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Abstract

This paper studies the effect of transport infrastructure on the real exchange rate (RER) and reaches two relatively strong conclusions. First, while the list of robust determinants of the RER is not long, transport infrastructure belongs to that list. Many other potential determinants proposed in the literature, such as net foreign asset position or terms of trade, turn out to be not robust. Second, in terms of economic significance, the infrastructure effect follows closely the well-known Balassa-Samuelson effect and is one of the most important explanatory variables for RER movements, especially in developing countries.

1 Introduction

The real exchange rate (RER) is a key relative price that directly affects many other relative prices across countries. The real exchange rate is also often a source of international tensions -witness the intense debate about whether the RER of the Chinese currency is undervalued. In this paper, we argue that the existing literature on the RER may have missed some economically important determinants. More concretely, we study the possible role of transportation infrastructure, especially roads and railways, in affecting the value of a country's RER. We reach two strong conclusions. First, while the list of robust determinants of the RER is not long, transport infrastructure belongs to that list. Many other potential determinants proposed in the literature turn out to be not robust. Second, in terms of economic significance, the infrastructure effect follows closely the well-known Balassa-Samuelson effect and is one of the most important explanatory variables for RER movements.

Since the theory of purchasing power parity (PPP) was formulated by Cassell (1918), the literature has identified additional determinants of the RER (which could be understood as fundamental factors

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underlying deviations of the real exchange rate from the PPP). In a widely cited survey of the literature on the real exchange rate up to 1996, Rogoff (1996) singled out three theories, presumably representing the three most prominent determinants of the real exchange rate beyond PPP. The first and perhaps the most well-known theory is the Balassa-Samuelson (BS) effect (Balassa, 1964; and Samuelson, 1964), which postulates that a country that exhibits a faster increase in the productivity of its tradable sector relative to its non-tradable sector, compared to the relative productivity increase of other countries, should experience an appreciation of its real exchange rate. Since high-income countries are more likely to have experienced a faster increase in the relative productivity of their tradable sectors during their development process, the Balassa-Samuelson effect is also often taken to imply that the real exchange rate tends to be higher in higher-income countries. It is important to note, however, that the positive correlation between income and real exchange rate could also result from factors other than the Balassa-Samuelson effect. In particular, if high-income countries have a higher capital-to-labor ratio than low-income countries, and capital cannot flow freely across countries, the wage rate tends to be systematically higher in high-income countries. Because the nontradable sector tends to be more labor intensive, the relative price of nontradable goods and hence the real exchange rate tend to be higher in high-income countries (Kravis and Lipsey, 1983; and Bhagwati,1984). The second important determinant of the real exchange rate, the Froot-Rogoff effect, postulates that because government spending tends to fall disproportionately on domestic non-tradable goods and services, the real exchange rate tends to rise with government consumption (Froot and Rogoff, 1991). The third effect singled out by Rogoff (1996) is a possible effect of current account imbalance on the real exchange rate. A voluminous empirical literature has tried to test these hypotheses or estimate the empirical relationship between the real exchange rate and its determinants. According to Rogoff (1996), there is considerable empirical support, though not unanimous support, for both the Balassa-Samuelson effect and the Froot-Rogoff effect, but much weaker evidence in favor of the current account imbalance effect.[1]

Perhaps no one takes the job of ascertaining the determinants of the real exchange rate more seriously than the International Monetary Fund, which needs to provide periodic assessments on whether a country's exchange rate deviates from the long-run equilibrium, using a methodology that can stand up to scrutiny by both academics and more importantly, vigilant member governments. For this reason, well-trained IMF economists carefully comb the literature on the exchange rate determination before settling down on its preferred model. In the official document describing its preferred model (the equilibrium real exchange rate approach), the IMF (2006) lists the following six fundamentals: net foreign assets, productivity differential (between tradable and nontradable sectors), terms of trade, government consumption, restrictions on international trade, and, for centrally planned or transition economies, the share of government-controlled prices in the CPI basket.[2] A survey of the exisiting

[1] There is a separate literature examining deviations of the real exchange rate from either the law of one price or purchasing power parity (e.g., Engel and Rogers, 1996; Parsley and Wei, 1996; Engel, 1999, and many others).

[2] The official IMF methodology on exchange rate assessments (IMF 2006) also considers two other approaches that do not involve a direct econometric estimation of exchange rate determinants. One - the macroeconomic balance approach - is to compute a current account norm, and to ask whether the real exchange rate needs to appreciate or depreciate

literature suggests that transport infrastructure has not been considered a determinant of the RER.

How can construction and improvement of roads and railways affect the RER? We argue that infrastructure improvement within a country tends to introduce more competition among firms operating in the country. Competition can foster a reduction in the price level. If the infrastructure improvement (and hence the price reduction) is faster in the country relative to the rest of the world, there would be a faster reduction in the overall price level and hence a reduction in the country's RER. This effect could be quantitatively important as infrastructure improvement tends to progress at very different speeds in different sets of countries. In the first three decades after World War II, massive road construction and other infrastructure projects in the United States, Western Europe, and other developed countries tended to widen the gap between their internal transport costs and those of developing countries such as China, India, and Brazil. In comparison, in the last three decades, many emerging markets have embarked on an expansive effort to improve their roads and other infrastructure, while many developed countries have slowed down their infrastructure upgrading. Indeed, even among emerging market economies, China has engaged in the most extensive road and railway construction during 1989-2010, with a cumulative increase of over 400% in road density (length of paved roads and railroads per square kilometers). Other countries with major improvements in transport infrastructure include Korea, Iran, Vietnam, and Pakistan. Empirically, we will show that the infrastructure effect on the RER is approximately of the same order as the income effect (a proxy that encompasses the Balassa-Samuelson effect), and is quantitatively more important than the Froot-Rogoff effect. Furthermore, a relatively demanding robustness check (the Bayesian model averaging) indicates that transport infrastructure belongs to a very short list of robust determinants of the real exchange rate. Many other variables proposed in the literature, such as net foreign assets, restrictions on international trade, and terms of trade, do not survive the robustness checks.

If transport infrastructure is an economically important determinant of the real exchange rate, it has important implications for economic policies. For example, if one uses an empirical exchange rate model that does not take into account the role of infrastructure (think of the official IMF approach to assess the equilibrium exchange rate as explained in IMF (2006)), one is likely to mis-label countries with an above-average improvement in transport infrastructure as having an under-valued real exchange rate. As another example, for a country that wishes to improve its external competitiveness but is stuck in a currency union, improving its internal transport infrastructure - to the extent there is still scope to do so - is an alternative to devaluing its exchange rate.

It is useful to point out that the effect of better infrastructure on the RER is different from the effect of reducing international trading costs. Indeed, in our model, lower cross-border trade barriers have an ambiguous effect on the RER. In the empirics, the effect of greater trade openness on the RER is not statistically significant either.

in order to close the gap between the current account norm and the actual current account. The other - the external sustainability approach - uses assumptions about a country's potential growth rate, inflation rate, and rates of return on external assets and liabilities, and asks what the country's real exchange rate needs to be so that its net foreign asset position as a share of GDP can be stabilized.

The rest of the paper is organized as follows. Section 2 uses a model to illustrate the mechanism through which better transport infrastructure affects the real exchange rate. Section 3 presents the empirical estimation and tests. After presenting some panel regression evidence on the association between road density and RER, we apply a Bayesian model averaging method to select robust determinants of the RER. We also report an instrumental variable approach to ascertain causality and an additional set of robustness checks, including results from various sub-samples and those from across regions within a single country. Finally, Section 4 provides concluding remarks.

2 Model

In this section, we formalize the connection between transport infrastructure and the real exchange rate. This will guide our subsequent empirical research.

2.1 Benchmark

We extend the model of Melitz and Ottaviano (2008) to having multiple regions in each country. Consider a two-country world: Home and Foreign. Suppose there are N and N^* regions in Home and Foreign, respectively. Consumers in all regions have an identical preference over a continuum of differentiated varieties indexed by $i \in \Omega$. The utility function is

$$U = q_0^c + \alpha \int_{i\in\Omega} q_i^c di - \frac{1}{2}\gamma \int_{i\in\Omega} (q_i^c)^2 \, di - \frac{1}{2}\eta \left(\int_{i\in\Omega} q_i^c di \right)^2$$

where q_0^c and q_i^c represent the individual consumption levels of the numeraire good (which has the same value in all regions) and of variety i, respectively. The demand parameters α, γ and η are positive. The parameter γ indexes the degree of product differentiation between the varieties. We assume that the aggregate income of consumers is large enough so that consumers have positive demand for the numeraire. Consider a representative consumer in region A, the inverse demand for each variety i is given by

$$p_i = \alpha - \gamma q_i^c - \eta Q^c \tag{2.1}$$

where p_i is the relative price of variety i in terms of the numeraire good and

$$Q^c = \int_{i\in\Omega} q_i^c di$$

Let $\bar{\Omega} \subset \Omega$ be the subset of varieties that are consumed ($q_i^c > 0$ for $i \in \bar{\Omega}$). By (2.1), we sum both sides across varieties

$$\bar{p} = \alpha - \gamma \frac{Q^c}{n} - \eta Q^c$$
$$\Rightarrow \quad Q^c = \frac{n(\alpha - \bar{p})}{\eta n + \gamma}$$

where

$$\bar{p} = \frac{1}{n} \int_{i \in \bar{\Omega}^*} p_i di$$

and n is the measure of consumed varieties in $\bar{\Omega}$. Then the market demand is

$$\begin{aligned} q_i &\equiv L_A q_i^c = \frac{L_A}{\gamma} (\alpha - \eta Q^c - p_i) \\ &= \frac{L_A}{\gamma} \left(\alpha - \eta \frac{n(\alpha - \bar{p})}{\eta n + \gamma} - p_i \right) = \frac{\alpha L_A}{\eta n + \gamma} - \frac{L_A}{\gamma} p_i + \frac{\eta n}{\eta n + \gamma} \frac{L_A}{\gamma} \bar{p} \end{aligned} \tag{2.2}$$

The set $\bar{\Omega}$ satisfies

$$p_i \leq \frac{\alpha\gamma + \eta n \bar{p}}{\eta n + \gamma} \equiv p_A^{\max} \tag{2.3}$$

We assume that labor is the only factor of production and is inelastically supplied in a competitive market in each region. Furthermore, we assume that one unit of numeraire good is produced by one unit of labor and its market is competitive. The last assumption implies that the wage equals one in all regions[3]. Entry in the differentiated product sector is costly as each firm has to pay some start-up costs. Subsequent production exhibits constant returns to scale at marginal cost c (recall that $w = 1$), which is drawn from a common and known distribution $G(\cdot)$ with support on $[0, c_M]$. Firms learn about their cost level only after making the irreversible investment f_E for entry. If firms can cover their sunk costs by selling differentiated goods to consumers, they survive; otherwise, they exit the market.

Markets in different regions are segmented. There exists a per-unit trade cost, for instance delivery cost, for a firm in Home region A to sell goods in Home region B or Foreign region F. We let τ_{kj} denote the trade cost from region k to region j. $\tau_{kj} > 1$ if $i \neq j$ and $\tau_{kk} = 1$.

Consider a representative firm in Home region k. Given its efficiency level c, firms obtain the profits π_{kk}, π_{kh} and π_{kf} from the local market, Home region h's market and Foreign region f's market

$$\begin{aligned} \pi_{kk}(c) &= [p_{kk}(c) - c] \, q_{kk}(c) \\ \pi_{kh}(c) &= [p_{kh}(c) - \tau_{kh} c] \, q_{kh}(c) \\ \pi_{kf}(c) &= [p_{kf}(c) - \tau_{kf} c] \, q_{kf}(c) \end{aligned}$$

[3]Appendix C considers a model with endogenous wages. In the empirical work, we will also control for the income effect on the real exchange rate.

which gives the first order condition

$$q_{kl}(c) = \frac{L_l}{\gamma}\left(p_{kl}(c) - \tau_{kl}c\right), \, l = k, h, f$$

Let c_D^k denote the cost of a local firm which is just indifferent about remaining in region k's market, which means that the firm earns zero profit as its price is driven down to marginal cost, $c_D^k = p_k^{\max}$. Then

$$p_{kk}(c) = \frac{1}{2}\left(c_D^k + c\right), \, q_{kk}(c) = \frac{L_k}{2\gamma}\left(c_D^k - c\right), \, \pi_{kk}(c) = \frac{L_k}{4\gamma}\left(c_D^k - c\right)^2$$

We can define the similar costs c_D^h and c_D^f in Home region h and Foreign region f. Firms in region k also maximize profits from Home region h and Foreign region f. The optimal prices, quantities, and profits are

$$\begin{aligned}
p_{kh}(c) &= \frac{\tau_{kh}}{2}\left(\frac{c_D^h}{\tau_{kh}} + c\right), \, q_{kh}(c) = \frac{L_h}{2\gamma}\tau_{kh}\left(\frac{c_D^h}{\tau_{kh}} - c\right), \, \pi_{kh}(c) = \frac{L_h}{4\gamma}\tau_{kh}^2\left(\frac{c_D^h}{\tau_{kh}} - c\right)^2 \\
p_{kf}(c) &= \frac{\tau_{kf}}{2}\left(\frac{c_D^f}{\tau_{kf}} + c\right), \, q_{kf}(c) = \frac{L_f}{2\gamma}\tau_{kf}\left(\frac{c_D^f}{\tau_{kf}} - c\right), \, \pi_{kf}(c) = \frac{L_f}{4\gamma}\tau_{kf}^2\left(\frac{c_D^f}{\tau_{kf}} - c\right)^2
\end{aligned}$$

The optimization problems for firms in Home region h and Foreign region f are similar.

