the countries’ payoffs are represented by the corresponding countries’ total welfare functions. We then show that the above game has a Nash equilibrium in pure strategies.

Proposition 5 *The game defined by $\Gamma = (I, U_i, \Theta_i)$ has a Nash equilibrium in pure strategies.*

Proof The proof is based on two facts. First, the strategy sets are non-empty, convex, and compact subsets of a metric vector space. Second, the payoff functionals are continuous on

$\Theta_1 \times \Theta_2$ and concave in the own strategy of a player: i.e., U_i is concave on Θ_i . In this case, according to Fan (1966), there exists a Nash equilibrium in pure strategies. See details in the Appendix.

As the countries are symmetric, in the following analysis we focus on the home country only. Given the infrastructure profile and the tax rate in the foreign country, the social planner at home solves the following maximization problem:

$$\{i^H(x), t^H\}_{x \in [0, \bar{s}]} = \arg \max_{t, i(x)} \left\{ (1-t) \left(\int_0^{\bar{s}} v(x) dx \right)^{\frac{1-\alpha}{\sigma-1}} \left| q \int_0^{\bar{s}} i(x) dx \leq bLt^H \right. \right\}, \quad (26)$$

where

$$v(x) = \int_0^{2\bar{s}} T(x, z)^{1-\sigma} dz.$$

Note that as agents consume both domestic and foreign products, the consumption utility, $v(x)$, depends not only on the domestic infrastructure profile, but also on the infrastructure investments undertaken abroad (through the transportation costs). As a result, the infrastructure investments in the foreign country affect the choice of the infrastructure investments in the home country, and vice versa. The next lemma describes the best response of the home social planner given a certain infrastructure profile in the foreign country.

Lemma 2 *Given an infrastructure profile in the foreign country, $\{i^F(x)\}_{x \in (\bar{s}, 2\bar{s}]}$, the home social planner chooses the infrastructure investments and the tax rate, $\{i^H(x), t^H\}_{x \in [0, \bar{s}]}$, that implicitly satisfy the following equations:*

$$\begin{aligned} i^H(x)^\delta &= \frac{bL\gamma(1-\alpha)(1-t^H)}{q} \left(\tilde{\phi}^L(x) + \tilde{\phi}^R(x) \right), \\ t^H &= \frac{q \int_0^{\bar{s}} i^H(x) dx}{bL}, \end{aligned}$$

where $\tilde{\phi}^R(x) = \phi^R(x)$ and

$$\tilde{\phi}^L(x) = \phi^L(x) + \frac{\int_0^x \left(\int_{\bar{s}}^{2\bar{s}} \left(1 + \frac{1}{\delta-1} \int_s^{\bar{s}} i^H(r)^{1-\delta} dr + \frac{1}{\delta-1} \int_{\bar{s}}^t i^F(r)^{1-\delta} dr \right)^{\gamma(1-\sigma)-1} dt \right) ds}{\int_0^{\bar{s}} v(s) ds},$$

with $\phi^L(x), \phi^R(x)$ given in Proposition 1 (at $m(x) = m$).

Proof In the Appendix.

As can be seen, the optimal infrastructure profile in an open economy has a similar form as that in the case of a closed economy. The main difference is the expression for $\tilde{\phi}^L(x)$ that represents the aggregate marginal welfare gains from a rise in $i^H(x)$ to the left of location x .

The reason behind is that infrastructure investments at location x affect the transportation costs from all foreign locations to the locations on the left of x (as the foreign country is located on the right of x). This in turn leads to additional welfare gains from a rise in infrastructure investment at location x compared to the closed economy case. As a result, in contrast to the closed economy case, $i^H(x)$ is strictly greater than zero at $x = \bar{s}$ if and only if $i^F(x)$ is strictly positive in some right neighborhood of $x = \bar{s}$ (meaning that the home country is not isolated from the foreign country). If $i^F(x)$ is equal to zero in some right neighborhood of $x = \bar{s}$, then $\tilde{\phi}^L(x)$ is exactly the same function as in the case of a closed economy, as in this case the transportation costs from foreign locations are infinitely high. Finally, as in the closed economy case, the infrastructure investment at location $x = 0$ is zero: $i^H(0) = 0$.

In the paper, we focus our analysis on the symmetric Nash equilibrium of the game. In the symmetric equilibrium, the countries' equilibrium infrastructure profiles are symmetric around $x = \bar{s}$, meaning that $i^F(x) = i^H(2\bar{s} - x)$ for $x \in [\bar{s}, 2\bar{s}]$. Taking into account the results stated in *Lemma 2*, we formulate the following proposition.

Proposition 6 *In the symmetric Nash equilibrium, the equilibrium home infrastructure profile and tax rate are implicitly determined by the following system of equations:*

$$\begin{aligned} i^H(x)^\delta &= \frac{bL\gamma(1-\alpha)(1-t^H)}{q} \left(\tilde{\phi}^{L,N}(x) + \tilde{\phi}^{R,N}(x) \right), \\ t^H &= \frac{q \int_0^{\bar{s}} i^H(x) dx}{bL}, \end{aligned}$$

where $\tilde{\phi}^{L,N}(x) = \tilde{\phi}^L(x)$ and $\tilde{\phi}^{R,N}(x) = \tilde{\phi}^R(x)$ from *Lemma 2* and $i^F(r) = i^H(2\bar{s} - r)$.

Proof The proof directly follows from *Lemma 2* and the fact that in the symmetric equilibrium $i^F(x) = i^H(2\bar{s} - x)$.

Next, we explore some properties of the equilibrium home infrastructure investments. Note that in the symmetric equilibrium, there always exists some left (right) neighborhood of $x = \bar{s}$ where $i^H(x)$ ($i^F(x)$) is strictly greater than zero. Indeed, if it is not true, then $i^H(x)$ is equal to zero around $x = \bar{s}$. This in turn means that $i^F(x)$ is equal to zero around $x = \bar{s}$ as well (due to the symmetry). As a result, there is no trade with the foreign country (because of infinitely large transportation costs) and the equilibrium infrastructure profile corresponds to the optimal infrastructure profile in the closed economy, which is, as was shown, strictly positive for any $x \in (0, \bar{s})$. This constitutes the contradiction. Thus, we can conclude that, in contrast to the closed economy case, the infrastructure investment at $x = \bar{s}$ is strictly positive due to the

possibility of trade with the foreign country. Specifically,

$$i^H(\bar{s})^\delta = \frac{bL\gamma(1-\alpha)(1-t^H)}{q} \tilde{\phi}^{L,N}(\bar{s}) > 0.$$

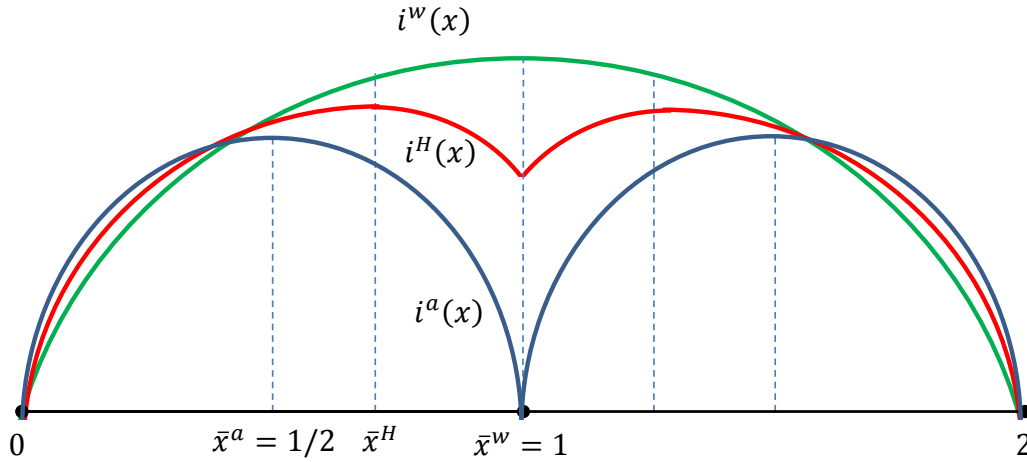
We then explore the behavior of the infrastructure profile around the border. The following proposition holds.

Proposition 7 *In the symmetric Nash equilibrium, $(i^H(x))'_{x=0} = \infty$ and $(i^H(x))'_{x=\bar{s}}$ is negative, but finite.*

Proof In the Appendix.

The above proposition suggests that the presence of the foreign country skews the distribution of infrastructure investments towards the border (compared to the closed economy case), as this increases the gains from trade with the foreign country. Nevertheless, the infrastructure profile still has a hump shape (as $(i^H(x))'_{x=0} > 0$ and $(i^H(x))'_{x=\bar{s}} < 0$), meaning that the investments at the border are lower than those in some internal locations. This in turn implies the underinvestment of infrastructure at the border compared to the first best allocation (the world planner's solution) where the maximum of infrastructure investments is achieved at the border. Figure 2 illustrates this reasoning and compares the optimal autarky $i^a(x)$, world-planner $i^w(x)$, and non-cooperative $(i^H(x), i^F(x))$ infrastructure investment schedules (for $\bar{s} = 1$).

Figure 2: The distribution of infrastructure investment across space



Notes. $i^a(x)$, $i^w(x)$, and $i^H(x)$ refer to the autarky, central-planer, and non-cooperative optimal infrastructure investment distributions.

5.3 Infrastructure Investments and Other Trade Costs

In this subsection, we discuss how the presence of additional trade costs (different from the transportation costs in the model) affects the equilibrium infrastructure profile. In particular, we assume that the cost of delivering one unit of a product produced at foreign location z to domestic location x is $\tau T(x, z)$, where $\tau > 1$ and $T(x, z)$ is modeled as before. Here, τ can be interpreted as some additional exogenous trade costs arising, for instance, from the presence of tariffs or other types of trade costs different from pure transportation costs. If τ is equal to one, then we have the framework considered above.²⁵

Under the presence of additional exogenous trade costs, $i^H(x)$ solves the similar system of equations (see *Proposition 6*):

$$\begin{aligned} i^H(x)^\delta &= \frac{bL\gamma(1-\alpha)(1-t^H)}{q} \left(\tilde{\phi}^{L,N}(x, \tau) + \tilde{\phi}^{R,N}(x, \tau) \right), \\ t^H &= \frac{q \int_0^{\bar{s}} i^H(x) dx}{bL}, \end{aligned}$$

where $\tilde{\phi}^{L,N}(x, \tau)$ and $\tilde{\phi}^{R,N}(x, \tau)$ depend on τ . Specifically, τ affects $\tilde{\phi}^{L,N}(x, \tau)$ and $\tilde{\phi}^{R,N}(x, \tau)$ through the costs of transporting products from Foreign to Home and through the aggregate consumption welfare (recall that the marginal gains from infrastructure investments are normalized by the aggregate consumption welfare, $\int_0^{\bar{s}} v(x) dx$). In the former case $\tilde{\phi}^{L,N}(x, \tau)$ is only affected, while in the latter case both $\tilde{\phi}^{L,N}(x, \tau)$ and $\tilde{\phi}^{R,N}(x, \tau)$ are affected (see the Appendix for details). Notice that as before, we focus only on the direct effects of changes in τ on the infrastructure investments.