In equilibrium, the entry condition for a firm in Home region k is

$$\sum_{h \in Home}\int_0^{\frac{c_D^h}{\tau_{kh}}} \pi_{kh}(c)dG(c) + \sum_{f \in Foreign}\int_0^{\frac{c_D^f}{\tau_{kf}}} \pi_{kf}(c)dG(c) = f_E$$

We assume that productivity draws $1/c$ follow a Pareto distribution with lower bound $1/c_M$ and shape parameter m. This implies a distribution of cost draws c given by

$$G(c) = \left(\frac{c}{c_M}\right)^m, \, m > 0 \text{ and } c \in [0, c_M]$$

Then, the entry conditions in all regions become

$$L_k\left(c_D^i\right)^{m+2} + \sum_{h \neq k} L_h \rho_{kh}\left(c_D^h\right)^{m+2} + \sum_f L_f \rho_{kf}\left(c_D^f\right)^{m+2} = \gamma\phi \tag{2.4}$$

where

$$\phi = 2(m+1)(m+2)\left(c^M\right)^m f_E$$

and

$$\rho_{kh} = (\tau_{kh})^{-m} \text{ and } \rho_{kf} = (\tau_{kf})^{-m}$$

Similarly, for a representative firm in Foreign region j, the entry condition is

$$\sum_{h} L_h \rho_{jh} \left(c_D^h\right)^{m+2} + L_j \left(c_D^j\right)^{m+2} + \sum_{f \neq j} L_f \rho_{jf} \left(c_D^f\right)^{m+2} = \gamma\phi \tag{2.5}$$

We need an assumption on the geography of the regions in the two countries to keep the algebra simple. Let all regions in Home be located on a circle, and all regions in Foreign be located on a different circle (as indicated in Figure 1). To go from one region to another region in the same country, one must go through the center of the country, which is O^H for Home and O^F for Foreign, respectively. For example, for a firm in Home region A to sell its products in Home region B's market, the goods must first be shipped from region A to Home center O^H then to region B. Due to the equal length from any point on the circle to the center, the trade costs for any pair of regions within a country are equal, i.e., τ_{kh} takes the same value for any two regions k and h. We use τ_1 to denote this common within-country trade cost between any two Home regions, and τ_1^* for the trade cost between any two Foreign regions. To sell in a foreign market, a firm first must ship the good to the center of the firm's own country, then to the center of the foreign country, and finally to a foreign regional market. For example, consider a firm from Home region A that wishes to export to Foreign region C. It must ship its product first from A to Home center O^H, then to Foreign center O^F before reaching Foreign region C. Given the assumption on the geography, the international trading costs are the same from any home region to any foreign region. We use τ_2 to denote the variable cost for a firm in Home to export to Foreign, and τ_2^* for the variable trading cost for a firm in Foreign to export to Home. τ_2 and τ_2^* can potentially be different as the two countries may have different tariff rates and other border costs.

Note that international trading costs in general are affected by domestic trading costs as well. We capture this by assuming that τ_2 and τ_2^* are each an increasing function of both τ_1 and τ_1^*. We intentionally represent Home by a smaller circle, suggesting that Home is small relative to the rest of the world. If Home is relatively small, the international trade costs mainly depend on international shipping and insurance costs, border costs and maybe trade costs within Foreign, whereas Home's internal trade costs will play a relatively small role in the overall international trading cost. Then a change in τ_1 has only a negligible effect on τ_2 and τ_2^*. In other words, the elasticities of τ_2 and τ_2^* with respect to a change in τ_1 are small.

We solve the linear system (2.4) and (2.5) by Cramer's rule; the solution is

$$c_D^j = \left. \frac{\gamma\phi}{L^j} \frac{\sum_{n=1}^{N+N^*} \det\left(C_{nj}\right)}{|\varrho|} \right)^{\frac{1}{m+2}}$$

where

$$\det(\varrho) = \begin{vmatrix} \rho_{11} & \rho_{12} & \cdots & \rho_{1,N+N^*} \\ \rho_{21} & \rho_{22} & \cdots & \rho_{2,N+N^*} \\ \vdots & \vdots & \ddots & \vdots \\ \rho_{N+N^*,1} & \rho_{N+N^*,2} & \cdots & \rho_{N+N^*,N+N^*} \end{vmatrix}$$

and C_{nj} is the co-factor of its ρ_{nj} element. Under our assumption on trade costs, the determinant of the square matrix ϱ is

$$\det(\varrho) = \begin{vmatrix} \overbrace{\begin{matrix} 1 & \rho_1 & \rho_1 & \cdots & \rho_1 \end{matrix}}^{N} & \rho_2 & \rho_2 & \rho_2 & \cdots & \rho_2 \\ \rho_1 \quad 1 \quad \rho_1 \quad \cdots \quad \rho_1 & \rho_2 & \rho_2 & \rho_2 & \cdots & \rho_2 \\ \rho_1 \quad \rho_1 \quad 1 \quad \cdots \quad \rho_1 & \rho_2 & \rho_2 & \rho_2 & \cdots & \rho_2 \\ \vdots \quad \vdots \quad \vdots \quad \ddots \quad \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ \rho_1 \quad \rho_1 \quad \rho_1 \quad \cdots \quad 1 & \rho_2 & \rho_2 & \rho_2 & \cdots & \rho_2 \\ \rho_2^* \quad \rho_2^* \quad \rho_2^* \quad \cdots \quad \rho_2^* & 1 & \rho_1^* & \rho_1^* & \cdots & \rho_1^* \\ \rho_2^* \quad \rho_2^* \quad \rho_2^* \quad \cdots \quad \rho_2^* & \rho_1^* & 1 & \rho_1^* & \cdots & \rho_1^* \\ \rho_2^* \quad \rho_2^* \quad \rho_2^* \quad \cdots \quad \rho_2^* & \rho_1^* & \rho_1^* & 1 & \cdots & \rho_1^* \\ \vdots \quad \vdots \quad \vdots \quad \ddots \quad \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ \rho_2^* \quad \rho_2^* \quad \rho_2^* \quad \cdots \quad \rho_2^* & \multicolumn{5}{c}{\underbrace{\begin{matrix} \rho_1^* & \rho_1^* & \rho_1^* & \cdots & 1 \end{matrix}}_{N^*}} \end{vmatrix}$$

In Appendix A, we show that

$$c_D^h = \left(\frac{\gamma\phi}{L_h} \frac{1 - \rho_2 + (N^* - 1)(\rho_1^* - \rho_2)}{(1 + (N-1)\rho_1)(1 + (N^* - 1)\rho_1^*) - NN^*\rho_2\rho_2^*} \right)^{\frac{1}{m+2}} \tag{2.6}$$

and

$$c_D^f = \left(\frac{\gamma\phi}{L_f} \frac{1 - \rho_2^* + (N - 1)(\rho_1 - \rho_2^*)}{(1 + (N-1)\rho_1)(1 + (N^* - 1)\rho_1^*) - NN^*\rho_2\rho_2^*} \right)^{\frac{1}{m+2}} \tag{2.7}$$

By (2.3) and $c_D^h = p_h^{\max}$, we can solve for the number of firms in Home region h's market

$$n^h = \frac{\gamma}{\eta} \frac{\alpha - c_D^h}{c_D^h - \bar{p}}$$

where, similar to Melitz and Ottaviano (2008), the average price level among three groups of firms from Home region h, other Home regions and Foreign is a constant:

$$\bar{p} = \frac{2m+1}{2m+2} c_D^h$$

Then the number of firms in region h's market is

$$n^h = \frac{(2m+2)\gamma}{\eta}\left(\frac{\alpha}{c_D^h} - 1\right) \tag{2.8}$$

Let n_E^h (n_E^f) denote the number of entrants from Home region h (Foreign region f). Then in a Home region k

$$n_E^k\left(\frac{c_D^k}{c^M}\right)^m + \sum_{h\neq k} n_E^h\left(\frac{c_D^k}{\tau_1 c^M}\right)^m + \sum_f n_E^f\left(\frac{c_D^k}{\tau_2^* c^M}\right)^m = n^k \tag{2.9}$$

and in a Foreign region j

$$n_E^j\left(\frac{c_D^j}{c^M}\right)^m + \sum_{f\neq j} n_E^f\left(\frac{c_D^j}{\tau_1^* c^M}\right)^m + \sum_h n_E^h\left(\frac{c_D^j}{\tau_2 c^M}\right)^m = n^j \tag{2.10}$$

In Home region k, the aggregate price index is

$$\begin{aligned} P_k &= n_E^k \int_0^{c_D^k} p_{kk}(c)\frac{p_{kk}(c)q_{kk}(c)}{R_k}dG(c) + \sum_{h\neq k} n_E^h \int_0^{\frac{c_D^k}{\tau_1}} p_{hk}(c)\frac{p_{hk}(c)q_{hk}(c)}{R_k}dG(c) \\ &\quad + \sum_f n_E^h \int_0^{\frac{c_D^k}{\tau_2^*}} p_{fk}(c)\frac{p_{fk}(c)q_{fk}(c)}{R_k}dG(c) \end{aligned}$$

where the total revenue generated from region k's market is

$$\begin{aligned} R_k &= n_E^k \int_0^{c_D^k} \frac{L_k}{4\gamma}\left(\left(c_D^k\right)^2 - c^2\right)dG(c) + \sum_{h\neq k} n_E^h \int_0^{\frac{c_D^k}{\tau_1}} \frac{L_k}{4\gamma}\left(\left(c_D^k\right)^2 - \tau_1^2 c^2\right)dG(c) \\ &\quad + \sum_f n_E^f \int_0^{\frac{c_D^k}{\tau_2^*}} \frac{L_k}{4\gamma}\left(\left(c_D^k\right)^2 - \tau_2^{*2} c^2\right)dG(c) \end{aligned}$$

Substituting the distribution function $G(c)$ into the expression above, we can obtain

$$R_k = \frac{1}{m+2}\frac{L_k}{2\gamma}G\left(c_D^k\right)\left(n_E^k + \rho_1 \sum_{h\neq k} n_E^h + \rho_2 \sum_f n_E^f\right)\left(c_D^k\right)^2 \tag{2.11}$$

Plugging (2.11) into the aggregate price index in Home region k, we obtain

$$P_k = \frac{2m^2+6m+3}{2(m+2)(m+3)}c_D^k \tag{2.12}$$

Note that consumers in different regions within a country may consume different baskets of goods.

For the purpose of constructing a national consumer price index (CPI), we define a (nationally) representative consumer as a weighted average of the consumers in different regions, with local population as the weight.[4] Then Home CPI is

$$P_H = \sum_{k \in Home} \frac{L_k}{\sum_{h \in Home} L_h} P_k \tag{2.13}$$

Similarly, Foreign CPI is

$$P_F = \sum_{j \in Foreign} \frac{L_j}{\sum_{f \in Foreign} L_f} P_j \tag{2.14}$$

Then Home's real exchange rate is

$$RER_H = \frac{P_H}{P_F} \tag{2.15}$$

Now we discuss some comparative statics of changing the trade cost:

(i) If Home's internal trade cost τ_1 declines while all other trade costs remain constant, by (2.6) and (2.12), we clearly see that the CPI in region h is a decreasing function in ρ_1 (and hence an increasing function in τ_1). Thus, as Home's internal trade cost falls, region h's CPI drops. The result is intuitive. A lower Home internal trade cost induces more local firms (those previously selling only locally) to enter Home markets. Otherwise, given the same level of competition in all Home regions, they would have earned higher profits in each Home region. In other words, all regional markets in Home become more competitive after a decline in τ_1. As a result, the local CPI in any Home region falls.

(Note, however, that the number of entrants from region h could either go up or down due to two opposing forces. On the one hand, a decline in τ_1 reduces firms' marginal costs which in turn may yield higher profits. More firms may choose to enter the market. On the other hand, a decline in τ_1 also makes it easier for firms from regions outside h to operate businesses in region h; the number of firms from other Home regions may rise which crowds out some unproductive local firms. Because these two forces go in the opposite directions, the net effect of a lower τ_1 on the number of producing firms in a given region is ambiguous.)

As for the impact on Foreign's regional price level, we can show that

$$\frac{dc_D^f}{d\tau_1} = \frac{d\rho_1}{d\tau_1} \frac{1}{m+2} \frac{L_f}{\gamma\phi} \frac{c_D^f (N-1) N\rho_2^*}{1-\rho_2^* + (N-1)(\rho_1 - \rho_2^*)} \frac{1-\rho_2 + (N^*-1)(\rho_1^* - \rho_2)}{(1+(N-1)\rho_1)(1+(N^*-1)\rho_1^*) - NN^*\rho_2\rho_2^*} < 0$$

where the inequality holds because we analyze some reasonable solutions ($c_D^h > 0$) in this model. By (2.12), as the within-Home trade cost declines, Foreign regional CPI rises. Here is the reason. Suppose, at some point, a decline in τ_1 induces more Home firms to export and such an effect is strong enough to reduce Foreign regional price levels. This cannot be an equilibrium, because firms in Foreign are now facing tougher markets in both Home and Foreign markets and some of them are bound to quit.

[4] Our qualitative results do not change if we use regional revenue R_k as the weight to compute the CPI.

The process continues until eventually fewer firms survive in each Foreign region. As a result, in each Foreign region, the local CPI rises.

(ii) If the international trade cost from Home to Foreign τ_2 declines while all other trade costs remain constant, on the price level,

$$\frac{dc_D^h}{d\tau_2} = -\frac{d\rho_2}{d\tau_2}\frac{1}{m+2}\frac{L_h}{\gamma\phi}\frac{c_D^h N^*\left[1+(N^*-1)\,\rho_1^*\right]}{1-\rho_2+(N^*-1)\left(\rho_1^*-\rho_2\right)}\frac{1-\rho_2^*+(N-1)\left(\rho_1-\rho_2^*\right)}{(1+(N-1)\rho_1)\left(1+(N^*-1)\rho_1^*\right)-NN^*\rho_2\rho_2^*} > 0$$

where the inequality holds because in this paper we analyze the reasonable solutions ($c_D^f > 0$). Then we can show that as the international trade cost faced by Home firms declines, Home regional CPI falls. Why? Although the change in the international trade cost will not directly affect competitions in Home regional markets, it will influence the Home local CPI indirectly. As Home firms face lower export trading costs, more Home firms export. Taking into account a higher level of export profit for a given level of productivity, more Home firms will choose to produce which leads to greater competition in all Home regional markets. As a result, Home regional CPI falls.

Similar to (i)'s analysis, the number of entrants from a specific region may decline since local firms may be crowded out by competitors from other Home regions.

Based on an intuition similar to the case in (i), we can show that Foreign CPI tends to rise after a fall in Home-to-Foreign trading cost τ_2.[5]

Since we assume that τ_2 and τ_2^* are each an increasing function of both τ_1 and τ_1^*, we can show the following proposition.

Proposition 1 *If* $\max(\tau_1, \tau_1^*) \leq \min(\tau_2, \tau_2^*)$, *and*

$$\frac{\partial\tau_2^*}{\partial\tau_1}\frac{\tau_1}{\tau_2^*} \leq \frac{N-1}{N}$$

we can show that, as τ_1 *falls, each Home region experiences a decline in CPI and Home's real exchange rate depreciates.*

Proof. (see Appendix B) ■

Some comments are in order. Since τ_2^* positively depends on τ_1, as τ_1 falls, τ_2^* also falls. As in previous analysis, a decline in τ_2^* can crowd out Home producers, which by itself could lead to a higher Home CPI. The sufficient condition on the elasticity of τ_2^* with respect to τ_1 in our proposition provides an upper bound on the response of τ_2^* to a change in τ_1. This condition is easily satisfied if Home is relatively small in the sense that its overall import costs depend mainly on international

[5] The result on the effect of a change in τ_2 on Foreign CPI can be overturned when we allow tradable goods in production, as shown in Appendix E. In particular, a decline in Foreign tariff (a decline in τ_2 while everything else remains constant) leads to lower total input prices. This can lead to a lower Foreign CPI and real exchange rate. By combining our benchmark model with the tradable good input model in Appendix E, the net effect of a decline in Foreign tariff on Foreign CPI and real exchange rate becomes ambiguous.

shipping and insurance costs and its own tariff rates and not so much on its internal trading cost. A decline in τ_1 leads to a lower Home CPI (but a moderately higher Foreign CPI). Home's real exchange rate depreciates.

For an existing firm in a Home region k, its profit to sales ratio is

$$r = \frac{\frac{L_k}{4\gamma}\left(c_D^k - c\right)^2 + \max\left(0, \sum_{h\neq k} \frac{L_h}{4\gamma}\tau_1^2\left(\frac{c_D^h}{\tau_1} - c\right)^2\right) + \max\left(0, \sum_f \frac{L_f}{4\gamma}\tau_2^2\left(\frac{c_D^f}{\tau_2} - c\right)^2\right)}{\frac{L_k}{4\gamma}\left(\left(c_D^k\right)^2 - c^2\right) + \max\left(0, \sum_{h\neq k} \frac{L_h}{4\gamma}\tau_1^2\left(\left(\frac{c_D^h}{\tau_1}\right)^2 - c^2\right)\right) + \max\left(0, \sum_f \frac{L_f}{4\gamma}\tau_2^2\left(\left(\frac{c_D^f}{\tau_2}\right)^2 - c^2\right)\right)}$$

1. If the firm only sells its products locally, then

$$r = \frac{c_D^k - c}{c_D^k + c}$$

As shown in Proposition 1, when τ_1 falls, c_D^k falls and hence the profit to sales ratio falls.

2. If the firm sells goods locally and in other domestic markets,

$$r = \frac{\frac{L_k}{4\gamma}\left(c_D^k - c\right)^2 + \sum_{h\neq k} \max\left(0, \frac{L_h}{4\gamma}\tau_1^2\left(\frac{c_D^h}{\tau_1} - c\right)^2\right)}{\frac{L_k}{4\gamma}\left(\left(c_D^k\right)^2 - c^2\right) + \sum_{h\neq k} \max\left(0, \frac{L_h}{4\gamma}\tau_1^2\left(\left(\frac{c_D^h}{\tau_1}\right)^2 - c^2\right)\right)}$$

then

$$\frac{dr}{d\tau_1} = \frac{\frac{L_k\left(c_D^k - c\right)}{2\gamma}\frac{dc_D}{d\tau_1} + \sum_{h\neq k, c\leq \frac{c_D^h}{\tau_1}} \frac{L_h\left(c_D^h - \tau_1 c\right)}{2\gamma}\left(\frac{dc_D^h}{d\tau_1} - c\right)}{\frac{L_k}{4\gamma}\left(\left(c_D^k\right)^2 - c^2\right) + \sum_{h\neq k, c\leq \frac{c_D^h}{\tau_1}} \frac{L_h}{4\gamma}\tau_1^2\left(\left(\frac{c_D^h}{\tau_1}\right)^2 - c^2\right)} - r\frac{\frac{L_k c_D}{2\gamma}\frac{dc_D}{d\tau_1} + \sum_{h\neq k, c\leq \frac{c_D^h}{\tau_1}} \frac{L_h}{2\gamma}\left(c_D\frac{dc_D^h}{d\tau_1} - \tau_1 c^2\right)}{\frac{L_k}{4\gamma}\left(\left(c_D^k\right)^2 - c^2\right) + \sum_{h\neq k, c\leq \frac{c_D^h}{\tau_1}} \frac{L_h}{4\gamma}\tau_1^2\left(\left(\frac{c_D^h}{\tau_1}\right)^2 - c^2\right)}$$

The sign of $\frac{dr}{d\tau_1}$ is ambiguous.

If we use μ to denote a firm's markup, then

$$\mu = \frac{1}{1 - r}$$

Markup is an increasing function of the profit to sales ratio. As shown above, for those firms that sell their products only locally, the markups decline as τ_1 falls. However, for firms that sell goods in other domestic markets, the change in markup is ambiguous. A decline in τ_1 has two impacts on those firms. First, a decline in τ_1 induces more competition in each Home region. Firms may set lower prices and hence markups decrease. However, due to the decline in the domestic trade cost, for firms who have business in other Home markets, they are facing a reduction in their marginal costs, which potentially increases firms' markups. The net effect is ambiguous.

Some papers in the literature study the change in firms' markups after a decline in the trade cost. Using Indian data, De Loecker et al. (2012) empirically find that markups rise after input tariff liberalization. Their paper assumes that all firms use tradable good input in production while this is not the assumption in our paper. If we allow the decline in the trade cost τ_1 to also lower the marginal cost for firms that only sell products locally, we can show that the change in the markups of those local firms now becomes ambiguous.[6] The logic is the same as in our previous analysis: the effect from a decline in the marginal cost may offset the effect from a higher competition in the markets. The result in De Loecker et al. (2012) potentially implies that, for Indian firms, the direct effect from a decline in the marginal cost dominates the competition effect.

Arkolakis et al. (2012) theoretically show that, although markups vary across firms, the distribution of markups is invariant to changes in the trade cost. Their result is clearly functional-form dependent. However, two countervailing forces behind this stark neutrality result are intuitive. As the trade cost falls, exporting firms become less efficient on average, which leads them to lower markups. On the other hand, more local firms exit due to higher competition. Since those firms who exit are the least efficient firms, this tends to increase the markups. The net effect on markups is ambiguous. In Arkolakis et al. (2012), the two effects offset completely under specific assumptions and the distribution of markups is invariant to any changes in the trade cost. Although we do not obtain the same neutrality result in our paper, we share the same intuition on the change in the threshold of firms' entry c_D^h, which in turn leads to the same argument on firms' markups.

A number of extensions to the basic model are developed in Appendices C, D, and E, including endogenous wages, and an introduction of additional channels (innovations, and lower costs of traded inputs) through which better transport infrastructure can lower the value of the real exchange rate.

3 Empirical Evidence

We now investigate the empirical relationship between transport infrastructure and the RER. We proceed in four steps. First, we augment existing empirical models on the RER by including country-level infrastructure as an additional regressor. While we present conventional panel regressions with country and year fixed effects, our primary focus will be to select robust determinants by a Bayesian Model Averaging (BMA) procedure. This is essentially a rigorous horse race between the transport infrastructure and other potential determinants of the RER. Second, to ensure that the association between roads and the RER is not driven by reverse causality or other endogeneity issues, we also employ an instrumental variable approach. Third, we report additional robustness checks including

[6] Considering other shocks such as a productivity increase, we can show that markup rises unambiguously.

conducting the analysis for various subsamples and examining the connection between roads and the RER across different regions within a country. Finally, we use some firm-level profit data to shed light on possible mechanisms through which transport infrastructure affects the RER.

3.1 Initial evidence

In the first part of the empirical analysis, we check whether better infrastructure is associated with a reduced value of the real exchange rate. To be precise, our specification is the following:

$$\log RER_{i,t} = \alpha + \beta \log Infrastructure_{i,t} + X_{i,t}\Gamma_{i,t} + country\&year\_fixed\_effects + \varepsilon_{i,t}$$

where $\log RER_{i,t}$ refers to country i's real exchange rate in logarithm in year t. $\log Infrastructure_{i,t}$ is the log of country $i's$ road density in year t, which is measured by the total length of railways and paved roads relative to the area size of the country. $X_{i,t}$ represents other possible determinants of the RER, including income per capita, government expenditure/GDP, net foreign asset/GDP, terms of trade, real interest rate, trade barriers, and relative productivity. The choice of potential determinants of the real exchange rate is guided by Rogoff's survey on the real exchange rate (Rogoff, 1996) and the International Monetary Fund in its considered effort to assess the equilibrium value of the real exchange rate (2006).

3.1.1 Data Description

We start with data for 97 economies over the period from 1980 to 2010. However, as different variables have different missing value structures, our panel regressions will be conducted for 61 economies during 1988-2007. A list of countries is provided in Appendix Table F1. The definitions and descriptive statistics for key variables of interest are presented in Table 1, with additional details including data sources in Appendix Table F2.

Our key outcome variable is a country's real effective exchange rate (REER), which is a weighted average of the bilateral real exchange rate with bilateral trade shares as weights, constructed by the IMF and published in its International Financial Statistics. The REER is defined in such a way that a reduction in value implies that the goods prices in the country become lower relative to the average goods prices in other countries when the prices are converted into a common currency. Because the price indices (rather than absolute price levels) are used in the computation, only changes in the REER, not the absolute values, can be meaningfully compared across countries. (In our regressions, this issue is controlled for by the inclusion of country fixed effects.)

As a robustness check, we will also examine a bilateral real exchange rate (BRER) relative to the United States, constructed as CPI(i,t)/[CPI(us, t)*E], where E is the nominal exchange rate in terms of the units of a country's currency per US dollar. Defined in this way, a reduction in country i's

BRER implies that the goods become cheaper in country i than in the United States when the goods prices in both countries are expressed in constant US dollars.

Our key regressor is the stock of transport infrastructure. We measure it by road density, or the total length of paved roads and railroads per square kilometers. The data comes primarily from the World Bank's World Development Indicator (WDI) and is supplemented by other sources. In particular, we extend the relatively sparse coverage of China in the WDI and ITF databases by obtaining more complete road and railway information from the China Transportation and Communications Yearbooks. Note that the absolute level of road density may not be directly comparable across countries due to differences in geographic and topological features. For example, if a country has more desert or surface water within its territory (e.g., Australia), even a relatively low road density could be compatible with a high quality transportation network. In our statistical analysis, we will always include country fixed effects to account for time-invariant geographic or topographic features.

One potential drawback of the infrastructure measure is that it ignores transportation by surface water or air. As a robustness check, we also construct another measure of infrastructure: the ratio of the volume of goods transported by all modes of transport to area size. More precisely, it is the total volume of goods transported by railways, roads, air and waterways measured in metric tons, times kilometers traveled, and scaled by the area size. The information on transport volume comes from the World Bank's WDI and International Transportation Forum. A key drawback of this data is its much smaller coverage (22 countries only). Nonetheless, as we will see, this alternative measure of infrastructure does not alter the statistical relationship between infrastructure and real exchange rate.

To develop some concrete impressions about the magnitude and dispersion of infrastructure buildup across countries in recent decades, we present, in the upper left graph in Figure 2, the evolution of road density for China, India, Mexico and the United States, and compare it with income per capita and government expenditure over GDP. We normalize the values of each variable in 1980 to 100, so the values in other years can be read as cumulative growth since 1980. For example, the infrastructure density for India reaches 184 in 2010. This means that India has increased its total length of railways and paved roads by 84% from 1980 to 2010. Similarly, the infrastructure density for China reaches 501 by 2010, implying a 401% increase from 1980 to 2010.

While the stock of transport infrastructure in the United States barely changes from 1980 to 2010, it exhibits a more visible increase in emerging market economies. China's infrastructure stock has increased by leaps and bounds, especially since 2005, when the rate of increase also picked up. Over the entire 30 year period, the pace of the infrastructure buildup is similar to that of GDP growth. There are of course variations both across countries and over time within a country.

The upper right graph in Figure 2 presents the evolution of the total volume of goods transported (from all modes of transportation) for the same four countries. By this measure, the United States exhibits an increase over time. This likely reflects a progressively more intensive use of the existing transport networks. However, the increasing gap between China and the United States is still striking. The intensity in the use of the transport network might have increased even faster in China than in the United States, although it could also reflect rapid increase in cargo transport by waterways and air. The lower left graph presents the evolution of income per capita (in constant 2005 international dollars in PPP, but with the 1980 value normalized to be 100), which is a key determinant of the real exchange rate as suggested by both the Balassa-Samuelson hypothesis and the Kravis-Lipsey-Bhagwati hypothesis.

The lower right graph presents the evolution of the share of government consumption in GDP, which is another determinant of the real exchange rate as suggested by Froot and Rogoff (1995). As we can see clearly, this share does not exhibit much increase over time for these countries.

As for the other control variables in the regressions, we are guided by the existing literature on the determinants of the real exchange rate (see, for example, the surveys by Froot and Rogoff 1995; Rogoff 1996; and for developing countries, Edwards 1989; Hinkle and Montiel 1999; Edwards and Savastano 1999; and Lee 2008). In principle, the CPI-based real effective exchange rate is expected to depend on the following fundamentals: income per capita, government expenditure, net foreign assets, commodity terms of trade, real interest rate, trade restriction, and productivity differential. Detailed data sources of these variables can be found in Table 1.

3.1.2 Initial Panel Regression Results

Table 2 reports panel regression estimations. The regressions include separate country and year fixed effects. In all regressions, we re-scale all the (non-dummy) regressors by their respective standard deviations in the sample (which are reported in Table 1). As a result, the regression coefficient on a given regressor can be interpreted as a percentage change in the real exchange rate if that regressor is increased by one standard deviation. This allows one to compare easily the relative economic significance across different regressors.

In Column 1 of Table 2, the key regressors are log infrastructure, log income, and the ratio of government expenditure in GDP (plus various fixed effects). The coefficients on both log infrastructure and log income are statistically significant at the 1% level and have the expected sign. Consistent with our theory, an improvement in infrastructure by one standard deviation is associated with a decline in the real exchange rate by 88%. In comparison, a rise in income by one standard deviation is associated with a rise in the RER by 42%. An increase in government expenditure share by one standard deviation is associated with an appreciation of the RER by 10%. These estimates suggest that the economic effect of an infrastructure improvement could be greater than the Balassa-Samuelson effect, and probably more than eight times bigger than the Froot-Rogoff effect.

In Columns 2-4 of Table 2, we expand the list of regressors to include terms of trade, the ratio of net foreign assets to GDP, the real interest rate, two different ways to measure cross-border trade barriers, and a proxy for the relative productivity of the tradable sector. There is some evidence that a larger net foreign asset position is associated with a higher RER value; a higher real interest rate is also associated with a higher RER value. Also, there is some evidence that the real exchange rate is lower in a country with a more open trade regime. The coefficient on the relative productivity of the non-tradable sector is not significant. [If we run a regression without log income, then the coefficient on relative productivity becomes positive and significant, which is consistent with the Balassa-Samuelson effect. The regression is not reported to save space.]

In any case, after controlling for these additional regressors, the coefficient on the infrastructure variable is always negative and significant. Note that in Column 4, the point estimate on log income is slightly bigger than that on log infrastructure, but the difference is not statistically significant. This suggests that the infrastructure effect and the Balassa-Samuelson effect are comparable. The coefficients on log infrastructure are always substantially bigger than those on the government spending share in all regressions. This suggests that the transport infrastructure effect is likely to be economically more important than the Froot-Rogoff effect. Other potential determinants of the real exchange rate appear to be even less significiant, either statistically, economically, or both.