One of the implications of considering only the direct effects is that we ignore the effects of changes in the tax rate t^H : that is, in the considered exercise t^H is fixed. This means that to some extent we explore the redistributive effects of τ on the infrastructure profile (as the total spendings on infrastructure remain unchanged). The following proposition holds:

Proposition 8 *The direct effect of a rise in τ is a decrease in $i^H(x)$ in some left neighborhood of the right border and an increase in $i^H(x)$ at locations that are relatively far from that border.*

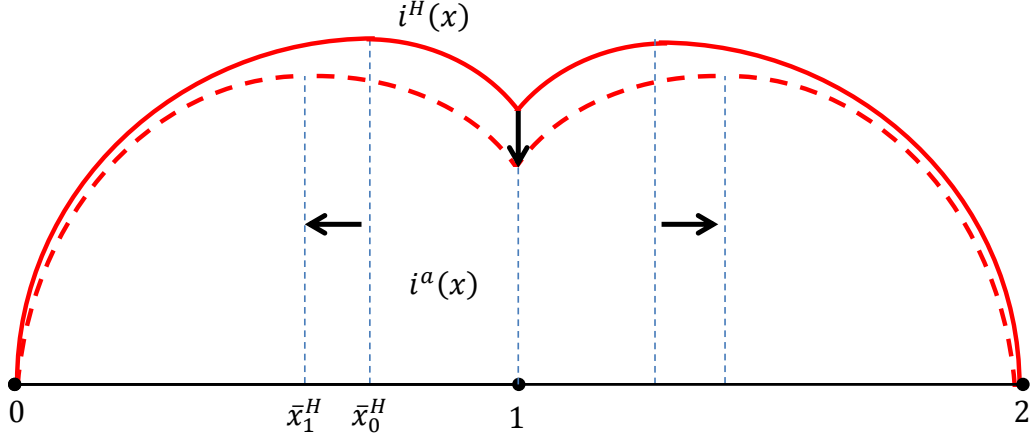
Proof In the Appendix.

Figure 3 provides an illustration.

In fact, the proposition implies that a rise in τ redistributes the infrastructure profile away from the border. This finding does not seem surprising, as a rise in the trade costs, τ , reduces

²⁵Notice that the additional trade costs take place only if a product is imported from foreign locations (there are no additional trade costs for transporting between domestic locations).

Figure 3: The effect of higher discrete border costs



Notes. Higher discrete border costs shift the Nash investment schedules down.

the gains from trade with the foreign country and, therefore, decreases the marginal returns from investing around the border, implying that $i^H(x)$ falls near the border. We believe that controlling for the indirect effects will not substantially change the above intuition and result in the similar redistribution of infrastructure investments. The numerical experiments we conduct in Section 6 confirms this belief.

The above results offer a natural explanation for the large border effect observed in the data. Indeed, a rise in τ not only increases the trade costs with the foreign country, but also decreases the stock of infrastructure around the border. As a result, the effect on the total transportation costs from Foreign to Home can be substantially magnified, implying a larger border effect.

6 Tentative empirical evidence

6.1 Testable implications from the model

The model has a range of predictions that can be put to an empirical test. In this section we discuss a number of those predictions without going into much detail. Appropriately discretized spatial data on intra- and international trade flows, associated to economic variables such as GDP, and direct information on the quantity and quality of transport infrastructure is difficult to construct and raises a number of important econometric issues, for example, related to spatial correlation of error terms.

The model also has interesting predictions relating to the effects of preferential trade liberalization. Infrastructure investment should be skewed towards that border which is economically

permeable. Subsequent waves of EU enlargement could be used to check this hypothesis.

The model could also be brought to a calibration exercise. Standard new economic geography models predict economic inequality, but require the existence of natural peripheries. Our argument would allow economic inequality across space even in circumstances where no natural periphery exists, and borders have exclusively political significance. Calibration exercises of the standard models often lead to simulated inequalities statistics that are too low compared to the data. Allowing for the endogenous allocation of $i(s)$ across space could help improve this fit.

Straightforward testing of the proposed model requires data on the quantity and quality of transport infrastructure across space. The actual distribution could then be compared to the distribution generated from a version of the model, where at least $m(s)$ is taken from real data. However, continuous data on $i(s)$, $m(s)$ or $q(s)$ is not available, hence, one has to discretize. This leads to a number of complications whose discussion we relegate to a full-fledged empirical analysis of the proposed model to future research.

In the present paper, we use a gravity-type estimation strategy to check whether easily available data for intra-US trade is consistent with our major result. While this ‘test’ is of limited reach, it nevertheless delivers results consistent with the model. However, any reasonable test of the model will have to relax the simplifying assumptions of a uniform distribution of population and investment prices adopted in the above analysis. We have already discussed what happens if $q(s)$ is not uniformly distributed and concluded that spatial variation in $q(s)$ needs to be very strong in order to undo the core results in our model. Similar considerations hold if $q(s)$ and $m(s)^{-1}$ are distributed in the same non-uniform manner. In the extreme case, where all agents are concentrated at \bar{x} so that $m(s) = 0$ if $s \neq \bar{x}$, the government would want to choose a infrastructure distribution much the same as individual agents would in the results presented in section , hence, $i(s)$ would have a hump-shaped form if the concentration of the mass of agent does not occur exactly at a border. If agents would locate arbitrarily close to borders, we would observe a U-shaped distribution of $i(s)$. However, it is clear that controlling for $m(s)$, we would recover our results, as investment beyond the benchmark of a uniform distribution would again take a hump-shaped form.

6.2 A gravity equation application

In the following empirical exercise, we want to explore data on US internal trade. We can test the above model using this specific data, since data from foreign countries is not necessary to check some of the predictions of the model. We now turn to the gravity equation that emanates from the structure of the model. Starting from the demand function for industrial

goods (8), substituting for $p(x, z)$ and the price index by (9) and (11), and recognizing that $Y^n = (1 - t) m(x) b$, it is possible to derive an expression for the c.i.f. value of trade from z to x :

$$X(x, z) = (1 - \alpha) (1 - t) m(x) b^{1-\sigma} \frac{T(x, z)^{1-\sigma}}{\left[\int_{z \in S} T(x, z)^{1-\sigma} dz \right]^{\frac{1}{1-\sigma}}} \text{ for } z \geq x. \quad (27)$$

The value of bilateral trade in industrial goods between x and z is a rather complicated function of the income of region x , $m(x) b$, and on the distribution of infrastructure in the interval $[x, z]$ which, in turn, shapes the cost factors $T(x, z)$. However, the comparative statics with respect to distance is relatively simple. The bilateral trade volume (27) between x and z depends on distance only through the term $T(x, z)^{1-\sigma}$. We may therefore write $X(x, z) = K(x) T(x, z)^{1-\sigma}$. Denoting the elasticity of X with respect to distance by $\varepsilon(x, z)$, we have

$$\varepsilon(x, z) \equiv \frac{\partial X(x, z)}{\partial z} \frac{z}{X(x, z)} = -\frac{\sigma - 1}{\delta - 1} z i(z)^{1-\delta} < 0.$$

Clearly,

$$\frac{\partial \varepsilon(x, z)}{\partial i(z)} = (\sigma - 1) z i(z)^{-\delta} > 0,$$

so that the marginal effect of an increase in distance depends positively on the stock of infrastructure invested at the marginal location. The higher that stock, the smaller the decline in trade volume.²⁶ Hence, the spatial variation in $i(s)$ translates directly into variation of ε . The equilibrium distribution function $i(z)$ achieves a series of local minima at border points. Hence, $\varepsilon(x, z)$ is more negative the closer z is to the border and is minimum at the border.

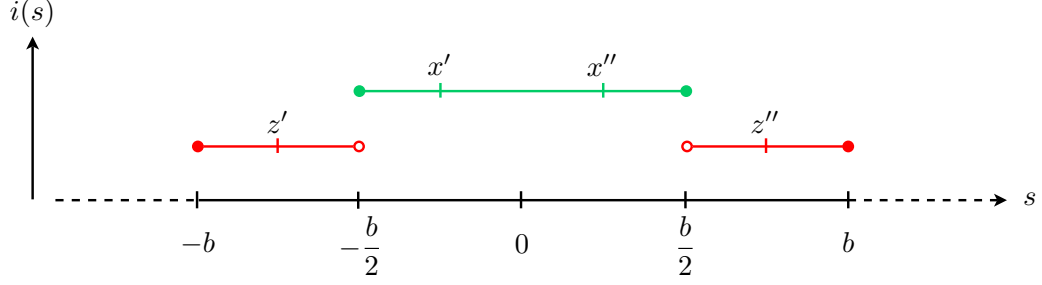
When bringing the theoretical model to the data, one has to discretize space. Data availability dictates how fine the grid of discretization can be. In the following empirical, distance to the closest border is proxied in a rather crude way by distinguishing between border regions and regions in the interior of the US. We keep, for the sake of simplicity, a uni-dimensional description of space. Let there be four regions in the US: two border regions and two central regions, as shown in figure .

Let i^b and i^c be the average stock of infrastructure investment in border and in central regions, respectively. Further, let x' and x'' be addresses in the interior of the US, and z', z'' be addresses in border regions. Let all these addresses be equidistant. Then, the model predicts that

$$\varepsilon(x', x'') > \varepsilon(x', z') \approx \varepsilon(x', z'') \approx \varepsilon(x'', z') \approx \varepsilon(x'', z'') > \varepsilon(z', z''). \quad (28)$$

²⁶Note the role of the elasticity of substitution σ between varieties of the industrial good. We have constrained $\sigma > 1$ in (6) when we have specified the utility function. Usually, with monopolistic competition, this assumption is required to ensure that the monopolists' decision problems are well defined. With perfect competition, however, this is not necessary. However, we need the assumption $\sigma > 1$ to ensure that the c.i.f. value of trade declines in iceberg costs.

Figure 4: Border and central regions in the empirical setup



Notes. Infrastructure investment on the real line.

6.3 Data and empirical strategy

We use data on bilateral trade volumes between US states for 1993. This data has been used by Anderson & van Wincoop (2003) and is extensively discussed in that article. The focus on the US follows from the fact that Canadian provinces are excessively large and have almost always a North–South extension that makes almost all of them border states.

In order to check a discretized version of (27), we run a standard gravity equation with importer/exporter fixed effects and usual covariates to explain intra US trade volumes. The model predicts that infrastructure investment is lower in border regions than in interior ones, hence trades involving border regions should be affected by a larger distance elasticity. For a formal empirical test, we interact the border-region dummy with the log of distance and see whether it turns out whether the absolute value of the elasticity of distance $\varepsilon(x, z)$ is indeed more negative for trades where either x or z or both belong to border regions. Note that the estimated elasticities are conditional on distance, regional GDPs, and the density of population in each state.