To see if the results over a somewhat longer time span are different, we also implement the same set of regressions when the data are sampled every third year. The results are reported in Columns 5-8 of Table 2. We note that all qualitative results remain broadly the same as before. In particular, the coefficients on log infrastructure are always negative and significant.

One way to gauge if and how the main results are affected by possible outliers is to look at some graphs. In the left column of Figure 3, we present a conditional scatter plot of the log RER against log infrastructure, based on the regression reported in Column 4 of Table 2. We can see a negative relationship between the two variables, which is not surprising as the slope simply reflects the coefficient estimate in the regression. Following the practice in empirical labor economics, we can filter out potential noises in the following way. First, we assign all data points into 50 equal-width bins based on the value of the residuals of log infrastructure. Second, for each bin, we compute the mean value of the residuals of log RER. In the right graph of Figure 3, we plot the mean value of the residual of log RER in each bin against the mid-value for each bin of the residual of log infrastructure. As we can see, the two variables are still negatively related. These graphs suggest that the negative relationship between transport infrastructure and real exchange rate is unlikely to be driven by one or two outliers.

We might conjecture that the effect of log infrastructure on the RER can be non-linear. Perhaps at high levels of transport infrastructure, any additional increase in road density may have a smaller effect on the RER. The right graph of Figure 3 allows us to check visually for the presence of possible non-linear effects. As far as we can see, there is no strong or obvious non-linear effect in the data. In subsequent discussions, we will assume that the effect of log infrastructure on log RER is (approximately) linear.

3.2 Selecting Robust Determinants by Bayesian Model Averaging

We now perform a relatively demanding type of robustness check by employing Bayesian model averaging (BMA). Specifically, we run a horse race between transport infrastructure and a set of other variables that the existing literature considers as plausibly important determinants of the real exchange rate[7]. Using Rogoff (1996) and the IMF approach to assess the equilibrium exchange rate (IMF 2006) as a guide, we consider seven such other potential determinants: income level (which reflects both the Balassa-Samuelson effect and the demand hypothesis of Bhagwati and Lipsey), government consumption/GDP (the Froot-Rogoff hypothesis), real interest rate, tariff rate, relative productivity, net foreign asset position/GDP, and terms of trade.

To implement the BMA procedure, we first take out both the country means and period means of all variables. By working with only de-meaned variables, we bypass a discussion of whether a particular country or year fixed effect should be part of the model.

Suppose we treat any linear combination of these eight potential variables as a possible model of the RER determination; there are $2^8 = 256$ possible models in total. (Note that if a given model has only a subset of variables, it is equivalent to assigning a zero coefficient to all other variables.) One can literally run all 256 regressions, and see how often a given variable is statistically significant and how big the likelihood value is for each regression. The BMA procedure can heuristically be thought of as a systematic and succinct way to summarize the results from running all these regressions.

We start with a prior on the size of the model (how many variables belong to the true model) and on the probability that a given variable may be part of the true model for each variable. Let us say that our prior is that the true model size has exactly five variables (we will later show this guess of the model size is a sensible one), and that any five variables out of these eight are *ex ante* equally likely to be in the true model. (That is, any given variable has a prior probability of 5/8 of belonging to the true model.) We report the results from the BMA in this case in Table 3. Column 1 reports the posterior probability for a given variable to belong to the true model. The variables are ordered in descending order of the values in this column. Five variables stand out as having a posterior probability of belonging to the true model that is greater than the prior probability. They are log income, log infrastructure, government spending share, real interest rate and relative productivity. In fact, for the first four variables, the posterior probability is greater than 99%, far exceeding the prior probability of 62.5%. In comparison, the fifth variable, relative productivity, has a posterior probability of 65%, which barely exceeds the prior probability.

The posterior inclusion probability for a given variable takes into account both how many times the variable is statistically significant across all models, and how likely each of these models is. For the first four variables to have a posterior probability of inclusion of 99% or better, it must mean that most models that do not include any of the four variables have a low likelihood value. In addition, in

[7] Sala-i-Martin, Doppelhofer, and Miller (2004) pioneered in applying the BMA methodology to selecting robust determinants of long-run economic growth.

models in which they are included, they are almost always statistically significant.

Columns 2 and 3 report posterior mean and standard deviations for a coefficient conditional on a given variable being included in the model. We can see that the mean estimates for the first four variables are all more than 2 standard deviations away from zero. The same cannot be said of the remaining 4 variables. Interestingly, the posterior means for income and infrastructure are very similar (with the coefficient on log income being slightly larger), and both are much greater than those on government spending and real interest rate.

Column 4 reports the fraction of times the point estimate of a given coefficient takes on a positive sign conditional on the variable being included in the model; a value of one means 100% of the times this occurs. Similarly, Column 5 reports the fraction of the times the point estimate of a given coefficient takes on a negative sign; a value of 1 means 100% of the times this occurs. We can see that for log income, government spending, and real interest rate, whenever they are included in the model, their coefficients are always strictly positive. For log infrastructure, whenever it is included in the model, its coefficient is always strictly negative.

In the exercises reported in Table 3, we start with a prior on the model size. We can gauge the appropriateness of this prior by re-doing the exercise with different priors. In particular, our prior could be that the number of variables in the true model is 1, 2, 3, 4, 5, 6 or 7. In Table 4, we tabulate the posterior probability of inclusion of these eight variables for various priors on the model size. For example, in the first column corresponding to a prior model size k=2, the BMA procedure suggests that, *ex post,* five variables have a posterior probability of inclusion that is greater than the prior probability (which is 2/8 or 25%). When we vary the prior on the model size, we always obtain the same conclusion *ex post*: five variables have higher posterior probabilities of inclusion than the prior ones, and all other variables fail on this criterion. Most remarkably, it is always the same five variables, namely log income, log infrastructure, government spending, real interest rate and relative productivity. This suggests that a prior model size of 5 variables (as used in Table 3) deserves special attention.

To summarize the main findings from Tables 3 and 4, we conclude that the list of robust correlates of the real exchange rate is relatively short, and transport infrastructure belongs to that short list. Moreover, the BMA procedure also reveals that the economic significance of the infrastructure effect is approximately comparable to that of the Balassa-Samuelson effect. More precisely, a change in either variable by one standard deviation has a similar effect on the real exchange rate. Both appear to be much stronger than the Froot-Rogoff effect. Many other potential determinants suggested by the literature such as terms of trade, trade barriers or net foreign asset position do not survive the scrutiny of the BMA robustness checks.

3.3 Two-Stage Least Squares

One might be worried about potential missing regressors or measurement errors or the endogeneity of transport infrastructure generally. In theory, a common solution to these problems is to find instrumental variables and perform a two-stage regression. In practice, it is hard to come up with satisfying instruments.

Our idea is to use earthquake damages as possible instruments. Major earthquakes cause damages to roads and bridges. If the damages are severe enough, the repair may not be completed within a given calendar year. Of course, a given earthquake creates proportionally larger damages in a smaller country. This suggests that some interactions between earthquakes and country size may be correlated with a country's stock of transport infrastructure.

In addition, intrinsic difficulties in building roads/railways in a country due to its natural terrain characteristics together with fluctuations in the global prices of construction material could also affect the pace at which a country builds transport infrastructure. So we consider some interactions between a country's terrain ruggedness and the global prices of construction material as a second set of instrumental variables.

It is possible that earthquakes or terrain ruggedness affect the real exchange rate directly without going through the infrastructure channel. In that case, some of the proposed instruments would be correlated with the error term in the main regression, invalidating the instruments. We will perform a number of statistical checks for the validity of our instrumental variable idea. First, we will check if, across countries and over time, interactions between earthquakes and country size, and interactions between terrain ruggedness and the price of construction material affect a country's infrastructure in a statistically significant way. More precisely, we will perform a weak IV test to see if we can reject the null that the proposed instruments are weak instruments. Second, we will check if the proposed instruments are correlated with the error term in the main regression. The proposed instruments are considered statistically valid if we reject the null of weak instruments but do not reject the null of a zero correlation between the instruments and the error term in the main regression.

We measure severity of earthquakes in a country and year by the ratio of total number of people affected by earthquakes to the total population in that country and year.

Our second set of instrumental variables is based on the interactions between a country's terrain ruggedness and the prices of materials used in road construction. Our measure of ruggedness is a geometric mean of five different measures of terrain ruggedness. One such measure is Terrain Ruggedness Index (TRI), originally devised by Riley, DeGloria and Elliot (1999) to quantify topographic heterogeneity in wildlife habitats providing concealment for preys and lookout posts. To calculate TRI, one first computes "TRI (100m) at the central point," which is given by the sum of the squared differences in elevation between the central point and the eight adjacent points. With TRI (100m) for each point on a grid, one then averages across all grid cells in the country not covered by water to obtain the average terrain ruggedness of the country's land area. The other four measures of terrain ruggedness come from Nunn and Puga (2012): Population weighted TRI across regions, average slope, local standard deviation in elevation, and percentage of terrarain that are rated as moderately to highly rugged (%).

We construct a time series measure of the weighted average of prices of main materials used in road construction, consisting of sand and gravel, crushed stone, cement, and steel. The weights on different material are based on "Materials in use in US interstate highways" published by US Geological Survey.

Table 5 presents regressions of road density on the proposed instruments, together with separate country and year fixed effects. Unsurprisingly, earthquake damages are found to be associated with a reduction in infrastructure. The effect of greater ruggedness on road construction is more nuanced. On the one hand, great ruggedness implies a greater difficulty in building roads; On the other hand, it may also imply a greater need for roads. We will let the data decide how the interactions between ruggedness and construction prices affect road building. Each column in Table 5 represents a first-stage regression that is used in conjunction with a second-stage regression reported in the corresponding column in Table 6.

The second stage regressions of the two-stage procedure are reported in Table 6. Before we look at the slope coefficients, let us first look at the statistical tests for the validity of the instruments. Based on the critical values reported in Stock, Wright, and Yogo (2002), we can reject the hypothesis that the proposed instrument variables are weak instruments in eight out of nine cases. In other words, the correlations between the proposed instruments and infrastructure are generally strong. We also perform an over-identification test (for the null hypothesis that the proposed instruments and the error term are uncorrelated). From the p-values of the Sargan N*R-sq test, we cannot reject that null of no correlation between the proposed instruments and the error term in the main regression at the 10% level. In a statistical sense, the instruments are unlikely to affect the RER directly without going through transport infrastructure.

Interestingly, the Durbin-Wu-Hausman chi-squared test fails to reject the null that the OLS and 2SLS estimates are the same at the 10% level in all cases. In other words, in our application, transport infrastructure appears exogenous, and in principle, no instrumental variables are needed.

In any case, from Table 6, with the instrumentation, log road density always has a negative and statistically significant coefficient. To the extent the instruments are valid (or not needed based on the Durbin-Wu-Hausman test), we conclude that an improvement in transport infrastructure typically *causes* a depreciation of the country's real exchange rate.

3.4 Extensions and Additional Robustness Checks

In this section, we consider various extensions and additional robustness checks.

3.4.1 Alternative measures of the real exchange rate and transport infrastructure

In addition to the real effective exchange rate (REER) computed by the IMF, we have constructed a bilateral real exchange rate vis-a-vis the US dollar (BRER). We summarize the results from the Bayesian Model Averaging exercise on this alternative dependent variable in Table 7. As we can see clearly, all the qualitative results are the same as when REER is used. In particular, four variables are found to be robust determinants of the BRER, and transport infrastructure is one of them. Recall that the same four variables were also robust when the real exchange rate is measured by REER. Other variables are found to be not robust. In particular, trade openness and net foreign asset position as a share of GDP are not robust determinants of the RER. It is interesting that relative productivity is not robustly significant when BRER rather than REER is used to measure the real exchange rate.

Because the scale of the BRER is not the same as the REER, the point estimates (the conditional means in Table 7) are different from their counterparts in Table 3. Nonetheless, the relative size of the coefficients is similar. In particular, the income effect and the transport infrastructure effect are broadly similar. Both are much greater than the effects of government spending share and real interest rate.

As an alternative to measuring infrastructure by road density, we also use the ratio of total goods volume transported to area size. There are two advantages associated with the alternative measure. First, it automatically takes into account potentially different transportation capacities of different roads. Second, it includes transportation by air or water. The disadvantage is that this variable is only available for a much smaller set of countries (22 now versus 46 before). In any case, this is a check on the robustness of the basic results. Our regression results, reported in Table 8, suggest that transport infrastructure measured in this way also has a negative and statistically significant effect on the RER.

3.4.2 Different sub-samples

We now consider different subsamples. Some of the countries are small economies or otherwise island economies. To ensure that our results are not dominated by such economies, we consider a sub-sample of countries that exclude small economies (those with a population of 1.5 million or less) and island economies. The BMA results (the posterior inclusion probability and the conditional mean of the coefficients) for the modified sample are reported in the first two columns of Table 9. The conclusions on the posterior inclusion probabilities are virtually identical to the earlier results. Transport infrastructure is one of the robust determinants of the RER, and its economic effect is nearly comparable to that of the Balassa-Samuelson effect.

Major oil exporters tend to run a persistent current account surplus, and may be different from other countries in other ways too. In the middle two columns of Table 9, we report the analysis on a subsample that excludes major oil exporters. Again, the results are virtually the same as before.

Since the IMF (2006) finds that transition economies (i.e., former centrally planned economies) appear to have a different RER behavior, we conduct a robustness check by excluding these countries from the sample and report the results in Columns 5-6 of Table 9. We find again that log income, log infrastructure, government spending share, real interest rate, relative productivity, and this time, net foreign asset position are robust determinants of the RER.

We can also identify potential outliers in a statistical (mechanical) way. We consider all country-years whose residuals from the regression in Column 4 of Table 2 are more than three standard deviations away from the mean (zero) as outliers. The BMA analysis on a sample that excludes these outliers are reported in the last two columns of Table 9. The results are again very similar to those in Table 3.

We can also slice the sample by country income level. We report the BMA results (still the posterior probability of inclusion and the conditional means of the coefficients) for the high-income sample in Columns 1 and 2 of Table 10, and those for developing countries in Columns 3 and 4 of Table 10. Income, infrastructure, real interest rate and government spending share are robustly significant in both cases (in the sense that the posterior inclusion probability is greater than the prior probability). None of the other variables is robustly significant for both samples.

Finally, we can cut the sample into two time periods: 1988-1997, and 1998-2007. The results for them are reported in Columns 5-6 and 7-8 of Table 10, respectively. In both sub-samples, income, infrastructure, government spending share, and real interest rate have posterior inclusion probabilities that are greater than the prior probabilities. It is interesting that the Froot-Rogoff effect appears more important in the earlier sample than the later one. None of the other variables is robustly significant in both periods.

3.4.3 Adding lagged real exchange rate

We do not employ a dynamic specification such as an error-correction model because the corresponding Baysian Model Averaging method has not been developed in the statistical literature. Without an explicit dynamic structure, we may interpret the results as identifying robust medium-term determinants of the real exchange rate. We now include a lagged RER as a regressor to capture some dynamics and check how many of the variables identified by the previous specification can remain as robust determinants.

We start with a list of nine candidate determinants (lagged RER plus the eight previously identified variables), and there are potentially 2^9=512 number of potential models. In Table 11, we report the posterior probability of inclusion for each candidate variable corresponding to a series of priors for model size, k=1, 2, 3, ...8. For example, if we make a guess that the true model has only one determinant but each of the nine variables *ex ante* is equally likely to be that determinant (i.e, with a prior probability of inclusion of 1/9). The BMA procedure indicates that three variables, namely lagged RER, log income, and log infrastructure, have a posterior probability of inclusion far exceeding the prior probabillity. So the initial guess of k=1 is incorrect. We perform similar checks for all other possible values of k in the remaining columns of Table 11. Remarkably, the BMA procedure consistently indicates that there will be three and only three regressors that are robust. The robust determinants are lagged RER, log income and log infrastructure.

In Table 12, we provide more information about the estimation results for the case of k=3. Unsurprising, the lagged RER has the largest coefficient conditional on inclusion (0.72). The conditional mean for the coefficient on log income is 0.34, and that for log instructure is -0.22. None of the other variables such as government shares, terms of trade, or net foreign asset position is significant. We conclude, therefore, that instructure is a robust determinant of the RER even if we allow for lagged exchange rate in the model to absorb persistent movements in the real exchange rate.

3.4.4 Evidence from across regions within a single country

We can go beyond cross-country regressions and check if the relationship between the real exchange rate and transport infrastructure is also replicated across regions within a country. This is a useful check since many country-level legal institutions, regulations, cultural factors, and nominal exchange rate fluctuations are automatically held constant in that setting, hence further alleviating concerns about missing regressors.

We do a case study on China because it is spatially large with regional variations in the infrastructure build-up. We use Beijing as the benchmark region and construct local real exchange rates for all provinces (and province-level super cities) against Beijing from 2001-2010. A region's real exchange rate in a given year is the value of the local CPI relative to the value of CPI in Beijing in the same year.

We have more information about road quality in China than in the cross-country data set. In particular, we know not only whether a road is paved or not, but also a capacity grade (maximum vehicle circulation volume) based on the width of a road and the construction material (The Technical Standard of Highway Engineering of China JGTB01-2003). The official capacity grades take on six discrete values, Express, Classes I, II, III, IV and Below Class roads, with Express for the highest capacity and Below Class for the lowest capacity. By using the median capacity numbers for a given class as specified in the technical standard, we convert every kilometer of Class I, II, III, IV and Below Class roads into equivalent kilometers of express paved roads. Using the assumption that railways are equivalent to express paved roads, our final road density is measured by the sum of the railways and equivalent express paved roads divided by a region's area size.[8] The subsequent results will be based on this measure. However, we have also adopted a simple measure of road density without quality adjustment (i.e., simple sum of the paved roads, regardless of quality class, and the railroads). The

[8] There are three different types of the quality adjusted ratio between rail, Express, Class I, II, III, IV, and Below Class in Technical Standard of Highway Engineering of China (JGTB01-2003). The median standard is set at 1:1:0.56:0.16:0.064:0.0192:0.00576; low standard (LS) is set at 1:1:0.6:0.2:0.08:0.016:0.0032; high standard is set at 1:1:0.55:0.15:0.06:0.02:0.0067.

main inferences are qualitatively similar. The summary statistics for the key variables are presented in Table 13.

In the first three columns of Table 14, we report a set of panel regression results. We again normalize all regressors by their respective standard deviations so that the coefficients on the regressors can be more easily compared.

In the first column of Table 14, we regress regional real exchange rate on regional road density, together with separate regional and year fixed effects, and obtain a negative coefficient on road density. This means that the local RER tends to be lower in regions and years in which there is a faster-than-average improvement in road density. In the second column, we add log income and government spending share; in the third column, we also add indicators for local product and factor market development, respectively. We observe that the local RER is always negatively related to local road density. Both log income and the share of government expenditure in local GDP have a positive sign, consistent with the Balassa-Samuelson and Froot-Rogoff hypotheses, respectively. In this within-country sample, judging from the point estimates, the infrastructure effect appears stronger than either the Balassa-Samuelson effect or the Froot-Rogoff effect.

To address concerns that the transport infrastructure may be mis-measured (or otherwise endogenous), we instrument it by some interactions between severity of earthquakes and region size (and its higher order polynomial terms in one-period lags), measured in a similar way to the cross-country sample. The last three columns of Table 14 report the second stage regressions of the 2SLS procedure. As we can see, transport infrastructure continues to have a negative coefficient. The coefficients on log infrastructure are significant in Columns 4 and 5, but in Column 6, infrastructure loses statistical significance. At the bottom of the table, we report tests (Sargan test) on whether the IVs are correlated with the error term in the main regressions. The results suggest that we cannot reject the null of zero correlation. The Stock-Yogo test suggests that we can reject the null that the instruments are weak. Hence, in a mechanical sense, we can say that the interaction between severity of earthquakes and region sizes (and its polynomial term) are reasonable instruments for this sample as well. Interestingly, the Durbin-Wu-Hausman test indicates that we cannot reject the null that the OLS and 2SLS coefficients are the same. We can read it as suggesting that endogeneity is not a major problem in this context, and the OLS estimates are reasonable. In other words, the OLS results reported in the first three columns of Table 14 are statistically valid.

We also perform robustness checks by the BMA procedure and report the results in Tables 15 and 16. All in all, the within-country evidence is consistent with the notion that transport infrastructure is a robust determinant of the real exchange rate, and that its economic significance is no less than the Balassa-Samuelson effect or the Froot-Rogoff effect.

3.4.5 Evidence on the competition channel: Transport infrastructure and markups

A key mechanism in our story is that improved transport infrastructure leads to more competition (firms selling in the local market have to compete more with firms from outside the region). The increased competition in turn leads to a lower markup by locally-selling firms, contributing to a reduction in the overall price level. In this subsection, we employ firm-level financial data to shed light on this mechanism.

We have annual balance sheet level data for Chinese industrial firms during 2000-2007 from an annual survey of firms by the National Bureau of Statistics. The data set is meant to cover all non-state firms with annual sales reaching or exceeding 5 million RMBs (about $625,000) plus all majority state-owned firms. Because we do not observe product-level markups directly, we look at three proxies. The first is return on assets (ROA), defined as net income scaled by the book value of total assets. The second is return on equity (ROE), defined as net income scaled by the total value of common equity. Finally, we look at profit rate, defined as the ratio of net profit to total revenue. We take advantage of the information on the location of the firms (most firms operate in one region) and relate changes in profitability to changes in local transport infrastructure.

As for any survey data, our firm-level data could be noisy and prone to have outliers. We clean the data by excluding firms whose reported annual growth rate of revenue is either greater than 100% or smaller than -100%, whose reported ownership across owners exceeds 100%, whose employment is negative, or whose ratio of long-term debt to asset is larger than 10 or negative. Because we have many data points, we do not need to worry about lack of statistical power and therefore choose to be relatively aggressive in the filtering process in order to minimize the influence of outliers.

We run variations of the following regression:

$$\begin{aligned} Firm\ profitability_{i,j,k,t} &= \alpha + \beta_1 \log Infrastructure_{k,t} + \beta_2 \log Infrastructure_{k,t} \cdot Export\_dmy_{i,t} \\ &\quad + X_{i,t}\Phi_{i,t} + Z_{k,t}\xi_{i,t} + firm \cdot year\ fixed\ effect \\ &\quad (or\ industry \cdot year\ fixed\ effect) + \varepsilon_{i,t} \end{aligned} \tag{3.1}$$

where the left-hand-side variable is ROA, ROE or Profit Margin for firm i in industry j and province k in year t; $\log Infrastructure_{k,t}$=log road density for province k in year t. In the basic regression, we use quality weighted road density. In robustness checks, we also use unweighted road density, which turns out to produce similar results. $\log Infrastructure_{k,t} \cdot Export\_dmy_{i,t}$=interaction of local infrastructure and export status of firm i in province k in year t. (The interaction term is to allow for a secondary feature of the model that firms that sell outside the region may not reduce their markups by as much as those that sell only locally. Ideally, we would like to distinguish among firms that sell only within a region, those that sell domestically but across regions, and those that also sell in the world market. Due to data constraints, we can only distinguish between firms that sell domestically and those that also export to the world market.)

$X_{i,t}$ is a set of firm characteristics including firm size (measured by log employment), leverage ratio, investment intensity, and revenue growth; $Z_{k,t}$ is a set of provincial characteristics including log GDP per capita, log consumption per capita, government expenditure/GDP, an index for product market development, and an index for factor market development.

We include firm fixed effects to absorb the impact of time-invariant sector and firm characteristics including potential sector specific tax treatments and managerial abilities. Importantly, we also include $industry \cdot year$ fixed effects, which are more general than either year fixed effects or industry fixed effects. They can absorb the impact of economy-wide factors such as inflation. They also absorb the impact of sector-level (and potentially time-varying factors) supply and demand factors such as worldwide price changes. We cluster standard errors at the $province \cdot year$ level (the same level at which transport infrastructure is measured).

The regression results are reported in Table 17 . The dependent variable is log ROE in the first two columns, log ROA in the middle two columns, and profit margin in the last two columns. In all six regressions, the coefficient on log road density is negative; in five out of six cases, the coefficient is also statistically significant at the five percent level. These patterns are consistent with the interpretation that better transport infrastructure tends to increase competition and reduce markups and profitability. Overall, the firm-level evidence suggests that better infrastructure promotes competition, leading firms to cut their markups.

In Table 18, we have also examined whether better transport infrastructure is associated with a lower price of intermediate inputs, and found supportive evidence for this. Consistent with our theoretical discussion, even if one holds the markup constant, lower input costs also give firms an opportunity to charge a lower price for their output. This is another channel for better infrastructure to produce a lower RER.

4 Conclusions

In this paper, we show that transport infrastructure is an important determinant of the real exchange rate. The Bayesian Model Averaging procedure suggests that the list of robust determinants is not long, but transport infrastructure belongs to the list. Moreover, the economic importance of the infrastructure effect is almost on par with the well-known Balassa-Samuelson effect, and much greater than the Froot-Rogoff effect. Many other potential determinants proposed in the literature such as net foreign asset position, terms of trade, and barriers to international trade do not appear to be robust.

The results have interesting policy implications. If one employs a model to assess equilibrium exchange rate that does not include transport infrastructure (think of the current IMF approach to assessing the exchange rate), one may mistakenly conclude that countries with a faster-than-average improvement in transport infrastructure have an undervalued real exchange rate. In addition, for countries that have an external competitiveness problem but are stuck in a currency union, improvement in domestic transport infrastructure (to the extent there is scope to do so) is another way to reduce real exchange rates and improve competitiveness.

Because the real exchange rate is such an important relative price, and exchange rate assessment is such an important task for the international financial system, more scrutiny of existing determinants and more searches for new ones are both beneficial. We hope this paper will stimulate additional research on the topic.

References

[1] Anderson, C. Ronald, and David M. Reeb, 2003, Founding-family ownership and firm performance: Evidence from the S&P 500, *The Journal of Finance* (58), 1301-1327.

[2] Arkolakis, Costas, Arnaud Costinot, Dave Donaldson, and Andres Rodriguez-Clare, 2012, The elusive pro-competitive effects of trade, unpublished working paper.

[3] Bhagwati, N. Jagdish, 1984, Why are services cheaper in the poor countries? *The Economic Journal* (94), 279-286.

[4] Brandt, Loren, Johannes Van Biesebroeck, and Yifan Zhang, 2012, Creative accounting or creative destruction? Firm-level productivity growth in Chinese manufacturing, *Journal of Development Economic* (97), 339-351.

[5] Cassel, Gustav, 1918, Abnormal deviations in international exchanges, *The Economic Journal* (28), 413-415.

[6] De Loecker, Jan, Pinelopi K Goldberg, Amit K Khandelwal, and Nina Pavcnik, 2012, Prices, markups and trade reform, *NBER working paper 17925.*

[7] Donaldson, Dave, 2010, Railroads of the Raj: Estimating the impact of transportation infrastructure, *NBER working paper 16487.*

[8] Edwards, Sebastian, and Miguel A Savastano, 1999, Exchange rates in emerging economies: What do we know? What do we need to know? *NBER working paper 7228.*

[9] EM-DAT: The OFDA/CRED International Disaster Database – www.emdat.be, Universite Catholique de Louvain, Brussels (Belgium).

[10] Engel, Charles, 1999, Accounting for US real exchange rate changes, *Journal of Political Economy* (107), 507-538.

[11] Engel, Charles, and John H Rogers, 1996, How wide is the border?, *The American Economic Review* (86), 1112-1125.

[12] Fan, Gang, Xiaolu Wang, and Liwen Zhang, 2001, Annual report 2000: Marketization index for China's provinces, *China & World Economy* (5).

[13] Floyd, Robert W, 1962, Algorithm 97: Shortest path, *Communications of the ACM* (5), 345.

[14] Froot, Kenneth A, and Kenneth Rogoff, 1991, The EMS, the EMU, and the transition to a common currency, *NBER Macroeconomics Annual* 1991 (6) 269-328.

[15] Froot, Kenneth A., and Kenneth Rogoff, 1995, Perspectives on ppp and long-run real exchange rates, *Handbook of International Economics* (3), 1647-1688.

[16] Hinkle, Lawrence E, 1999. Exchange rate misalignment: Concepts and measurement for developing countries, Washington DC: The World Bank.

[17] International Monetary Fund, 2006, Methodology for CGER Exchange Rate Assessments, Washington DC: International Monetary Fund.

[18] Ju, Jiandong, Kang Shi, and Shang-Jin Wei, 2011, On the connections between intertemporal and intra-temporal trades, *National Bureau of Economic Research working paper 17549*.

[19] Kravis, B. Irving, and Robert E. Lipsey, 1983. Toward an explanation of national price levels, Princeton Univ International Economics.

[20] Krugman, R. Paul, 1990, Equilibrium Exchange Rates, in *International Monetary Policy Coordination and Exchange Rate Fluctuations*. Eds. by William Branson, Jacob Frenkel and Morris Goldstein, Chicago: University of Chicago Press, pp. 159-87.

[21] Lee, Jaewoo, Jonathan David Ostry, Gian Maria Milesi-Ferretti, Alessandro Prati, and Luca Antonio Ricci, 2008, Exchange rate assessments: CGER methodologies, Occasional Paper No. 261, Washington DC: International Monetary Fund.

[22] Maury, Benjamin, 2006, Family ownership and firm performance: Empirical evidence from Western European corporations, *Journal of Corporate Finance* (12), 321-341.