6.4 Results

Table 3 shows the results of our regression. Column (1) shows the results of a very standard gravity equation with importer and exporter fixed effects. These fixed effects are meant to capture all unobserved state specific variables that may be important for the determination of bilateral trade volumes. Most importantly for the economic environment at hand, they control for differences across states in infrastructure investment relating to non land-borne transit, e.g., air traffic.²⁷ A bunch of control is included to control for geographical variation in economic

²⁷They also control for interregional differences in multilateral resistance indexes, see Anderson and van Wincoop (2003) or Feenstra (2004) for more details on the econometric foundation of the specific version of the gravity

Table 4: Trade flow elasticity of distance is higher if peripheral regions are involved

Within US trade, 1993					
	(1)	(2)	(3)	(4)	(5)
Ln Distance	-0.957*** (0.042)	-0.884*** (0.044)	-0.827*** (0.038)	-0.876*** (0.051)	-0.831*** (0.046)
Ln Distance X Border		-0.194*** (0.073)	-0.142 (0.096)		
Ln Distance X Importer Border				-0.127** (0.064)	
Ln Distance X Exporter Border					-0.245*** (0.060)
Border (dummy)		1.530*** (0.56)	1.052 (0.72)		
Exporter border (dummy)					-0.189* (0.097)
Importer border (dummy)				0.0164 (0.11)	
Ln GDP Exporter	1.111*** (0.053)	1.069*** (0.054)	1.053*** (0.024)	1.515*** (0.22)	1.150*** (0.034)
Ln GDP Importer	1.238*** (0.051)	1.199*** (0.053)	1.063*** (0.023)	1.180*** (0.036)	2.073*** (0.21)
Density Exporter	-0.725** (0.28)	-0.579** (0.28)	-0.840*** (0.23)	-1.87*** (0.66)	-0.881*** (0.31)
Density Importer	-1.14*** (0.26)	-1.00*** (0.26)	-1.49*** (0.25)	-0.989*** (0.31)	-3.52*** (0.62)
Contiguity	0.499*** (0.089)	0.505*** (0.089)	0.606*** (0.098)	0.517*** (0.090)	0.531 ^a (0.088)
RMSE	0.453	0.450	0.573	0.452	0.447
R^2	93.5	93.6	89.7	93.6	93.7
Notes. $N = 832$. Robust standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$ All regressions include state dummies; not shown.					

activity and the price of infrastructure investment. GDP measures are country specific and would drop out of the equation if the panel were balanced. It is not, which explains why they show up in the table. However, their estimates take values close to unity, which is exactly what gravity theory would predict. Also the distance elasticity, which can be interpreted as an average over interior and border regions takes a value very close to what the literature finds. All covariates are estimated with substantial precision, delivering an overall R^2 statistics of 94 percent.

Column (2) shows that $\varepsilon(x', x'') = 0.884$ and $\varepsilon(z', z'') = 1.078$, with both estimates significantly different from each other. Hence, a marginal increase in distance hurts significantly more for trade relations that involve only border states than for trade relations involving only

equation used here.

central locations. This finding is consistent with the proposed literature. Note, however, when the model is estimated without fixed effects (column (3)), the interaction term still takes the same sign and similar size, but is no longer statistically different from zero. This is expected, see the recent discussion on the correct specification of the gravity equation (Anderson and van Wincoop, 2003, or Feenstra, 2004, p. 161 ff). Columns (4) and (5) show that in line with theory, trade relations that involve only one border region have distance elasticities lying in the interval $[\varepsilon(x', x''), \varepsilon(z', z'')]$, namely 1,003 and 1,076. While the latter estimate is close to the one obtained for both partners being border regions, column (4) and (5) can still be interpreted as lending additional support to the theoretical model.

The presented econometric evidence is suggestive, but not more. There are a couple of problems that relate to the discretization of economic space into unevenly designed states. Ideally, one would run a model where the distance coefficients are interacted with a measure of distance to the border. Continuous space trade data being unavailable, the researcher has to make compromises. However, drawing on European NUTS or US county level data, one could expect to make more precise inference than using state level data.

7 A Robustness Check and Extensions

In this section, we consider an example when infrastructure investments are made by a third party and discuss potential extensions of the model.

7.1 The Monopolist Case

In the analysis above, we assume that the infrastructure profile is chosen by the government. However, it can be the case that the government "outsources" infrastructure investments to a third party. Below we consider a simple example of such a situation and show that the qualitative implications of the model do not change.

We assume that there is a monopolist, who decides on the infrastructure profile. The decision is based on the profit maximization and the profits of the monopolist are given by

$$\pi(i^M) = p \int_0^{\bar{s}} \bar{R}(x) dx - \int_0^{\bar{s}} q(x) i^M(x) dx, \quad (29)$$

where p is the price per unit of the traffic the monopolist receives, $\bar{R}(x)$ is the measure of the total traffic through location x , $i^M(x)$ is infrastructure investments at location x , and $q(x)$ is the cost of the investments. In the above specification, we assume that the government subsidizes the transportation sector by paying the fixed price p per unit of the traffic to the monopolist

(for example, such a subsidy can be financed through an income tax), who conditional on that invests in the transportation infrastructure. This implies that the monopolist takes the price p as given and p does not affect the transportation costs and, therefore, the c.i.f. prices of products (as p is paid by the government). Such an assumption removes the distortive effects of p on the infrastructure profile.

Next, we describe the infrastructure profile chosen by the monopolist in case of closed and open economies.

7.1.1 The Closed Economy

In the closed economy, the total traffic through location x is given by

$$\bar{R}(x) = \int_0^x \left(\int_x^{\bar{s}} R(y, z) dz \right) dy + \int_x^{\bar{s}} \left(\int_0^x R(y, z) dz \right) dy,$$

where

$$R(y, z) = (1 - \alpha)(1 - t^M) \frac{Y(z)T(y, z)^{1-\sigma}}{\int_0^{\bar{s}} T(v, z)^{1-\sigma} dv}.$$

Here, $R(y, z)$ is interpreted as the traffic from y to z : the number of units of a product produced at y and transported to z . It is determined by demand at location z and the transportation costs from y to z . Note that in general $R(y, z)$ is not equal to $R(z, y)$. Finally, t^M is the income tax imposed by the government to finance the infrastructure investments and $Y(z)$ is the aggregate income at location z . We assume that the monopolist takes the income tax and the location sizes as given.

It is possible to show that in case of the interior solution, the infrastructure profile maximizing the monopolist's profit is given by

$$i^M(x)^\delta = \frac{p\gamma(1 - \alpha)(1 - t^M)(\sigma - 1)}{q(x)} (\phi^{L,M}(x) + \phi^{R,M}(x)), \quad (30)$$

where $\phi^{L,M}(x)$ ($\phi^{R,M}(x)$) represents the aggregate marginal profits due to a rise in traffic from the right (the left) to the left (the right) of location x .²⁸ The infrastructure profile chosen by the monopolist has qualitative properties that are similar to those in the benchmark case. Specifically, $i^M(0) = i^M(\bar{s}) = 0$. If $q(x) = q$ and $Y(z) = Y$ for all $x, z \in [0, \bar{s}]$ (implying no asymmetries in the cost of infrastructure and the distribution of income), the infrastructure profile has a hump shape and is symmetric around $\bar{s}/2$.

However, there is also a conceptual difference. Under certain parameters, it can be the case that the monopolist finds it optimal to put zero investments into the locations, which are

²⁸The corresponding derivations and the expressions for $\phi^{L,M}(x)$ and $\phi^{R,M}(x)$ are available in the Online Appendix.

relatively close to the borders. As a result, there can be regions (with positive measure) that do not have transport infrastructure at all. In contrast, the social planner chooses positive infrastructure investments for all locations (except $x = 0$ and $x = \bar{s}$).

The intuition behind this outcome is as follows. A rise in the infrastructure investments in a certain region has two effects on the total traffic. On the one hand, due to better infrastructure the traffic through the region goes up, increasing the total traffic. On the other hand, the traffic through other regions goes down because of the corresponding changes in the price indices. This tends to decrease the total traffic. It appears that in some cases the negative effect prevails over the positive one in the border regions, resulting in zero infrastructure investments around the borders.

Figure XX simulates the infrastructure distributions (in the symmetric case) chosen by the monopolist and the social planner under the same set of the parameters in the model. In the numerical experiment, the value of p is chosen such that the total cost of infrastructure investments is the same in both cases: i.e., the two distributions have the same average. As can be seen from the figure, the social planner tends to invest more around the periphery, while the monopolist invests more around the geographical center of the economy.

FIGURE

7.1.2 The Open Economy

In the open economy, the total traffic through location x is given by

$$\bar{R}(x) = \int_0^x \left(\int_x^{2\bar{s}} R(y, z) dz \right) dy + \int_x^{2\bar{s}} \left(\int_0^x R(y, z) dz \right) dy.$$

As in the benchmark case, we assume that the monopolists at Home and Foreign choose the corresponding infrastructure investments in a non-cooperative way. In the symmetric Nash equilibrium with no asymmetries in the cost of infrastructure and the location size, the domestic infrastructure profile (in case of the interior solution) is given by

$$\tilde{i}^M(x)^\delta = \frac{p\gamma(1-\alpha)(1-\tilde{t}^M)(\sigma-1)}{q} \left(\tilde{\phi}^{L,M}(x) + \tilde{\phi}^{R,M}(x) \right),$$

where as before $\tilde{\phi}^{L,M}(x)$ ($\tilde{\phi}^{R,M}(x)$) represents the aggregate marginal profits due to a rise in traffic from the right (the left) to the left (the right) of location x . Similar to the social planner solution in the open economy, the infrastructure profile is skewed towards the border with the foreign country. Moreover, numerical simulations show that the infrastructure distribution has

a hump shape.²⁹ Finally, it is straightforward to show that the presence of costs associated with crossing the border will redistribute the infrastructure away from the border, amplifying the border effect.

Figure XX compares the simulated infrastructure distributions chosen by the social planner and the monopolist in the open economy (as in the previous figure, the two distributions have the same average) with the distribution chosen by the world social planner. As can be inferred from the figure, the monopolist tends to invest more around the border with the foreign country, while the social planner invests more at the periphery. This is in line with the idea outlined in the previous section that the monopolist invests more at central locations of the economy. However, simulations demonstrate that even though the monopolist invests more around the border than the social planner does, there is still substantial underinvestments in the infrastructure compared to the first best allocation.

FIGURE

7.2 Extensions

Toll taxes. In reality, many countries operate toll taxes for freight traffic. The ratio of interregional highways subject to decentrally administered toll systems ranges from 6 percent to 52 percent in France.³⁰ Countries such as Germany and Austria have centrally administered distance dependent road pricing for lorries. User fees may be contingent on a wide array of factors such as the situation of the environment (e.g., smog), the degree of congestion, the time at which a road is traveled (fees may be higher for travel during night or weekends), or whether an sensible region is crossed (e.g., some protected zone).

How a toll system affects the main argument in this paper depends very much on its specific design. Suppose, the government decides on the infrastructure allocation across space, but rather than taxing consumers through lump-sum taxes, it taxes road users without discriminating between home- or foreign-bound transport. This kind of taxation is of course distortionary, since it will affect goods prices of the regional and the world economy. Further assume that the fee may vary continuously on the space of addresses and that it works just as our iceberg transportation costs, albeit with the shaved transported good not lost but transferred into the governments coffers. In that case, the government has two margins of action: it sets a distribution of fees, $f(s)$, $s \in [0, 1]$ and decides on the infrastructure allocation, $i(s)$. Total income from fees

²⁹A strict proof of a hump shape of the infrastructure distribution appears to be quite complicated.