[23] Melitz, Marc, and Gianmarco Ottaviano, 2008, Market Size, Trade, and Productivity. *Review of Economic Studies* (75), 295-316.

[24] Miguel, Edward, Shanker Satyanath, and Ernest Sergenti, 2004, Economic shocks and civil conflict: An instrumental variables approach, *Journal of Political Economy* (112), 725-753.

[25] Nunn, Nathan, and Diego Puga, 2012, Ruggedness: The blessing of bad geography in Africa, *Review of Economics and Statistics* (94), 20-36.

[26] Parsley, David, and Shang-Jin Wei, 1996, Convergence to the law of one price without trade barriers or currency fluctuations, *The Quarterly Journal of Economics* (111), 1211-1236.

[27] Ramsay, W Kristopher, 2011, Revisiting the resource curse: Natural disasters, the price of oil, and democracy, *International Organization* (65), 507-529.

[28] Riley, Shawn J, Stephen D DeGloria, and Robert Elliot, 1999, A terrain ruggedness index that quantifies topographic heterogeneity, *Intermountain Journal of Sciences* (5), 23-27.

[29] Rogoff, Kenneth, 1996, The purchasing power parity puzzle, *Journal of Economic Literature* (34), 647-668.

[30] Sala-i-Martin, Xavier, Gernot Doppelhofer, and Ronald I Miller, 2004, Determinants of long-term growth: A Bayesian averaging of classical estimates (BACE) approach, *American Economic Review* (94), 813-835.

[31] Schreyer, Paul, and Dirk Pilat, 2001, Measuring productivity, *OECD Economic Studies* (33), 127-170.

[32] Spatafora, Nikola, and Irina Tytell, 2009. Commodity terms of trade: The history of booms and busts, (International Monetary Fund).

[33] Stock, H James, Jonathan H Wright, and Motohiro Yogo, 2002, A survey of weak instruments and weak identification in generalized method of moments, *Journal of Business & Economic Statistics* (20), 518-529.

[34] Wacziarg, Romain, and Karen Horn Welch, 2008, Trade liberalization and growth: New evidence, *The World Bank Economic Review* (22), 187-231.

[35] Wang, Zhihua, Qide Xu, Bin Xu, and Wei Zhang, 2009, Emergency aero-photo survey after the May 12 Wenchuan earthquake, China, *Science in China Series E: Technological Sciences* (52), 835-843.

[36] Yang, Dean, 2008, Coping with disaster: The impact of hurricanes on international financial flows, 1970-2002, *The BE Journal of Economic Analysis & Policy* 8(1): Article 13.

Appendices

A Computing c_D^h and c_D^f (for online publication only)

We first compute the determinant of matrix ϱ.

1. Starting from $n=1$ to $N-1$, we use the nth row minus the $n+1$th row. Then from $n=N+1$ to $N+N^*-1$, we do the same computation. We can obtain

$$\det(\varrho)=\begin{vmatrix} 1-\rho_1 & \rho_1-1 & 0 & \cdots & 0 & 0 & 0 & 0 & \cdots & 0 \\ 0 & 1-\rho_1 & \rho_1-1 & \cdots & 0 & 0 & 0 & 0 & \cdots & 0 \\ 0 & 0 & 1-\rho_1 & \cdots & 0 & 0 & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ \rho_1 & \rho_1 & \rho_1 & \cdots & 1 & \rho_2 & \rho_2 & \rho_2 & \cdots & \rho_2 \\ 0 & 0 & 0 & \cdots & 0 & 1-\rho_1^* & \rho_1^*-1 & 0 & \cdots & 0 \\ 0 & 0 & 0 & \cdots & 0 & 0 & 1-\rho_1^* & \rho_1^*-1 & \cdots & 0 \\ 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 1-\rho_1^* & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ \rho_2^* & \rho_2^* & \rho_2^* & \cdots & \rho_2^* & \rho_1^* & \rho_1^* & \rho_1^* & \cdots & 1 \end{vmatrix}$$

2. Starting from $n=2$ to N, we use the nth column plus the $n-1$th column. Then from $n=N+2$ to $N+N^*$, we do the same computation. We can obtain

$$\det(\varrho)=\begin{vmatrix} 1-\rho_1 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & \cdots & 0 \\ 0 & 1-\rho_1 & 0 & \cdots & 0 & 0 & 0 & 0 & \cdots & 0 \\ 0 & 0 & 1-\rho_1 & \cdots & 0 & 0 & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ \rho_1 & 2\rho_1 & 3\rho_1 & \cdots & 1+(N-1)\rho_1 & \rho_2 & 2\rho_2 & 3\rho_2 & \cdots & N^*\rho_2 \\ 0 & 0 & 0 & \cdots & 0 & 1-\rho_1^* & 0 & 0 & \cdots & 0 \\ 0 & 0 & 0 & \cdots & 0 & 0 & 1-\rho_1^* & 0 & \cdots & 0 \\ 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 1-\rho_1^* & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ \rho_2^* & 2\rho_2^* & 3\rho_2^* & \cdots & N\rho_2^* & \rho_1^* & 2\rho_1^* & 3\rho_1^* & \cdots & 1+(N^*-1)\rho_1^* \end{vmatrix}$$

3. Now we can calculate the determinant

$$\begin{aligned} \det(\varrho) &= (1-\rho_1)^{N-1} \left[\begin{array}{c} (1+(N-1)\rho_1)(1-\rho_1^*)^{N^*-1}(1+(N^*-1)\rho_1^*) \\ +(-1)^{N^*+1+1} N\rho_2^* (-1)^{1+N^*} N^*\rho_2 (1-\rho_1^*)^{N^*-1} \end{array} \right] \\ &= (1-\rho_1)^{N-1}(1-\rho_1^*)^{N^*-1}\left[(1+(N-1)\rho_1)(1+(N^*-1)\rho_1^*) - NN^*\rho_2\rho_2^*\right] \end{aligned}$$

Under our assumption, it is easy to show that

$$\sum_{n=1}^{N+N^*} \det(C_{nj}) = \sum_{n=1}^{N+N^*} \det(C_{nk}) \quad for any k \neq j$$

Then we only need to calculate $\sum_{n=1}^{N+N^*} \det(C_{n1})$. The steps are as follows:

1. We rewrite $\sum_{n=1}^{N+N^*} \det(C_{n1})$ as

$$\sum_{n=1}^{N+N^*} \det(C_{n1}) = \left| \begin{array}{cccccccccc} 1 & \overbrace{\rho_1 \quad \rho_1 \quad \cdots \quad \rho_1}^{N} & & & & \rho_2 & \rho_2 & \rho_2 & \cdots & \rho_2 \\ 1 & 1 & \rho_1 & \cdots & \rho_1 & \rho_2 & \rho_2 & \rho_2 & \cdots & \rho_2 \\ 1 & \rho_1 & 1 & \cdots & \rho_1 & \rho_2 & \rho_2 & \rho_2 & \cdots & \rho_2 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & \rho_1 & \rho_1 & \cdots & 1 & \rho_2 & \rho_2 & \rho_2 & \cdots & \rho_2 \\ 1 & \rho_2^* & \rho_2^* & \cdots & \rho_2^* & 1 & \rho_1^* & \rho_1^* & \cdots & \rho_1^* \\ 1 & \rho_2^* & \rho_2^* & \cdots & \rho_2^* & \rho_1^* & 1 & \rho_1^* & \cdots & \rho_1^* \\ 1 & \rho_2^* & \rho_2^* & \cdots & \rho_2^* & \rho_1^* & \rho_1^* & 1 & \cdots & \rho_1^* \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & \rho_2^* & \rho_2^* & \cdots & \rho_2^* & \underbrace{\rho_1^* \quad \rho_1^* \quad \rho_1^* \quad \cdots \quad 1}_{N^*} & & & & \end{array} \right|$$

2. Starting from $n = 1$ to $N-1$, we use the nth row minus the $n+1$th row. Then from $n = N+1$

to $N+N^*-1$, we do the same computation. We can obtain

$$\sum_{n=1}^{N+N^*} \det\left(C_{n1}\right) = \begin{vmatrix} 0 & \rho_1-1 & 0 & \cdots & 0 & 0 & 0 & 0 & \cdots & 0 \\ 0 & 1-\rho_1 & \rho_1-1 & \cdots & 0 & 0 & 0 & 0 & \cdots & 0 \\ 0 & 0 & 1-\rho_1 & \cdots & 0 & 0 & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & \rho_1 & \rho_1 & \cdots & 1 & \rho_2 & \rho_2 & \rho_2 & \cdots & \rho_2 \\ 0 & 0 & 0 & \cdots & 0 & 1-\rho_1^* & \rho_1^*-1 & 0 & \cdots & 0 \\ 0 & 0 & 0 & \cdots & 0 & 0 & 1-\rho_1^* & \rho_1^*-1 & \cdots & 0 \\ 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 1-\rho_1^* & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & \rho_2^* & \rho_2^* & \cdots & \rho_2^* & \rho_1^* & \rho_1^* & \rho_1^* & \cdots & 1 \end{vmatrix}$$

3. Using the last row minus the Nth row, we can obtain

$$\sum_{n=1}^{N+N^*} \det\left(C_{n1}\right) = \begin{vmatrix} 0 & \rho_1-1 & 0 & \cdots & 0 & 0 & 0 & 0 & \cdots & 0 \\ 0 & 1-\rho_1 & \rho_1-1 & \cdots & 0 & 0 & 0 & 0 & \cdots & 0 \\ 0 & 0 & 1-\rho_1 & \cdots & 0 & 0 & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & \rho_1 & \rho_1 & \cdots & 1 & \rho_2 & \rho_2 & \rho_2 & \cdots & \rho_2 \\ 0 & 0 & 0 & \cdots & 0 & 1-\rho_1^* & \rho_1^*-1 & 0 & \cdots & 0 \\ 0 & 0 & 0 & \cdots & 0 & 0 & 1-\rho_1^* & \rho_1^*-1 & \cdots & 0 \\ 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 1-\rho_1^* & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & \rho_2^*-\rho_1 & \rho_2^*-\rho_1 & \cdots & \rho_2^*-\rho_1 & \rho_1^*-\rho_2 & \rho_1^*-\rho_2 & \rho_1^*-\rho_2 & \cdots & 1-\rho_2 \end{vmatrix}$$

4. Starting from the $N+2$ to $N+N^*$, we use the nth column plus the $n-1$th column, we can obtain

$$\sum_{n=1}^{N+N^*} \det\left(C_{n1}\right) = \begin{vmatrix} 0 & \rho_1-1 & \cdots & 0 & 0 & 0 & \cdots & 0 \\ 0 & 1-\rho_1 & \cdots & 0 & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & \rho_1 & \cdots & 1 & \rho_2 & \rho_2 & \cdots & \rho_2 \\ 0 & 0 & \cdots & 0 & 1-\rho_1^* & 0 & \cdots & 0 \\ 0 & 0 & \cdots & 0 & 0 & 1-\rho_1^* & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & \rho_2^*-\rho_1 & \cdots & \rho_2^*-\rho_1 & \rho_1^*-\rho_2 & 2\left(\rho_1^*-\rho_2\right) & \cdots & 1-\rho_2+\left(N^*-1\right)\left(\rho_1^*-\rho_2\right) \end{vmatrix}$$

5. We can calculate the determinant

$$\sum_{n=1}^{N+N^*} \det(C_{n1}) = (-1)^{N+1}(\rho_1 - 1)^{N-1}(1-\rho_1^*)^{N^*-1}[1-\rho_2+(N^*-1)(\rho_1^*-\rho_2)]$$
$$= (1-\rho_1)^{N-1}(1-\rho_1^*)^{N^*-1}[1-\rho_2+(N^*-1)(\rho_1^*-\rho_2)]$$

Therefore,

$$c_D^h = \left(\frac{\gamma\phi}{L_h}\frac{1-\rho_2+(N^*-1)(\rho_1^*-\rho_2)}{(1+(N-1)\rho_1)(1+(N^*-1)\rho_1^*)-NN^*\rho_2\rho_2^*}\right)^{\frac{1}{m+2}}$$

and

$$c_D^f = \left(\frac{\gamma\phi}{L_f}\frac{1-\rho_2^*+(N-1)(\rho_1-\rho_2^*)}{(1+(N-1)\rho_1)(1+(N^*-1)\rho_1^*)-NN^*\rho_2\rho_2^*}\right)^{\frac{1}{m+2}}$$

B Proof of Proposition 1 (for online publication only)

Proof. We can show that

$$\begin{aligned}
\frac{dc_D^h}{d\tau_1} &= \frac{d\rho_1}{d\tau_1}\left(\frac{\partial c_D^h}{\partial\rho_1}+\frac{\partial c_D^h}{\partial\rho_2}\frac{d\rho_2}{d\rho_1}+\frac{\partial c_D^h}{\partial\rho_2^*}\frac{d\rho_2^*}{d\rho_1}\right)\\
&= \frac{d\rho_1}{d\tau_1}\left(\frac{\partial c_D^h}{\partial\rho_2}\frac{d\rho_2}{d\rho_1}+\frac{1}{m+2}\frac{c_D^h(N-1)\left((1+(N^*-1)\rho_1^*)-\frac{NN^*}{N-1}\rho_2\frac{d\rho_2^*}{d\rho_1}\right)}{\frac{\gamma\phi}{L_h}(1+(N-1)\rho_1)(1+(N^*-1)\rho_1^*)-NN^*\rho_2\rho_2^*}\right)\\
&> \frac{d\rho_1}{d\tau_1}\left(\frac{\partial c_D^h}{\partial\rho_2}\frac{d\rho_2}{d\rho_1}-\frac{1}{m+2}\frac{\rho_2 c_D^h(N-1)N^*\left(\frac{\rho_1^*}{\rho_2}-\frac{N}{N-1}\frac{d\rho_2^*}{d\rho_1}\right)}{\frac{\gamma\phi}{L_h}(1+(N-1)\rho_1)(1+(N^*-1)\rho_1^*)-NN^*\rho_2\rho_2^*}\right)\\
&\geq \frac{d\rho_1}{d\tau_1}\left(\frac{\partial c_D^h}{\partial\rho_2}\frac{d\rho_2}{d\rho_1}-\frac{1}{m+2}\frac{\rho_2 c_D^h(N-1)N^*\left(1-\frac{N}{N-1}\frac{d\rho_2^*}{d\rho_1}\right)}{\frac{\gamma\phi}{L_h}(1+(N-1)\rho_1)(1+(N^*-1)\rho_1^*)-NN^*\rho_2\rho_2^*}\right)
\end{aligned}$$

It is easy to show that $\frac{\partial c_D^h}{\partial\rho_2}<0$ and under the assumption $\frac{\partial\tau_2^*}{\partial\tau_1}\frac{\tau_1}{\tau_2^*}\leq\frac{N-1}{N}$

$$1-\frac{N}{N-1}\frac{d\rho_2^*}{d\rho_1}=1-\frac{N}{N-1}\left(\frac{\tau_1}{\tau_2^*}\right)\left(\frac{d\tau_2^*}{d\tau_1}\frac{\tau_1}{\tau_2^*}\right)>1-\frac{N}{N-1}\left(\frac{d\tau_2^*}{d\tau_1}\frac{\tau_1}{\tau_2^*}\right)>0$$

Therefore,

$$\frac{dc_D^h}{d\tau_1}>0$$

In each Home region, the CPI is

$$P_h=\frac{m+2}{m+3}c_D^h$$

Then, as τ_1 falls, region h's price index falls.

Then the real exchange rate in Home is

$$RER_H = \frac{\sum_{h=1}^{N} \frac{L_h}{L^H} c_D^h}{\sum_{f=1}^{N} \frac{L_f}{L^F} c_D^f} = \frac{L^F}{L^H} \frac{\sum_{h=1}^{N} (L_h)^{1-\frac{1}{m+2}}}{\sum_{f=1}^{N^*} (L_f)^{1-\frac{1}{m+2}}} \left(\frac{1-\rho_2+(N^*-1)(\rho_1^*-\rho_2)}{1-\rho_2^*+(N-1)(\rho_1-\rho_2^*)} \right)^{\frac{1}{m+2}}$$

where L^H and L^F are total populations in Home and Foreign, respectively. It is easy to show that, as τ_1 falls, $1-\rho_2+(N^*-1)(\rho_1^*-\rho_2)$ decreases. Under the assumption $\frac{\partial \tau_2^*}{\partial \tau_1}\frac{\tau_1}{\tau_2^*} \leq \frac{N-1}{N}$, we can show that

$$\begin{aligned}
\frac{d(1-\rho_2^*+(N-1)(\rho_1-\rho_2^*))}{d\tau_1} &= (N-1)\left(1-\frac{N}{N-1}\frac{d\rho_2^*}{d\rho_1}\right)\frac{d\rho_1}{d\tau_1} \\
&= (N-1)\left(1-\frac{N}{N-1}\left(\frac{\tau_1}{\tau_2^*}\right)\left(\frac{d\tau_2^*}{d\tau_1}\frac{\tau_1}{\tau_2^*}\right)\right)\frac{d\rho_1}{d\tau_1} \\
&\leq (N-1)\left(1-\frac{N}{N-1}\left(\frac{d\tau_2^*}{d\tau_1}\frac{\tau_1}{\tau_2^*}\right)\right)\frac{d\rho_1}{d\tau_1} \leq 0
\end{aligned}$$

Then $1-\rho_2^*+(N-1)(\rho_1-\rho_2^*)$ is non-increasing in τ_1. Therefore, as τ_1 falls, RER_H declines, i.e., Home's real exchange rate depreciates. ■

C Endogenous wages (for online publication only)

In the benchmark model, we do not consider a possible endogenous wage response to a change in domestic trade costs (although in the empirical analysis we control for income differences across countries). In this extension, we show that, with endogenous wages in the two countries, we still obtain the same qualitative results under some reasonable assumptions. In other words, the greater competition effect triggered by a decline in the trade cost is economically large enough to dominate other possible effects (through a change in wages) that might influence the real exchange rate.

To allow for endogenous wages, we modify slightly the utility function as follows

$$U = w - \int_{i\in\Omega} p_i^c q_i^c di + \alpha \int_{i\in\Omega} q_i^c di - \frac{1}{2}\gamma \int_{i\in\Omega} (q_i^c)^2 di - \frac{1}{2}\eta \left(\int_{i\in\Omega} q_i^c di \right)^2$$

where w is the wage rate and $\int_{i\in\Omega} p_i^c q_i^c di$ is the expenditure on differentiated goods. Given this utility function, all equations on the demand side in the benchmark hold. We continue to assume that everyone supplies one unit of labor inelastically.

Now we assume that firms will produce differentiated goods using labor with marginal cost cw, where c represents the efficiency of a firm's production. We assume that c is a random variable drawn from the same distribution as in the benchmark. In this case, similar to the benchmark model, we can show that the optimal prices, quantities, and profits for a representative firm in Home region k are

$$\begin{aligned} p_{kh}(c) &= \frac{\tau_{kh}}{2}\left(\frac{c_D^h w_h}{\tau_{kh}w_k}+c\right)w_k,\ q_{kh}(c)=\frac{L_h}{2\gamma}\tau_{kh}\left(\frac{c_D^h w_h}{\tau_{kh}w_k}-c\right)w_k,\ \pi_{kh}(c)=\frac{L_h}{4\gamma}\tau_{kh}^2\left(\frac{c_D^h w_h}{\tau_{kh}w_k}-c\right)^2 w_k^2 \\ p_{kf}(c) &= \frac{\tau_{kf}}{2}\left(\frac{c_D^f w_f}{\tau_{kf}w_k}+c\right)w_k,\ q_{kf}(c)=\frac{L_f}{2\gamma}\tau_{kf}\left(\frac{c_D^f w_f}{\tau_{kf}w_k}-c\right)w_k,\ \pi_{kf}(c)=\frac{L_f}{4\gamma}\tau_{kf}^2\left(\frac{c_D^f w_f}{\tau_{kf}w_k}-c\right)^2 w_k^2 \end{aligned}$$

We assume that entry barrier is no longer a constant and differs across regions. For regions with a higher wage rate, the entry cost is larger. For simplicity, we assume that the entry cost for a firm in region h is $f_E w_h$. We can show that the entry condition for firms in Home region k now becomes

$$L_k\left(c_D^k\right)^{m+2}+\sum_{h\neq k}L_h\rho_{kh}\left(\frac{c_D^h w_h}{w_k}\right)^{m+2}+\sum_f L_f\rho_{kf}\left(\frac{c_D^f w_f}{w_k}\right)^{m+2}=\frac{\gamma\phi}{w_k} \tag{C.1}$$

and for Foreign firms in region j,

$$\sum_h L_h\rho_{jh}\left(\frac{c_D^h w_h}{w_j}\right)^{m+2}+L_j\left(c_D^j\right)^{m+2}+\sum_{f\neq j}L_f\rho_{jf}\left(\frac{c_D^f w_f}{w_j}\right)^{m+2}=\frac{\gamma\phi}{w_j} \tag{C.2}$$

where ϕ is defined by the same expression as in the benchmark model.

In equilibrium, the labor markets clear in all regions. In Home region k, the labor market clearing condition is

$$L_k=n_E^k\left[\begin{array}{c}\frac{L_k w_k}{2\gamma}\int_0^{c_D^k}c\left(c_D^k-c\right)dG(c)+\sum_{h\neq k}\frac{L_h w_k}{2\gamma}\int_0^{\frac{c_D^h w_h}{\tau_{kh}w_k}}\tau_{kh}^2\left(\frac{c_D^h w_h}{\tau_{kh}w_k}-c\right)cdG(c)\\ +\sum_f\frac{L_f w_k}{2\gamma}\int_0^{\frac{c_D^f w_f}{\tau_{kh}w_k}}\tau_{kf}^2\left(\frac{c_D^f w_f}{\tau_{kh}w_k}-c\right)cdG(c)\end{array}\right] \tag{C.3}$$

and in Foreign region j,

$$L_j=n_E^j\left[\begin{array}{c}\frac{L_j w_j}{2\gamma}\int_0^{c_D^j}c\left(c_D^j-c\right)dG(c)+\sum_h\frac{L_h w_j}{2\gamma}\int_0^{\frac{c_D^h w_h}{\tau_{jh}w_k}}\tau_{jh}^2\left(\frac{c_D^h w_h}{\tau_{jh}w_j}-c\right)cdG(c)\\ +\sum_{f\neq j}\frac{L_f w_k}{2\gamma}\int_0^{\frac{c_D^f w_f}{\tau_{jf}w_k}}\tau_{jf}^2\left(\frac{c_D^f w_f}{\tau_{jf}w_k}-c\right)cdG(c)\end{array}\right] \tag{C.4}$$

By (C.1), (C.2), (C.3) and (C.4), we can show that, for any Home region h and Foreign region f,

$$\frac{\gamma\phi}{w_h}=\frac{2\gamma L_h(m+1)(m+2)\left(c^M\right)^m}{mn_E^h w_h}\text{ and }\frac{\gamma\phi}{w_f}=\frac{2\gamma L_f(m+1)(m+2)\left(c^M\right)^m}{mn_E^f w_f}$$

By substituting the expression for ϕ, we can obtain

$$\frac{L_h}{n_E^h}=\frac{L_f}{n_E^f}=mf_E \tag{C.5}$$

The worker-to-firm ratio is a common constant across regions. Then by (C.3), all Home regions have a symmetric labor market clearing condition. Hence, the wage is constant across Home regions. The same result also holds for Foreign. Let w_H and w_F denote the Home wage rate and Foreign wage rate, respectively. By (C.3) and (C.4), we can show that

$$\frac{w_F}{w_H}=\frac{L_k\left(c_D^k\right)^{m+2}+\sum_{h\neq k}L_h\rho_{kh}\left(c_D^h\right)^{m+2}+\sum_f L_f\rho_{kf}\left(\frac{c_D^f w_F}{w_H}\right)^{m+2}}{\sum_h L_h\rho_{jh}\left(\frac{c_D^h w_H}{w_F}\right)^{m+2}+L_j\left(c_D^j\right)^{m+2}+\sum_{f\neq j}L_f\rho_{jf}\left(c_D^f\right)^{m+2}} \tag{C.6}$$

Similar to the benchmark, solving equations (C.1) and (C.2), we obtain the solution

$$c_D^1=\left(\frac{\gamma\phi}{L_1}\frac{1}{w_1}\frac{\sum_{n=1}^{N+N^*}\left(\frac{w_n}{w_1}\right)^m\det\left(C_{n1}\right)}{|\varrho|}\right)^{\frac{1}{m+2}}$$

where C_{n1} is the co-factor of the $n\times 1$ element in matrix ϱ.

We can rewrite the denominator $\sum_{n=1}^{N+N^*}\left(\frac{w_n}{w_1}\right)^m\det\left(C_{n1}\right)$ as following

$$\sum_{n=1}^{N+N^*}\left(\frac{w_n}{w_1}\right)^m\det\left(C_{n1}\right)=\left|\begin{array}{ccccc|ccccc}
\multicolumn{5}{c}{\overbrace{\hphantom{1\quad\rho_1\quad\rho_1\quad\cdots\quad\rho_1}}^{N}} & & & & & \\
1 & \rho_1 & \rho_1 & \cdots & \rho_1 & \rho_2 & \rho_2 & \rho_2 & \cdots & \rho_2\\
\frac{w_2^2}{w_1^2} & 1 & \rho_1 & \cdots & \rho_1 & \rho_2 & \rho_2 & \rho_2 & \cdots & \rho_2\\
\frac{w_3^2}{w_1^2} & \rho_1 & 1 & \cdots & \rho_1 & \rho_2 & \rho_2 & \rho_2 & \cdots & \rho_2\\
\vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots\\
\frac{w_N^2}{w_1^2} & \rho_1 & \rho_1 & \cdots & 1 & \rho_2 & \rho_2 & \rho_2 & \cdots & \rho_2\\
\frac{w_{N+1}^2}{w_1^2} & \rho_2^* & \rho_2^* & \cdots & \rho_2^* & 1 & \rho_1^* & \rho_1^* & \cdots & \rho_1^*\\
\frac{w_{N+2}^2}{w_1^2} & \rho_2^* & \rho_2^* & \cdots & \rho_2^* & \rho_1^* & 1 & \rho_1^* & \cdots & \rho_1^*\\
\frac{w_{N+3}^2}{w_1^2} & \rho_2^* & \rho_2^* & \cdots & \rho_2^* & \rho_1^* & \rho_1^* & 1 & \cdots & \rho_1^*\\
\vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots\\
\frac{w_{N+N^*}^2}{w_1^2} & \rho_2^* & \rho_2^* & \cdots & \rho_2^* & \rho_1^* & \rho_1^* & \rho_1^* & \cdots & 1\\
 & & & & & \multicolumn{5}{c}{\underbrace{\hphantom{\rho_1^*\quad\rho_1^*\quad\rho_1^*\quad\cdots\quad 1}}_{N^*}}
\end{array}\right|$$

The first term in the summation is

$$\det\left(C_{11}\right)=\left(1-\rho_1\right)^{N-2}\left(1-\rho_1^*\right)^{N^*-1}\left[\left(1+(N-2)\rho_1\right)\left(1+(N^*-1)\rho_1^*\right)-\left(N-1\right)N^*\rho_2\rho_2^*\right]$$

The second term in the summation is

$$\left(\frac{w_2}{w_1}\right)^m\det\left(C_{21}\right)=(-1)^{1+2}\left(\frac{w_2}{w_1}\right)^m\det\left(\Lambda\right)$$

where

$$\det(\Lambda) = \begin{vmatrix} \overbrace{\rho_1 \quad \rho_1 \quad \cdots \quad \rho_1}^{N-1} & \rho_2 & \rho_2 & \rho_2 & \cdots & \rho_2 \\ \rho_1 \quad 1 \quad \cdots \quad \rho_1 & \rho_2 & \rho_2 & \rho_2 & \cdots & \rho_2 \\ \vdots \quad \vdots \quad \ddots \quad \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ \rho_1 \quad \rho_1 \quad \cdots \quad 1 & \rho_2 & \rho_2 & \rho_2 & \cdots & \rho_2 \\ \rho_2^* \quad \rho_2^* \quad \cdots \quad \rho_2^* & 1 & \rho_1^* & \rho_1^* & \cdots & \rho_1^* \\ \rho_2^* \quad \rho_2^* \quad \cdots \quad \rho_2^* & \rho_1^* & 1 & \rho_1^* & \cdots & \rho_1^* \\ \rho_2^* \quad \rho_2^* \quad \cdots \quad \rho_2^* & \rho_1^* & \rho_1^* & 1 & \cdots & \rho_1^* \\ \vdots \quad \vdots \quad \ddots \quad \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ \rho_2^* \quad \rho_2^* \quad \cdots \quad \rho_2^* & \multicolumn{5}{c}{\underbrace{\rho_1^* \quad \rho_1^* \quad \rho_1^* \quad \cdots \quad 1}_{N^*}} \end{vmatrix}$$