³⁰Data from 1998 for France (Combes and Lafourcade, 2005), and 2006 for the US.

will be $B = \int_0^1 f(s) X(s) ds$, where $X(s)$ is the value of goods, measured at ex-factory prices, that are transported through the point s . Note that $X(s)$ depends on the domestic and foreign distribution of infrastructure. If the government is free to spend B on whatever infrastructure distribution it prefers, and does not impose any additional tax, it will find it optimal to make fees dependent on the distance to the border, with higher fees the closer the border. Moreover, it will concentrate its spending as before in the central regions of the jurisdiction. The reason for this result is identical to the one discussed above: The government cares only about home welfare, thus taxing foreigners and transferring the receipts to home citizens is a welcome option.

If governments are not allowed to spend toll income on places other than those where the income has been generated, there will now be a direct link between infrastructure investment and transit volume, $f(s) X(s) / q(s) = i(s)$. Governments will then set $f(s)$ such that native welfare is maximized. By imposing high fees in border regions, governments tax foreign consumers more strongly than domestic ones; however, the implied high investment volumes are of little value for domestic consumers. By imposing high fees in the center, governments affect domestic consumers, but also achieve high utility for them. The implied distribution of infrastructure need not exhibit excessive spatial variation, but it still can; the exact outcome depending on underlying model parameters.

There are a number of institutional arrangements that involve the private sector into the construction and maintenance of transport infrastructure projects. Governments could sell exploitation licenses to private firms who construct roads and set fee structures $f(s)$. While this is a choice of many governments, the economic modeling poses a number of problems, since one would have to decide whether the licenses are sold to a single provider, to a consortium, or to local monopolists, and whether those firms can commit to certain fee schedules and infrastructure investments when making their bids.

Supranational entities. Since decentralized transport infrastructure decisions generate positive externalities leading to a global underprovision and excessive spatial variation of infrastructure investment, there is a case for a supranational entity, such as the European Union (EU), to intervene. Indeed, the EU is involved in a large project, the Trans-European-Networks (TEN), that strives to coordinate and cofinance national infrastructure provision efforts. Member states have committed themselves to construct a number of road and rail links that link European regions. The EU, in turn, cofinances these projects. The degree of cofinancing is higher in peripheral regions than in central ones. Is this policy able to internalize the externalities highlighted in the present paper?

In principle, the answer is yes. In order to achieve the first-best infrastructure distribution,

the EU should be allowed to tax citizens (or member state governments on their behalf) and subsidize the price of infrastructure. For example if $q'(s) = 1$ for all s , so that the efficient infrastructure schedule should exhibit no spatial variation, the EU could allow subsidize $q(s)$ such that the effective price of infrastructure projects paid by domestic governments declines as we move closer to the border. The optimal rate of decline should be related to the rate at which the the share of domestic beneficiaries falls, so that the growth rates of the stock of infrastructure investment is zero across space.

The problem with the above subsidization principle is that it does not ensure that the overall quantity of infrastructure provision is efficient. To the extent that the domestic planner overinvests in the neighborhood of the median address \bar{x} , a policy geared towards a uniform spatial distribution of infrastructure leads to overinvestment.

Internal labor mobility. Instead of allowing goods prices to adjust to demand conditions so that an endogenous distribution $p(s)$ emerges but leave the distribution $m(s)$ uniform, one could also let $m(s)$ adjust endogenously so that indirect utilities are equalized across space. The governments would nevertheless propose uneven infrastructure investment schedules, since they still fail to take into account the positive externality that they exert on consumers in the rest of the world.

8 Conclusions

This paper develops a model where consumers demand goods from the entire world, but the world is fragmented into jurisdictions which set infrastructure investment schedules in a non-cooperative way. Governments caring only for their own welfare constituency will ignore the effects that their decisions have on foreign consumers; this basic externality leads to global underinvestment. The externality is stronger the more foreign-bound transit flows through an address, and the size of such transit is larger the closer national borders are to that address. Hence, infrastructure underinvestment is stronger in peripheral regions of jurisdictions rather than in central ones.

The local lack of infrastructure investment makes imports from other countries more expensive than imports from other regions from the same country, even if geographical distance or incomes of trading partners are the same. Our infrastructure story may therefore contribute towards unpacking trade costs and explaining the border puzzle highlighted by McCallum (1995).

The paper also presents some tentative empirical support for the theoretical results, drawing on trade data for US states. It turns out that trade relations that involve at least one border

region feature higher distance elasticities. Hence, transportation costs seem higher for the same distance when a border is crossed.

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Appendix

In the Appendix, we provide all the necessary proofs for the lemmas and propositions in the paper.

Proof of Lemma 1

Property (iv)

The behavior of $T(x, z)$ with respect to geographical distance can be checked by looking at the derivative of $T(x, z)$ with respect to z . Specifically, we have that

$$\begin{aligned}
T(x, z) &= \left(1 + \frac{1}{\delta - 1} \int_x^z i(s)^{1-\delta} ds\right)^\gamma, \\
T_z(x, z) &= \gamma \left(1 + \frac{1}{\delta - 1} \int_x^z i(s)^{1-\delta} ds\right)^{\gamma-1} \frac{1}{\delta - 1} [i(z)^{1-\delta}] > 0, \\
T_{zz}(x, z) &= \gamma \left(1 + \frac{1}{\delta - 1} \int_x^z i(s)^{1-\delta} ds\right)^{\gamma-1} \left((\gamma - 1) \frac{\left(\frac{1}{\delta - 1} [i(z)^{1-\delta}]\right)^2}{1 + \frac{1}{\delta - 1} \int_x^z i(s)^{1-\delta} ds} - i(z)^{-\delta} i'(z) \right) \geq 0 \\
&\iff \frac{(\gamma - 1)}{(T(x, z))^{1/\gamma}} \left(\frac{i(z)^{1-\delta}}{\delta - 1}\right)^2 \geq i'(z) i(z)^{-\delta}.
\end{aligned}$$

The left-hand side shows the effect of a marginal increase in distance on $T_z(x, z)$ under the assumption that $i(z + dz) = i(z)$. It reflects variation in trade costs due to an increase in distance, holding infrastructure constant. The right-hand side makes the opposite assumption and reports the change in $T_z(x, z)$ due to the difference in infrastructure investment between z and $z + dz$, holding the sheer costs of distance constant. $T(x, z)$ is convex (as in Krugman), if the left-hand side dominates.

Property (v)

We compute the elasticity of substitution between investment at two different locations $s', s'' \in [x, z]$ as follows

$$-\frac{d \ln [i(s') / i(s'')]}{d \ln \left| \frac{\partial T(x, z)}{\partial i(s')} / \frac{\partial T(x, z)}{\partial i(s'')} \right|},$$

where for any $s \in [x, z]$

$$\frac{\partial T(x, z)}{\partial i(s)} \stackrel{d.}{=} \gamma \left(1 + \frac{1}{\delta - 1} \int_x^z i(s)^{1-\delta} ds\right)^{\gamma-1} i(s)^{-\delta}.$$

As a result, the elasticity of substitution is given by

$$-\frac{d \ln [i(s') / i(s'')]}{-d \delta \ln |i(s') / i(s'')|} = \frac{1}{\delta} < 1.$$

Property (vi)

The Lagrangian for the cost minimizing problem can be written as follows:

$$\Lambda(\{i(s)\}, \lambda) = q \int_x^z i(s) ds + \lambda \left[1 + \frac{1}{\delta - 1} \int_x^z i(s)^{1-\delta} ds - \bar{T}^{1/\gamma} \right],$$

where q is the cost of infrastructure investment at location s . It is straightforward to see that the first order conditions imply that, for any two locations $k, l \in [x, z]$,

$$i(k) = i(l).$$

Taking into account the budget constraint, we derive that

$$i(k) = i(l) = \left\{ (z - x) / \left[(\delta - 1) \left(\bar{T}^{1/\gamma} - 1 \right) \right] \right\}^{1/(\delta-1)}.$$

Proof of Proposition 1

To find the optimal infrastructure investments on $[0, \bar{s}]$, we first formulate and analyze a discrete modification of the social planner's maximization problem (which approximates the actual continuous maximization problem). Remember that the social planner solves

$$\{i^a(x), t^a\}_{x \in S} = \arg \max \left\{ (1 - t) \left(\int_{x \in S} \tilde{m}(x) v(x) dx \right)^{\frac{1-\alpha}{\sigma-1}} \mid \int_{x \in S} q(x) i(x) dx \leq btL \right\}.$$

where

$$\begin{aligned} v(x) &= \int_{z \in S} T(x, z)^{1-\sigma} dz \\ &= \int_0^{\bar{s}} \left(1 + \frac{1}{\delta-1} \left| \int_x^z i(s)^{1-\delta} ds \right| \right)^{\gamma(1-\sigma)} dz \\ &= \int_0^x \left(1 + \frac{1}{\delta-1} \int_z^x i(s)^{1-\delta} ds \right)^{\gamma(1-\sigma)} dz + \int_x^{\bar{s}} \left(1 + \frac{1}{\delta-1} \int_x^z i(s)^{1-\delta} ds \right)^{\gamma(1-\sigma)} dz. \end{aligned}$$

In the discrete version of the problem, we assume that the geography of the economy consists of n points (transportation hubs) uniformly distributed on $[0, \bar{s}]$: $0 = x_1 < x_2 < \dots < x_n = \bar{s}$. We define the distance between location x_i and x_{i+1} by Δ_n : that is, $x_2 - x_1 = \dots = x_n - x_{n-1} = \Delta_n$. We also assume that the transportation costs between two locations, x_i and x_j , depend on the level of infrastructure at the location of the producer and the intermediate locations between x_i and x_j (not including the location of the consumer) and the distance between the locations determined by Δ_n .³¹ Specifically, if a product is sent from x_i to x_j ($x_i < x_j$), the transportation costs are

$$T(x_i, x_j) = \left(1 + \frac{1}{\delta-1} \sum_{k=i}^{j-1} i(x_k)^{1-\delta} \Delta_n \right)^{\gamma}.$$

We then formulate the social planner's problem in the case of the discrete geography in the following way:

$$\{i^a(x_i), t^a\}_{i=1..n} = \arg \max \left\{ (1 - t) \left(\sum_{i=1}^n \tilde{m}(x_i) v(x_i) \Delta_n \right)^{\frac{1-\alpha}{\sigma-1}} \right\}, \quad (31)$$

subject to

$$\sum_{i=1}^n q(x_i) i(x_i) \Delta_n \leq btL, \quad (32)$$

$$i(x_i) \geq 0, i = 1..n. \quad (33)$$

³¹The fact that the transportation costs between x_i and x_j do not include the level of infrastructure investment at the destination location (the location of the consumer) means non-symmetric transport costs. However, taking the limit ($n \rightarrow \infty$) will imply symmetric transport costs between any locations, as in this case the contribution of the infrastructure of a single location into the total transport costs will be zero.

Here,

$$v(x_i) = \Delta_n \left(\begin{array}{c} \sum_{k=1}^{i-1} \left(1 + \frac{1}{\delta-1} \sum_{j=k}^{i-1} i(x_j)^{1-\delta} \Delta_n \right)^{\gamma(1-\sigma)} + \\ \sum_{k=i+1}^n \left(1 + \frac{1}{\delta-1} \sum_{j=i+1}^k i(x_j)^{1-\delta} \Delta_n \right)^{\gamma(1-\sigma)} + 1 \end{array} \right), \quad (34)$$

where the first term in the brackets describes the welfare derived from trade with locations on the left side of x_i , the second term describes the welfare derived from trade with locations on the right side of x_i , and one stands for the transportation costs from x_i to x_i (that are normalized to unity). In this case, the social planner's problem is to choose the level of transportation infrastructure at each location x_i that maximizes the social welfare. This maximization problem is the approximation of the maximization problem in the main text (see (14)). Specifically, taking the limit ($n \rightarrow \infty$), one can derive the actual maximization problem described in the main text. This in turn implies that the solution of the continuous maximization problem is the limit of the solution of the discrete problem (when $n \rightarrow \infty$).

Note that the existence of the global maximum in the above discrete maximization problem follows from the continuity of the objective function and the fact that the objective function is maximized on the compact subset of R^n (which is given by the constraints in (32) and (33)). Moreover, it is straightforward to show that if $\gamma(\sigma-1)(\delta-1) < 1$ (as assumed in the paper), $\left(1 + \frac{1}{\delta-1} \sum_{j=i+1}^k i(x_j)^{1-\delta} \Delta_n\right)^{\gamma(1-\sigma)}$ is a concave function in $i(x) = \{i(x_j)\}_{j=1..n}$ for any i and k . This in turn implies that $\tilde{v}(x_i)$ is concave in $i(x)$ as the sum of concave functions, but not strictly concave, as $v(x_i)$ does not depend on $i(x_i)$. However, it is straightforward to show that $\sum_{i=1}^n \tilde{m}(x_i) v(x_i)$ is strictly concave with respect to $i(x)$. Finally, since $(1-\alpha)/(\sigma-1)$ is assumed to be strictly less than one, the objective function in (31) is strictly concave in infrastructure investments, $i(x)$.

Next, we formulate the corresponding Lagrange function that can be written as follows:

$$\Lambda \equiv (1-t) \left(\Delta_n \sum_{i=1}^n \tilde{m}(x_i) v(x_i) \right)^{\frac{1-\alpha}{\sigma-1}} - \lambda_0 \left(\sum_{i=1}^n q(x_i) i(x_i) \Delta_n - btL \right),$$

where λ_0 is the Lagrange multiplier of the corresponding constraint. The necessary and sufficient condition for the global maximum is that

$$\begin{aligned} \frac{\partial \Lambda}{\partial i(x_i)} &= 0, \quad i = 1..n, \\ \frac{\partial \Lambda}{\partial t} &= 0. \end{aligned}$$

Next, we find the expression for $\partial \Lambda / \partial i(x_i)$. Specifically,

$$\frac{\partial \Lambda}{\partial i(x_i)} = \frac{(1-t)(1-\alpha)}{\sigma-1} \Delta_n \left(\Delta_n \sum_{l=1}^n \tilde{m}(x_l) v(x_l) \right)^{\frac{1-\alpha}{\sigma-1}-1} \sum_{l=1}^n \tilde{m}(x_l) (v(x_l))'_{i(x_i)} - \lambda_0 \Delta_n q(x_i). \quad (35)$$

It is straightforward to see that

$$\begin{aligned} (v(x_l))'_{i(x_i)} &= (\Delta_n)^2 \gamma(\sigma-1) i(x_i)^{-\delta} \sum_{k=1}^i \left(1 + \frac{1}{\delta-1} \sum_{j=k}^{l-1} i(x_j)^{1-\delta} \Delta_n \right)^{\gamma(1-\sigma)-1} & \text{if } i < l, \\ (v(x_l))'_{i(x_i)} &= (\Delta_n)^2 \gamma(\sigma-1) i(x_i)^{-\delta} \sum_{k=i}^n \left(1 + \frac{1}{\delta-1} \sum_{j=l+1}^k i(x_j)^{1-\delta} \Delta_n \right)^{\gamma(1-\sigma)-1} & \text{if } i > l, \\ (v(x_l))'_{i(x_i)} &= 0 & \text{if } i = l. \end{aligned}$$

As a result,

$$\begin{aligned} \frac{\partial \Lambda}{\partial i(x_i)} &= \frac{(\Delta_n)^3 \frac{\gamma(1-\alpha)(1-t)}{i(x_i)^\delta} \sum_{l=1}^{i-1} \tilde{m}(x_l) \left(\sum_{k=i}^n \left(1 + \frac{1}{\delta-1} \frac{k}{j=l+1} i(x_j)^{1-\delta} \Delta_n \right)^{\gamma(1-\sigma)-1} \right)}{(\Delta_n \sum_{l=1}^n \tilde{m}(x_l) v(x_l))^{1-\frac{1-\alpha}{\sigma-1}}} \\ &+ \frac{(\Delta_n)^3 \frac{(1-\alpha)(1-t)}{i(x_i)^\delta} \sum_{l=i+1}^n \tilde{m}(x_l) \left(\sum_{k=1}^i \left(1 + \frac{1}{\delta-1} \frac{l-1}{j=k} i(x_j)^{1-\delta} \Delta_n \right)^{\gamma(1-\sigma)-1} \right)}{(\Delta_n \sum_{l=1}^n \tilde{m}(x_l) v(x_l))^{1-\frac{1-\alpha}{\sigma-1}}} \\ &- \lambda_0 \Delta_n q(x_i). \end{aligned} \quad (36)$$

Finally,

$$\begin{aligned} \frac{\partial \Lambda}{\partial t} &= - \left(\Delta_n \sum_{l=1}^n \tilde{m}(x_l) v(x_l) \right)^{\frac{1-\alpha}{\sigma-1}} + \lambda_0 bL = 0 \iff \\ \lambda_0 &= \frac{(\Delta_n \sum_{l=1}^n \tilde{m}(x_l) v(x_l))^{\frac{1-\alpha}{\sigma-1}}}{bL}. \end{aligned} \quad (37)$$

Note that since $\frac{\partial \Lambda}{\partial i(x_i)}|_{i(x_i)=0} = \infty$ (because of $\gamma(\sigma-1)(\delta-1) < 1$), $i^a(x_i)$ is strictly greater than zero for all $i = 1..n$. That is, the global maximum $\{i^a(x_i), t^a\}_{i=1..n}$ does not include zero investments and, therefore, solves the following system of equations

$$\begin{aligned} \frac{q(x_i) i^a(x_i)^\delta}{\Delta_n bL \gamma(1-\alpha)(1-t^a)} &= \frac{\sum_{l=1}^{i-1} \tilde{m}(x_l) \left(\sum_{k=i}^n \left(1 + \frac{1}{\delta-1} \frac{k}{j=l+1} i^a(x_j)^{1-\delta} \Delta_n \right)^{\gamma(1-\sigma)-1} \right)}{\sum_{i=1}^n \tilde{m}(x_i) v(x_i)} \\ &+ \frac{\sum_{l=i+1}^n \tilde{m}(x_l) \left(\sum_{k=1}^i \left(1 + \frac{1}{\delta-1} \frac{l-1}{j=k} i^a(x_j)^{1-\delta} \Delta_n \right)^{\gamma(1-\sigma)-1} \right)}{\sum_{i=1}^n \tilde{m}(x_i) v(x_i)}, \\ \sum_{i=1}^n q(x_i) i^a(x_i) \Delta_n &= bt^a L. \end{aligned} \quad (38)$$

As the solution of the continuous maximization problem is the limit of the solution of the discrete problem (when $n \rightarrow \infty$), it is straightforward to see that the optimal infrastructure investment function $i^a(x)$ and the tax rate t^a solve

$$\begin{aligned} i^a(x)^\delta &= \frac{bL \gamma(1-\alpha)(1-t^a)}{q(x)} (\phi^L(x) + \phi^R(x)), \\ t^a &= \frac{\int_0^{\bar{s}} q(s) i^a(s) ds}{b}, \end{aligned}$$

where

$$\begin{aligned} \phi^L(x) &= \frac{\int_0^x \tilde{m}(s) \left(\int_x^{\bar{s}} \left(1 + \frac{1}{\delta-1} \int_s^t i^a(r)^{1-\delta} dr \right)^{\gamma(1-\sigma)-1} dt \right) ds}{\int_0^{\bar{s}} \tilde{m}(s) v(s) ds}, \\ \phi^R(x) &= \frac{\int_x^{\bar{s}} \tilde{m}(s) \left(\int_0^x \left(1 + \frac{1}{\delta-1} \int_t^s i^a(r)^{1-\delta} dr \right)^{\gamma(1-\sigma)-1} dt \right) ds}{\int_0^{\bar{s}} \tilde{m}(s) v(s) ds}. \end{aligned}$$

Proof of Proposition 2

Property (ii)

Note that the derivative of $i^a(x)$ with respect to x can be written as follows:

$$\begin{aligned} q(x)\delta i^a(x)^{\delta-1} (i^a(x))' + q'(x)i^a(x)^\delta &= bL\gamma(1-\alpha)(1-t^a) \left((\phi^L(x))' + (\phi^R(x))' \right) \iff \\ (i^a(x))' &= \frac{bL\gamma(1-\alpha)(1-t^a) \left((\phi^L(x))' + (\phi^R(x))' \right) - q'(x)i^a(x)^\delta}{q(x)\delta i^a(x)^{\delta-1}}. \end{aligned}$$

We have that

$$\begin{aligned} (\phi^L(x))' &= \frac{\tilde{m}(x) \left(\int_x^{\bar{s}} \left(1 + \frac{1}{\delta-1} \int_x^t i(r)^{1-\delta} dr \right)^{\gamma(1-\sigma)-1} dt \right) - \int_0^x \tilde{m}(s) \left(1 + \frac{1}{\delta-1} \int_s^x i(r)^{1-\delta} dr \right)^{\gamma(1-\sigma)-1} ds}{\int_0^{\bar{s}} \tilde{m}(s) v(s) ds}, \\ (\phi^R(x))' &= \frac{-\tilde{m}(x) \left(\int_0^x \left(1 + \frac{1}{\delta-1} \int_t^x i(r)^{1-\delta} dr \right)^{\gamma(1-\sigma)-1} dt \right) + \int_x^{\bar{s}} \tilde{m}(s) \left(1 + \frac{1}{\delta-1} \int_x^s i(r)^{1-\delta} dr \right)^{\gamma(1-\sigma)-1} ds}{\int_0^{\bar{s}} \tilde{m}(s) v(s) ds}. \end{aligned}$$

It is straightforward to see that

$$\begin{aligned} (\phi^L(0))' + (\phi^R(0))' &> 0, \\ (\phi^L(1))' + (\phi^R(1))' &< 0. \end{aligned}$$

Since $q'(x)$ is continuous on $[0, \bar{s}]$ and $i^a(0) = i^a(\bar{s}) = 0$, $q'(0)i^a(0)^\delta = q'(\bar{s})i^a(\bar{s})^\delta = 0$. This in turn immediately implies that

$$\begin{aligned} (i^a(0))' &= \infty \\ (i^a(\bar{s}))' &= -\infty. \end{aligned}$$

Property (iii)

First, we show that $i^a(x)$ is symmetric around $x = \bar{s}/2$. To do so, we use the fact that the objective function of the planner's problem is strictly concave, implying that there is a unique solution of (19). Indeed, if there are two different solutions of (19), then there are two different stationary points, which is not possible with a strictly concave objective function. It is straightforward to see that if there is no variation in the cost of infrastructure investment and the household size across the locations: $q(x) = q$ and $m(x) = m$ for any $x \in [0, \bar{s}]$, symmetric investments indeed solve (19). Taking into account the uniqueness of the solution, we can conclude that the symmetric infrastructure profile delivers the global maximum of the maximization problem. Finally, if $i^a(x)$ is symmetric around $x = \bar{s}/2$, the transportation costs are symmetric and, thereby, $v(x)$ is symmetric as well (this immediately follows from the definition of $v(x)$ (see (15)).

Next, we prove that $i^a(x)$ has a hump shape with the peak at $x = \bar{s}$. Note that the optimal investment profile can be considered as a unique fixed point of a certain functional $J : E \rightarrow E$. Here, E is the subset of the space of symmetric (around $x = \bar{s}/2$) continuous functions on $[0, \bar{s}]$, which is determined by the constraints in the maximization problem. Specifically, the functional is given by

$$J(i^a(x)) = \left(\frac{bL\gamma(1-\alpha)(1-t^a)}{q} (\phi^L(x) + \phi^R(x)) \right)^{1/\delta},$$

where

$$\begin{aligned}\phi^L(x) &= \frac{\int_0^x \left(\int_x^{\bar{s}} \left(1 + \frac{1}{\delta-1} \int_s^t i^a(r)^{1-\delta} dr \right)^{\gamma(1-\sigma)-1} dt \right) ds}{\int_0^{\bar{s}} v(s) ds}, \\ \phi^R(x) &= \frac{\int_x^{\bar{s}} \left(\int_0^x \left(1 + \frac{1}{\delta-1} \int_t^s i^a(r)^{1-\delta} dr \right)^{\gamma(1-\sigma)-1} dt \right) ds}{\int_0^{\bar{s}} v(s) ds}.\end{aligned}$$

We then show that if $i^a(x)$ has a hump shape with the peak at $x = \bar{s}/2$, then $J(i^a(x))$ has a hump shape. This in turn means that the fixed point of the functional has a hump shape. That is, the optimal investment profile has a hump shape.

Consider a function $i_1^a(x) \in E$ that has a hump shape. We define $i_2^a(x)$ as the value of the functional at $i_1^a(x)$: i.e., $i_2^a(x) = J(i_1^a(x))$. Next, we prove that $i_2^a(x)$ has a hump shape. To show this, we consider the derivative of $i_2^a(x)$. It is straightforward to see that

$$i_2^a(x)^{\delta-1} (i_2^a(x))' = 2 \frac{bL\gamma(1-\alpha)(1-t^a)}{q\delta} \frac{1}{\int_0^{\bar{s}} v(s) ds} H(x),$$

where

$$H(x) = \int_x^{\bar{s}} \left(1 + \frac{1}{\delta-1} \int_x^z i_1^a(s)^{1-\delta} ds \right)^{\gamma(1-\sigma)-1} dz - \int_0^x \left(1 + \frac{1}{\delta-1} \int_z^x i_1^a(s)^{1-\delta} ds \right)^{\gamma(1-\sigma)-1} dz.$$

The first thing to notice is that $H(\bar{s}/2) = 0$ (which follows from the symmetry of $i_1^a(x)$). Consider any $x < \bar{s}/2$, then the function $H(x)$ can be written as follows:

$$\begin{aligned}H(x) &= \int_x^{2x} \left(1 + \frac{1}{\delta-1} \int_x^z i_1^a(s)^{1-\delta} ds \right)^{\gamma(1-\sigma)-1} dz - \int_0^x \left(1 + \frac{1}{\delta-1} \int_z^x i_1^a(s)^{1-\delta} ds \right)^{\gamma(1-\sigma)-1} dz \\ &\quad + \int_{2x}^{\bar{s}} \left(1 + \frac{1}{\delta-1} \int_x^z i_1^a(s)^{1-\delta} ds \right)^{\gamma(1-\sigma)-1} dz,\end{aligned}$$

where

$$\int_{2x}^{\bar{s}} \left(1 + \frac{1}{\delta-1} \int_x^z i_1^a(s)^{1-\delta} ds \right)^{\gamma(1-\sigma)-1} dz > 0.$$

Note that as $i_1^a(s)$ is symmetric around $x = \bar{s}/2$ and has a hump shape at $\bar{s}/2$, for any $\Delta \in (0, x]$

$$i_1^a(x + \Delta) > i_1^a(x - \Delta).$$

This in turn means that for any $\Delta \in (0, x]$,

$$1 + \frac{1}{\delta-1} \int_x^{x+\Delta} i_1^a(s)^{1-\delta} ds < 1 + \frac{1}{\delta-1} \int_x^{x-\Delta} i_1^a(s)^{1-\delta} ds,$$

implying that

$$\left(1 + \frac{1}{\delta-1} \int_x^{x+\Delta} i_1^a(s)^{1-\delta} ds \right)^{\gamma(1-\sigma)-1} > \left(1 + \frac{1}{\delta-1} \int_x^{x-\Delta} i_1^a(s)^{1-\delta} ds \right)^{\gamma(1-\sigma)-1},$$

as $\gamma(1-\sigma)-1$ is negative. As a result, it is straightforward to see that

$$\int_x^{2x} \left(1 + \frac{1}{\delta-1} \int_x^z i_1^a(s)^{1-\delta} ds \right)^{\gamma(1-\sigma)-1} dz > \int_0^x \left(1 + \frac{1}{\delta-1} \int_z^x i_1^a(s)^{1-\delta} ds \right)^{\gamma(1-\sigma)-1} dz.$$

That is, for any $x < \bar{s}/2$, $H(x) > 0$. Similarly, it is possible to show that for any $x > \bar{s}/2$, $H(x) < 0$. Thus, $(i_2^a(x))'$ is strictly greater than zero on $x \in [0, \bar{s}/2)$ and strictly less than zero on $(\bar{s}/2, 1]$. This means that $i_2^a(x)$ has a hump shape. Therefore, the solution of (19) has a hump shape.

Finally, we show that $v(x)$ has a hump shape as well. We have that

$$\begin{aligned} v'(x) &= \left(\int_0^x \left(1 + \frac{1}{\delta-1} \int_z^x i(s)^{1-\delta} ds \right)^{\gamma(1-\sigma)} dz + \int_x^{\bar{s}} \left(1 + \frac{1}{\delta-1} \int_x^z i(s)^{1-\delta} ds \right)^{\gamma(1-\sigma)} dz \right)' \\ &= \frac{\gamma(\sigma-1)i(x)^{1-\delta}}{\delta-1} \left(\int_x^{\bar{s}} \left(1 + \frac{1}{\delta-1} \int_x^z i(s)^{1-\delta} ds \right)^{\gamma(1-\sigma)-1} dz - \int_0^x \left(1 + \frac{1}{\delta-1} \int_z^x i_1^a(s)^{1-\delta} ds \right)^{\gamma(1-\sigma)-1} dz \right) \\ &= \frac{\gamma(\sigma-1)i(x)^{1-\delta}}{\delta-1} H(x). \end{aligned}$$

Taking into account the properties of $H(x)$, we can conclude that $v(x)$ has a hump shape.

Proof of Proposition 3

Recall that the direct effect of a certain parameter on $i^a(x)$ is given by the partial derivative of $i^a(x)$ with respect to this parameter, where $i^a(x)$ is given by

$$i^a(x) = \left(\frac{\gamma(1-\alpha)(bL - \int_{s \in S} q(s) i^a(s) ds)}{q(x)} (\phi^L(x) + \phi^R(x)) \right)^{1/\delta}.$$

Hence, it is straightforward to see that

$$\frac{\partial i^a(x)}{\partial(1-\alpha)} > 0,$$

which proves (i).

The direct impact of b on $i^a(x)$ is also straightforward as $\partial i^a(x)/\partial b > 0$. Consider the direct impact of b on the tax rate. The optimal tax rate is equal to $\left(\int_0^{\bar{s}} q(x) i^a(x) dx \right) / (bL)$. As can be seen, on the one hand, a rise in b reduces the tax rate (as the denominator rises), on the other hand, it raises the tax (as the numerator rises as well). Using the expression for $i^a(x)$, we can derive that

$$\int_0^{\bar{s}} i^a(x) q(x) dx = \left(\gamma(1-\alpha)(bL - \int_{s \in S} q(s) i^a(s) ds) \right)^{1/\delta} \int_0^{\bar{s}} (q(x)^{\delta-1} (\phi^L(x) + \phi^R(x)))^{1/\delta} dx.$$

That is, the tax rate t^a solves

$$t^a (bL)^{1-1/\delta} = (\gamma(1-\alpha)(1-t^a))^{1/\delta} \int_0^{\bar{s}} (q(x)^{\delta-1} (\phi^L(x) + \phi^R(x)))^{1/\delta} dx.$$

Exploring the direct effect of b on t^a , we ignore the corresponding changes in $\int_0^{\bar{s}} (q(x)^{\delta-1} (\phi^L(x) + \phi^R(x)))^{1/\delta} dx$. As a result, it is straightforward to see that a rise in b decreases t^a (as $1 - 1/\delta > 0$). This proves (ii).

If $m(x)$ is the same at all locations, $\phi^L(x)$ and $\phi^R(x)$ do not directly depend on m , as it is canceled out. In this case, the direct impact of m on the infrastructure investments and the tax rate is the same as that of b . That is, $i^a(x)$ rises for all x and t^a falls (if m rises). Similarly, if $q(x)$ is equal to q for all x (the cost of infrastructure is uniform), the impact of q on the infrastructure investments and the tax rate is the opposite of that of b . That is, $i^a(x)$ falls for all x and t^a rises (if q rises). These prove (iii) and (v).

If $m(x)$ is the same at all locations, then $L = m\bar{s}$ and

$$i^a(x) = \left(\frac{\gamma(1-\alpha)(bm\bar{s} - \int_0^{\bar{s}} q(s) i^a(s) ds)}{q(x)} (\phi^L(x) + \phi^R(x)) \right)^{1/\delta}.$$

In this case, the partial derivative of $i^a(x)$ with respect to \bar{s} is given by (here we use the fact that $i^a(\bar{s}) = 0$)

$$\frac{\partial i^a(x)}{\partial \bar{s}} = \frac{\gamma(1-\alpha)}{q(x)\delta} (i^a(x))^{1-\delta} \left((\phi^L(x) + \phi^R(x))'_s (bm\bar{s} - \int_0^{\bar{s}} q(s) i^a(s) ds) + bm(\phi^L(x) + \phi^R(x)) \right).$$

The derivatives of $\phi^L(x)$ and $\phi^R(x)$ with respect to \bar{s} are given by

$$(\phi^j(x))'_s = \frac{\int_0^x \left(1 + \frac{1}{\delta-1} \int_s^{\bar{s}} i^a(r)^{1-\delta} dr\right)^{\gamma(1-\sigma)-1} ds - v(\bar{s})\phi^j(x)}{\int_0^{\bar{s}} v(s) ds},$$

where $j \in \{L, R\}$. Thus,

$$\frac{\partial i^a(x)}{\partial \bar{s}} = \frac{bm\gamma(1-\alpha)}{q(x)\delta} (i^a(x))^{1-\delta} \left(\frac{2\bar{s}(1-t^a) \int_0^x \left(1 + \frac{1}{\delta-1} \int_s^{\bar{s}} i^a(r)^{1-\delta} dr\right)^{\gamma(1-\sigma)-1} ds}{\int_0^{\bar{s}} v(s) ds} + (\phi^L(x) + \phi^R(x)) \left(1 - \frac{\bar{s}v(\bar{s})(1-t^a)}{\int_0^{\bar{s}} v(s) ds}\right) \right).$$

As can be seen, if x is sufficiently close to \bar{s} , then $(\phi^j(x))'_s > 0$ (as $\phi^j(\bar{s}) = 0$) and, thereby, $\partial i^a(x)/\partial \bar{s} > 0$. Moreover, if the cost of infrastructure is uniform,

$$\frac{\partial i^a(x)}{\partial \bar{s}} > 0 \text{ for all } x.$$

This is due to fact that if $q(x) = q$ for all x , $v(x)$ is symmetric around $x = \bar{s}/2$ and has a hump shape. As a result, $v(\bar{s}) \leq v(s)$ for any $s \in S$. This in turn means that

$$\begin{aligned} \int_0^{\bar{s}} v(s) ds &> \bar{s}v(\bar{s}) \implies \\ 1 - \frac{\bar{s}v(\bar{s})(1-t^a)}{\int_0^{\bar{s}} v(s) ds} &> 0. \end{aligned}$$

This illustrates (iv) .

Proof of Proposition 5

Remember that the i th country's payoff functional is given by the total welfare of that country. In particular,

$$\begin{aligned} U_H &= (1-t^H) \left(\int_0^{\bar{s}} v(x) dx \right)^{\frac{1-\alpha}{\sigma-1}}, \\ U_F &= (1-t^F) \left(\int_{\bar{s}}^{2\bar{s}} v(x) dx \right)^{\frac{1-\alpha}{\sigma-1}}, \end{aligned}$$

where

$$v(x) = \int_0^{2\bar{s}} T(x, z)^{1-\sigma} dz.$$

As the constraints, $\int_0^{\bar{s}} i^H(x) dx \leq bLt^H/q$ and $\int_{\bar{s}}^{2\bar{s}} i^F(x) dx \leq bLt^F/q$, are binding, we can rewrite the payoff functionals as follows:

$$U_H = \left(1 - q/(bL) \int_0^{\bar{s}} i^H(x) dx\right) \left(\int_0^{\bar{s}} v(x) dx\right)^{\frac{1-\alpha}{\sigma-1}}, \quad (39)$$

$$U_F = \left(1 - q/(bL) \int_{\bar{s}}^{2\bar{s}} i^F(x) dx\right) \left(\int_{\bar{s}}^{2\bar{s}} v(x) dx\right)^{\frac{1-\alpha}{\sigma-1}}. \quad (40)$$

Taking into the account the latter expressions for the payoffs, we can slightly redefine the game as $\tilde{\Gamma} = (I, U_i, \tilde{\Theta}_i)$, where $\tilde{\Theta}_H$ is the set of $\{i^H(x)\}_{x \in [0, \bar{s}]}$ such that $i^H(x) \geq 0$ and $q/(bL) \int_0^{\bar{s}} i^H(x) dx \leq 1$, and $\tilde{\Theta}_F$ is the set of $\{i^F(x)\}_{x \in [\bar{s}, 2\bar{s}]}$ such that $i^F(x) \geq 0$ and $q/(bL) \int_{\bar{s}}^{2\bar{s}} i^F(x) dx \leq 1$. Finally, U_i is determined by (39) and (39).

Consider a metric space of all continuos functions on $[a, b]$ with the metrics given by:

$$\rho(f(x), g(x)) = \int_a^b |f(x) - g(x)| dx.$$

It is straightforward to see that $\tilde{\Theta}_i$ is the subset of such a metric space. Since $\tilde{\Theta}_i$ is determined by the non-negativity and budget constraints, $\tilde{\Theta}_i$ is a convex and compact subset of the corresponding metric space. Moreover, given the assumptions about the parameters in the model (see (17) and (18)), the payoff function U_i is concave on $\tilde{\Theta}_i$ (and continuos on $\tilde{\Theta}_H \times \tilde{\Theta}_F$). Therefore, we can refer the results derived in Fan (1966) that imply the existence of the Nash equilibrium of the game in pure strategies.

Proof of Lemma 2

As in the proof of Proposition 1, we first formulate and analyze a discrete modification of the social planner's maximization problem, which approximates the actual continuos maximization problem, and then take the limit. Recall that the home social planner solves

$$\{i^H(x), t^H\}_{x \in [0, \bar{s}]} = \arg \max_{t, i(x)} \left\{ (1-t) \left(\int_0^{\bar{s}} v(x) dx \right)^{\frac{1-\alpha}{\sigma-1}} \left| q \int_0^{\bar{s}} i(x) dx \leq bLt^H \right. \right\},$$

where

$$\begin{aligned} v(x) &= \int_0^{2\bar{s}} T(x, z)^{1-\sigma} dz \\ &= \int_0^x \left(1 + \frac{1}{\delta-1} \int_z^x i(r)^{1-\delta} dr \right)^{\gamma(1-\sigma)} dz + \int_x^{\bar{s}} \left(1 + \frac{1}{\delta-1} \int_x^z i(r)^{1-\delta} dr \right)^{\gamma(1-\sigma)} dz \\ &\quad + \int_{\bar{s}}^{2\bar{s}} \left(1 + \frac{1}{\delta-1} \int_x^{\bar{s}} i(s)^{1-\delta} ds + \frac{1}{\delta-1} \int_{\bar{s}}^z i^F(s)^{1-\delta} ds \right)^{\gamma(1-\sigma)} dz. \end{aligned}$$

To formulate the corresponding discrete maximization problem, we consider a uniform partition of the $[0, 2\bar{s}]$ -interval given by $\{x_i\}_{i=0..2n}$, where $x_0 = 0$, $x_n = \bar{s}$, and $x_{2n} = 2\bar{s}$. Then, the discrete analogue of the continuos maximization problem can be written as follows (without loss of generality, we assume that location n belongs to the home country) :

$$\{i^H(x_i), t^H\}_{i=0..n} = \arg \max_{t, i(x_i)} \left\{ (1-t) \left(\sum_{i=0}^n v(x_i) \Delta_n \right)^{\frac{1-\alpha}{\sigma-1}} \right\},$$

subject to

$$q \sum_{i=0}^n i(x_i) \Delta_n \leq bLt.$$

where

$$\begin{aligned} v(x_i) = \Delta_n & \left(1 + \sum_{k=0}^{i-1} \left(1 + \frac{1}{\delta-1} \sum_{j=k}^{i-1} i(x_j)^{1-\delta} \Delta_n \right)^{\gamma(1-\sigma)} + \sum_{k=i+1}^n \left(1 + \frac{1}{\delta-1} \sum_{j=i+1}^k i(x_j)^{1-\delta} \Delta_n \right)^{\gamma(1-\sigma)} \right. \\ & \left. + \sum_{k=n+1}^{2n} \left(1 + \frac{1}{\delta-1} \sum_{j=i+1}^n i(x_j)^{1-\delta} \Delta_n + \frac{1}{\delta-1} \sum_{j=n+1}^k i^F(x_j)^{1-\delta} \Delta_n \right)^{\gamma(1-\sigma)} \right) \end{aligned}$$

and $\Delta_n = 1/n$.

The first order conditions are given by

$$\begin{aligned}\frac{\partial \Lambda}{\partial i(x_i)} &= 0, i = 0..n, \\ \frac{\partial \Lambda}{\partial t} &= 0,\end{aligned}$$

where Λ is the corresponding Lagrange function. It is straightforward to see that

$$\begin{aligned}\frac{\partial \Lambda}{\partial i(x_i)} &= \frac{(1-t)(1-\alpha)}{\sigma-1} \left(\sum_{i=0}^n v(x_i) \Delta_n \right)^{\frac{1-\alpha}{\sigma-1}-1} \Delta_n \sum_{l=0}^n (v(x_l))'_{i(x_i)} - \lambda_0 \Delta_n q, \\ \frac{\partial \Lambda}{\partial t} &= - \left(\sum_{i=0}^n v(x_i) \Delta_n \right)^{\frac{1-\alpha}{\sigma-1}} + \lambda_0 bL.\end{aligned}$$

We have that for $i < l$,

$$(v(x_l))'_{i(x_i)} = (\Delta_n)^2 \gamma(\sigma-1) i(x_i)^{-\delta} \sum_{k=0}^i \left(1 + \frac{1}{\delta-1} \frac{l-1}{j=k} i(x_j)^{1-\delta} \Delta_n \right)^{\gamma(1-\sigma)-1},$$

for $i > l$,

$$\begin{aligned}(v(x_l))'_{i(x_i)} &= (\Delta_n)^2 \gamma(\sigma-1) i(x_i)^{-\delta} \sum_{k=i}^n \left(1 + \frac{1}{\delta-1} \frac{k}{j=l+1} i(x_j)^{1-\delta} \Delta_n \right)^{\gamma(1-\sigma)-1} \\ &\quad + (\Delta_n)^2 \gamma(\sigma-1) i(x_i)^{-\delta} \sum_{k=n+1}^{2n} \left(1 + \frac{1}{\delta-1} \frac{n}{j=l+1} i(x_j)^{1-\delta} \Delta_n + \frac{1}{\delta-1} \frac{k}{j=n+1} i^F(x_j)^{1-\delta} \Delta_n \right)^{\gamma(1-\sigma)-1}.\end{aligned}$$

Finally, $(v(x_l))'_{i(x_i)} = 0$ if $i = l$.

Thus, the optimal infrastructure profile, $\{i^H(x_i)\}_{i=0..n}$, solves the following system of equations:

$$\begin{aligned}\frac{q i^H(x_i)^\delta}{\Delta_n b L \gamma (1-\alpha) (1-t^H)} &= \frac{\sum_{l=0}^{i-1} \left(\sum_{k=i}^n \left(1 + \frac{1}{\delta-1} \frac{k}{j=l+1} i^H(x_j)^{1-\delta} \Delta_n \right)^{\gamma(1-\sigma)-1} \right)}{\sum_{i=0}^n v(x_i)} \\ &\quad + \frac{\sum_{l=0}^{i-1} \left(\sum_{k=n+1}^{2n} \left(1 + \frac{1}{\delta-1} \frac{n}{j=l+1} i^H(x_j)^{1-\delta} \Delta_n + \frac{1}{\delta-1} \frac{k}{j=n+1} i^F(x_j)^{1-\delta} \Delta_n \right)^{\gamma(1-\sigma)-1} \right)}{\sum_{i=0}^n v(x_i)} \\ &\quad + \frac{\sum_{l=i+1}^n \left(\sum_{k=0}^i \left(1 + \frac{1}{\delta-1} \frac{l-1}{j=k} i^H(x_j)^{1-\delta} \Delta_n \right)^{\gamma(1-\sigma)-1} \right)}{\sum_{i=0}^n v(x_i)}.\end{aligned}$$

Taking the limit, we obtain the solution of the continuous maximization problem:

$$\begin{aligned}\frac{q i^H(x)^\delta}{b L \gamma (1-\alpha) (1-t^H)} &= \frac{\int_0^x \left(\int_x^{\bar{s}} \left(1 + \frac{1}{\delta-1} \int_s^t i^H(r)^{1-\delta} dr \right)^{\gamma(1-\sigma)-1} dt \right) ds}{\int_0^{\bar{s}} v(s) ds} \\ &\quad + \frac{\int_x^{\bar{s}} \left(\int_0^x \left(1 + \frac{1}{\delta-1} \int_t^s i^H(r)^{1-\delta} dr \right)^{\gamma(1-\sigma)-1} dt \right) ds}{\int_0^{\bar{s}} v(s) ds} \\ &\quad + \frac{\int_0^x \left(\int_{\bar{s}}^{2\bar{s}} \left(1 + \frac{1}{\delta-1} \int_s^{\bar{s}} i^H(r)^{1-\delta} dr + \frac{1}{\delta-1} \int_{\bar{s}}^t i^F(r)^{1-\delta} dr \right)^{\gamma(1-\sigma)-1} dt \right) ds}{\int_0^{\bar{s}} v(s) ds}.\end{aligned}$$

Finally, the optimal tax rate solves

$$t^H = \frac{q \int_0^{\bar{s}} i^H(s) ds}{bL}.$$

Proof of Proposition 7

From the expression for $i^H(x)$, we can see that

$$\delta i^H(x)^{\delta-1} (i^H(x))' = \frac{bL\gamma(1-\alpha)(1-t^H)}{q} \left(\tilde{\phi}^{L,N}(x) + \tilde{\phi}^{R,N}(x) \right)'.$$

It is straightforward to see that

$$\left(\tilde{\phi}^{R,N}(x) \right)'_{x=0} > 0 \text{ and } \left(\tilde{\phi}^{R,N}(x) \right)'_{x=\bar{s}} < 0.$$

Consider the derivative of $\tilde{\phi}^{L,N}(x)$ with respect to x . We have that

$$\begin{aligned} \left(\tilde{\phi}^{L,N}(x) \right)' &= \frac{\int_x^{\bar{s}} \left(1 + \frac{1}{\delta-1} \int_x^t i^H(r)^{1-\delta} dr \right)^{\gamma(1-\sigma)-1} dt}{\int_0^{\bar{s}} v(s) ds} - \frac{\int_0^x \left(1 + \frac{1}{\delta-1} \int_s^x i^H(r)^{1-\delta} dr \right)^{\gamma(1-\sigma)-1} ds}{\int_0^{\bar{s}} v(s) ds} \\ &\quad + \frac{\int_{\bar{s}}^{2\bar{s}} \left(1 + \frac{1}{\delta-1} \int_x^t i^H(r)^{1-\delta} dr + \frac{1}{\delta-1} \int_{\bar{s}}^t i^H(2\bar{s}-r)^{1-\delta} dr \right)^{\gamma(1-\sigma)-1} dt}{\int_0^{\bar{s}} v(s) ds}. \end{aligned}$$

As can be inferred from the above expression, $\left(\tilde{\phi}^{L,N}(x) \right)'_{x=0} > 0$. Moreover, as

$$\begin{aligned} \int_0^{\bar{s}} \left(1 + \frac{1}{\delta-1} \int_s^{\bar{s}} i^H(r)^{1-\delta} dr \right)^{\gamma(1-\sigma)-1} ds &= \int_{\bar{s}}^{2\bar{s}} \left(1 + \frac{1}{\delta-1} \int_{\bar{s}}^t i^H(2\bar{s}-r)^{1-\delta} dr \right)^{\gamma(1-\sigma)-1} dt, \\ \left(\tilde{\phi}^{L,N}(x) \right)'_{x=\bar{s}} &= 0. \end{aligned}$$

Hence, we can conclude that $(i^H(x))'_{x=0} = \infty$ (as $i^H(0)^{\delta-1} = 0$) and $(i^H(x))'_{x=\bar{s}}$ is negative, but finite (as $i^H(\bar{s})^{\delta-1} > 0$).

Proof of Proposition 8

Recall that the infrastructure profile is determined by

$$i^H(x)^\delta = \frac{bL\gamma(1-\alpha)(1-t^H)}{q} \left(\tilde{\phi}^{L,N}(x, \tau) + \tilde{\phi}^{R,N}(x, \tau) \right).$$

It is straightforward to see that if there are additional transport costs for products produced in the foreign country, then

$$\begin{aligned} \tilde{\phi}^{L,N}(x, \tau) &= \frac{\int_0^x \left(\int_x^{\bar{s}} \left(1 + \frac{1}{\delta-1} \int_s^t i^H(r)^{1-\delta} dr \right)^{\gamma(1-\sigma)-1} dt \right) ds}{\int_0^{\bar{s}} \left(\int_0^{\bar{s}} T(s, z)^{1-\sigma} dz \right) ds + \tau^{1-\sigma} \int_0^{\bar{s}} \left(\int_{\bar{s}}^{2\bar{s}} T(s, z)^{1-\sigma} dz \right) ds} \\ &\quad + \frac{\tau^{1-\sigma} \int_0^x \left(\int_{\bar{s}}^{2\bar{s}} \left(1 + \frac{1}{\delta-1} \int_s^1 i^H(r)^{1-\delta} dr + \frac{1}{\delta-1} \int_{\bar{s}}^t i^H(2-r)^{1-\delta} dr \right)^{\gamma(1-\sigma)-1} dt \right) ds}{\int_0^{\bar{s}} \left(\int_0^{\bar{s}} T(s, z)^{1-\sigma} dz \right) ds + \tau^{1-\sigma} \int_0^{\bar{s}} \left(\int_{\bar{s}}^{2\bar{s}} T(s, z)^{1-\sigma} dz \right) ds}, \\ \tilde{\phi}^{R,N}(x, \tau) &= \frac{\int_x^{\bar{s}} \left(\int_0^x \left(1 + \frac{1}{\delta-1} \int_t^s i^H(r)^{1-\delta} dr \right)^{\gamma(1-\sigma)-1} dt \right) ds}{\int_0^{\bar{s}} \left(\int_0^{\bar{s}} T(s, z)^{1-\sigma} dz \right) ds + \tau^{1-\sigma} \int_0^{\bar{s}} \left(\int_{\bar{s}}^{2\bar{s}} T(s, z)^{1-\sigma} dz \right) ds}. \end{aligned}$$

Therefore, to explore the direct effect of τ on $i^H(x)$, we need to analyze how changes in τ affect $\tilde{\phi}^{L,N}(x, \tau) + \tilde{\phi}^{R,N}(x, \tau)$. Specifically, we find that the sign of $\left(\tilde{\phi}^{L,N}(x, \tau) + \tilde{\phi}^{R,N}(x, \tau)\right)'_{\tau}$ is the same as the sign of the following expression (remember that taking the derivative, we ignore all the indirect effects):

$$\begin{aligned} R(x) \equiv & \int_0^x \left(\int_x^{\bar{s}} \left(1 + \frac{1}{\delta-1} \int_s^t i^H(r)^{1-\delta} dr \right)^{\gamma(1-\sigma)-1} dt \right) ds \int_0^{\bar{s}} \left(\int_{\bar{s}}^{2\bar{s}} T(s, z)^{1-\sigma} dz \right) ds \\ & + \int_x^{\bar{s}} \left(\int_0^x \left(1 + \frac{1}{\delta-1} \int_t^s i^H(r)^{1-\delta} dr \right)^{\gamma(1-\sigma)-1} dt \right) ds \int_0^{\bar{s}} \left(\int_{\bar{s}}^{2\bar{s}} T(s, z)^{1-\sigma} dz \right) ds \\ & - \int_0^x \left(\int_{\bar{s}}^{2\bar{s}} \left(1 + \frac{1}{\delta-1} \int_s^{\bar{s}} i^H(r)^{1-\delta} dr + \frac{1}{\delta-1} \int_{\bar{s}}^t i^H(2\bar{s}-r)^{1-\delta} dr \right)^{\gamma(1-\sigma)-1} dt \right) ds \int_0^{\bar{s}} \left(\int_0^{\bar{s}} T(s, z)^{1-\sigma} dz \right) ds. \end{aligned}$$

As can be seen, $R(x)$ is negative in some left neighborhood of $x = \bar{s}$, implying that $i^H(x)$ falls for all x from this neighborhood. Finally, as $\int_0^{\bar{s}} i^H(x) dx$ remains the same, $i^H(x)$ must rise at some locations that are relatively far from the border.

A Data Appendix to Table 1

Table 5: Summary statistics for Table 1

Variable	Mean	Std. Dev.	Min	Max
Ln variable transport costs ^(a)	1.57	0.11	1.18	1.73
Ln geographical difficulty ^(b)	-0.51	1.02	-2.35	1.52
Ln population	13.03	0.70	11.20	14.74
Ln area in square km	8.53	0.70	5.16	9.23
Remoteness measures				
Ln distance to Paris	0.33	0.17	0.01	0.66
Ln trade costs weighted distance to Paris ^(c)	5.25	0.84	2.48	6.24
Ln distance to rest of France ^(d)	7.84	0.15	7.58	8.27
Ln trade costs weighted distance to rest of France ^(e)	0.42	0.19	0.08	0.90

Construction of variables.

(a) Miren Lafourcade has kindly provided access to generalized trade cost data for France départements for the year of 1993. Those data are constructed as the (more disaggregated, but unfortunately confidential) data that Combes et Lafourcade (2005) describe. The data contains trade costs département by département. One can recover total variable transport costs by subtracting the costs of loading and unloading the truck of FF 60. To obtain a measure of transit costs, we average total variable transport costs per kilometer between neighboring départements, using the neighbours' area as weights.

(b) Geographical difficulty is the measured by the difference between the points of highest and lowest altitude above sea level in a département.

(c) Trade cost weighted distance to Paris is the generalized trade cost index (including fixed costs, as reported by Combes and Lafourcade, 2005) for transportation from or to Paris to or from the respective département.

(d) Distance to rest of France is computed as the average unweighted distance of some département to all the other départements.

(e) Repeats the exercise conducted for (d), but uses generalized trade costs instead of distance (as reported by Combes and Lafourcade, 2005).