In matrix Λ, from $i = 2$ to $N-1$, we use the ith column minus the first column. From $j = N+1$ to $N + N^* - 1$, we use the jth column minus the Nth column. Then we use the Nth column minus the product of the first column and $\frac{\rho_2}{\rho_1}$. We can obtain

$$\det(\Lambda) = \begin{vmatrix} \rho_1 & 0 & \cdots & 0 & 0 & 0 & 0 & \cdots & 0 \\ \rho_1 & 1-\rho_1 & \cdots & 0 & 0 & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ \rho_1 & 0 & \cdots & 1-\rho_1 & 0 & 0 & 0 & \cdots & 0 \\ \rho_2^* & 0 & \cdots & 0 & 1-\frac{\rho_2}{\rho_1}\rho_2^* & \rho_1^*-1 & \rho_1^*-1 & \cdots & \rho_1^*-1 \\ \rho_2^* & 0 & \cdots & 0 & \rho_1^*-\frac{\rho_2}{\rho_1}\rho_2^* & 1-\rho_1^* & 0 & \cdots & 0 \\ \rho_2^* & 0 & \cdots & 0 & \rho_1^*-\frac{\rho_2}{\rho_1}\rho_2^* & 0 & 1-\rho_1^* & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ \rho_2^* & 0 & \cdots & 0 & \rho_1^*-\frac{\rho_2}{\rho_1}\rho_2^* & 0 & 0 & \cdots & 1-\rho_1^* \end{vmatrix}$$

From $j = N+1$ to $N + N^* - 1$, we add the Nth row to the jth row, we can obtain

$$\det(\Lambda) = \begin{vmatrix} \rho_1 & 0 & \cdots & 0 & 0 & 0 & 0 & \cdots & 0 \\ \rho_1 & 1-\rho_1 & \cdots & 0 & 0 & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ \rho_1 & 0 & \cdots & 1-\rho_1 & 0 & 0 & 0 & \cdots & 0 \\ (N^*-1)\rho_2^* & 0 & \cdots & 0 & 1+(N^*-1)\rho_1^*-N^*\frac{\rho_2}{\rho_1}\rho_2^* & 0 & 0 & \cdots & 0 \\ \rho_2^* & 0 & \cdots & 0 & \rho_1^*-\frac{\rho_2}{\rho_1}\rho_2^* & 1-\rho_1^* & 0 & \cdots & 0 \\ \rho_2^* & 0 & \cdots & 0 & \rho_1^*-\frac{\rho_2}{\rho_1}\rho_2^* & 0 & 1-\rho_1^* & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ \rho_2^* & 0 & \cdots & 0 & \rho_1^*-\frac{\rho_2}{\rho_1}\rho_2^* & 0 & 0 & \cdots & 1-\rho_1^* \end{vmatrix}$$

Then

$$\det(\Lambda) = \rho_1 (1-\rho_1)^{N-2} (1-\rho_1^*)^{N^*-1} \left[1 + (N^*-1)\rho_1^* - N^* \frac{\rho_2}{\rho_1} \rho_2^*\right]$$

The third term in the summation is

$$\det(C_{31}) = (-1)^{1+3} \begin{vmatrix} \overbrace{\begin{matrix}\rho_1 & \rho_1 & \cdots & \rho_1\end{matrix}}^{N-1} & \begin{matrix}\rho_2 & \rho_2 & \rho_2 & \cdots & \rho_2\end{matrix} \\ \begin{matrix}1 & \rho_1 & \cdots & \rho_1\end{matrix} & \begin{matrix}\rho_2 & \rho_2 & \rho_2 & \cdots & \rho_2\end{matrix} \\ \begin{matrix}\vdots & \vdots & \ddots & \vdots\end{matrix} & \begin{matrix}\vdots & \vdots & \vdots & \ddots & \vdots\end{matrix} \\ \begin{matrix}\rho_1 & \rho_1 & \cdots & 1\end{matrix} & \begin{matrix}\rho_2 & \rho_2 & \rho_2 & \cdots & \rho_2\end{matrix} \\ \begin{matrix}\rho_2^* & \rho_2^* & \cdots & \rho_2^*\end{matrix} & \begin{matrix}1 & \rho_1^* & \rho_1^* & \cdots & \rho_1^*\end{matrix} \\ \begin{matrix}\rho_2^* & \rho_2^* & \cdots & \rho_2^*\end{matrix} & \begin{matrix}\rho_1^* & 1 & \rho_1^* & \cdots & \rho_1^*\end{matrix} \\ \begin{matrix}\rho_2^* & \rho_2^* & \cdots & \rho_2^*\end{matrix} & \begin{matrix}\rho_1^* & \rho_1^* & 1 & \cdots & \rho_1^*\end{matrix} \\ \begin{matrix}\vdots & \vdots & \ddots & \vdots\end{matrix} & \begin{matrix}\vdots & \vdots & \vdots & \ddots & \vdots\end{matrix} \\ \begin{matrix}\rho_2^* & \rho_2^* & \cdots & \rho_2^*\end{matrix} & \underbrace{\begin{matrix}\rho_1^* & \rho_1^* & \rho_1^* & \cdots & 1\end{matrix}}_{N^*} \end{vmatrix}$$

We swap the first and the second column in the matrix,

$$\left(\frac{w_3}{w_1}\right)^m \det(C_{31}) = -\left(\frac{w_3}{w_1}\right)^m \det(\Lambda)$$

Using similar steps, we can show that

$$\left(\frac{w_n}{w_1}\right)^m \det(C_{n1}) = -\left(\frac{w_n}{w_1}\right)^m \det(\Lambda)$$

for $n \in [2, N]$.

For $n = N+1$,

$$\left(\frac{w_n}{w_1}\right)^m \det(C_{n1}) = (-1)^{2+N} \left(\frac{w_{N+1}}{w_1}\right)^m \det(\Gamma)$$

where

$$\det(\Gamma) = \begin{vmatrix} \overbrace{\rho_1 \quad \rho_1 \quad \cdots \quad \rho_1}^{N} & \rho_2 & \rho_2 & \rho_2 & \cdots & \rho_2 \\ 1 \quad \rho_1 \quad \cdots \quad \rho_1 & \rho_2 & \rho_2 & \rho_2 & \cdots & \rho_2 \\ \rho_1 \quad 1 \quad \cdots \quad \rho_1 & \rho_2 & \rho_2 & \rho_2 & \cdots & \rho_2 \\ \vdots \quad \vdots \quad \ddots \quad \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ \rho_1 \quad \rho_1 \quad \cdots \quad 1 & \rho_2 & \rho_2 & \rho_2 & \cdots & \rho_2 \\ \rho_2^* \quad \rho_2^* \quad \cdots \quad \rho_2^* & \rho_1^* & 1 & \rho_1^* & \cdots & \rho_1^* \\ \rho_2^* \quad \rho_2^* \quad \cdots \quad \rho_2^* & \rho_1^* & \rho_1^* & 1 & \cdots & \rho_1^* \\ \vdots \quad \vdots \quad \ddots \quad \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ \rho_2^* \quad \rho_2^* \quad \cdots \quad \rho_2^* & \rho_1^* & \rho_1^* & \rho_1^* & \cdots & 1 \end{vmatrix}$$

In matrix Γ, from $i = N + 2$ to $N + N^* - 1$, we use the ith column minus the last column. From $j = 2$ to N, we use the jth column minus the Nth column. We use the Nth column minus the product of the last column and $\frac{\rho_1}{\rho_2}$, and from $n = 2$ to N, we use the ith row minus the first row, we can obtain

$$\det(\Gamma) = \begin{vmatrix} 0 & 0 & \cdots & 0 & 0 & 0 & 0 & \cdots & \rho_2 \\ 1-\rho_1 & 0 & \cdots & 0 & 0 & 0 & 0 & \cdots & \rho_2 \\ 0 & 1-\rho_1 & \cdots & 0 & 0 & 0 & 0 & \cdots & \rho_2 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ \rho_1 - 1 & \rho_1 - 1 & \cdots & 1-\rho_1 & 0 & 0 & 0 & \cdots & \rho_2 \\ 0 & 0 & \cdots & \rho_2^* - \rho_1^* \frac{\rho_1}{\rho_2} & 0 & 1-\rho_1^* & 0 & \cdots & \rho_1^* \\ 0 & 0 & \cdots & \rho_2^* - \rho_1^* \frac{\rho_1}{\rho_2} & 0 & 0 & 1-\rho_1^* & \cdots & \rho_1^* \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \rho_2^* - \frac{\rho_1}{\rho_2} & \rho_1^* - 1 & \rho_1^* - 1 & \rho_1^* - 1 & \cdots & 1 \end{vmatrix}$$

Then

$$\det(\Gamma) = (-1)^{N-1} \rho_2 \left[(1-\rho_1)^{N-1} (1-\rho_1^*)^{N^*-1} \right]$$

and

$$\left(\frac{w_{N+1}}{w_1} \right)^m \det(C_{N+1,1}) = -\left(\frac{w_{N+1}}{w_1} \right)^m \rho_2 \left[(1-\rho_1)^{N-1} (1-\rho_1^*)^{N^*-1} \right]$$

For $n = N + 2$,

$$\left(\frac{w_n}{w_1}\right)^m \det\left(C_{n1}\right) = (-1)^{3+N}\left(\frac{w_{N+2}}{w_1}\right)^m \begin{vmatrix} \rho_1 & \rho_1 & \cdots & \rho_1 & \rho_2 & \rho_2 & \rho_2 & \cdots & \rho_2 \\ 1 & \rho_1 & \cdots & \rho_1 & \rho_2 & \rho_2 & \rho_2 & \cdots & \rho_2 \\ \rho_1 & 1 & \cdots & \rho_1 & \rho_2 & \rho_2 & \rho_2 & \cdots & \rho_2 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ \rho_1 & \rho_1 & \cdots & 1 & \rho_2 & \rho_2 & \rho_2 & \cdots & \rho_2 \\ \rho_2^* & \rho_2^* & \cdots & \rho_2^* & 1 & \rho_1^* & \rho_1^* & \cdots & \rho_1^* \\ \rho_2^* & \rho_2^* & \cdots & \rho_2^* & \rho_1^* & \rho_1^* & 1 & \cdots & \rho_1^* \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ \rho_2^* & \rho_2^* & \cdots & \rho_2^* & \rho_1^* & \rho_1^* & \rho_1^* & \cdots & 1 \end{vmatrix}$$

$$= (-1)^{N}\left(\frac{w_{N+2}}{w_1}\right)^m \det\left(\Gamma\right)$$

if we swap the $N+1$th column with the $N+2$th column.

Similarly, we can show that, for $n > N$,

$$\left(\frac{w_n^2}{w_1^2}\right)\det\left(C_{n1}\right) = \left(\frac{w_n^2}{w_1^2}\right)\rho_2\left[\left(1-\rho_1\right)^{N-1}\left(1-\rho_1^*\right)^{N^*-1}\right]$$

Therefore,

$$\begin{aligned} \sum_{n=1}^{N+N^*}\left(\frac{w_n}{w_1}\right)^m \det\left(C_{n1}\right) &= \left(1-\rho_1\right)^{N-2}\left(1-\rho_1^*\right)^{N^*-1}\left[\left(1+(N-2)\rho_1\right)\left(1+(N^*-1)\rho_1^*\right) - \left(N-1\right)N^*\rho_2\rho_2^*\right] \\ &\quad -\sum_{n=2}^{N}\left(\frac{w_n}{w_1}\right)^m \rho_1\left(1-\rho_1\right)^{N-2}\left(1-\rho_1^*\right)^{N^*-1}\left[1+\left(N^*-1\right)\rho_1^* - N^*\frac{\rho_2}{\rho_1}\rho_2^*\right] \\ &\quad -\sum_{n=N+1}^{N^*}\left(\frac{w_n}{w_1}\right)^m \rho_2\left[\left(1-\rho_1\right)^{N-1}\left(1-\rho_1^*\right)^{N^*-1}\right] \end{aligned}$$

Due to the symmetry and the constant wages within a country, we can show that

$$\begin{aligned} c_D^h &= \left(\frac{\gamma\phi}{L_h}\frac{1}{w_h}\frac{\left(1+(N^*-1)\rho_1^*\right) - N^*\rho_2\left(\frac{w_f}{w_h}\right)^m}{\left(1+(N-1)\rho_1\right)\left(1+(N^*-1)\rho_1^*\right) - NN^*\rho_2\rho_2^*}\right)^{\frac{1}{m+2}} \\ c_D^f &= \left(\frac{\gamma\phi}{L_f}\frac{1}{w_f}\frac{\left(1+(N-1)\rho_1\right) - N\rho_2^*\left(\frac{w_h}{w_f}\right)^m}{\left(1+(N-1)\rho_1\right)\left(1+(N^*-1)\rho_1^*\right) - NN^*\rho_2\rho_2^*}\right)^{\frac{1}{m+2}} \end{aligned}$$

for any Home region h and Foreign region f.

Plugging the expressions for c_D^h and c_D^f into (C.6), we can show that

$$\frac{L_h\left(c_D^h\right)^{m+2}}{L_f\left(c_D^f\right)^{m+2}}=\frac{w_F}{w_H}\frac{\left(1+(N^*-1)\rho_1^*\right)-N^*\rho_2\left(\frac{w_F}{w_H}\right)^m}{\left(1+(N-1)\rho_1\right)-N\rho_2^*\left(\frac{w_H}{w_F}\right)^m}=\frac{w_F}{w_H}\frac{\left(1+(N^*-1)\rho_1^*\right)-N^*\rho_2\left(\frac{w_F}{w_H}\right)^{m+1}}{\left(1+(N-1)\rho_1\right)-N\rho_2^*\left(\frac{w_H}{w_F}\right)^{m+1}}$$

The above condition holds for any ρ_1, ρ_1^*, ρ_2 and ρ_2^*, therefore

$$\frac{w_F}{w_H}=1$$

Home and Foreign have the same wage rates. Then, all results on the RER from our benchmark setup still hold.

Note that, n^k, the total number of firms in Home region k is

$$\begin{aligned} n^k &= n_E^k\left(\frac{c_D^k}{c^M}\right)^m+\sum_{h\neq k}n_E^h\left(\frac{c_D^k w_k/w_h}{\tau_1 c^M}\right)^m+\sum_f n_E^f\left(\frac{c_D^k w_k/w_f}{\tau_2^* c^M}\right)^m \\ &= mf_E\left(\frac{c_D^k}{c^M}\right)^m\left(L_k+\rho_1\sum_{h\neq k}L_h+\rho_2\sum_f L_f\right) \end{aligned}$$

Similarly, in Foreign region j, n^j is

$$\begin{aligned} n^j &= n_E^j\left(\frac{c_D^j}{c^M}\right)^m+\sum_{f\neq j}n_E^f\left(\frac{c_D^j w_j/w_f}{\tau_1^* c^M}\right)^m+\sum_h n_E^h\left(\frac{c_D^j w_j/w_h}{\tau_2 c^M}\right)^m \\ &= mf_E\left(\frac{c_D^j}{c^M}\right)^m\left(L_j+\rho_1^*\sum_{f\neq j}L_h+\rho_2^*\sum_h L_h\right) \end{aligned}$$

Similar to the benchmark case, we can also show that,

$$n^k=\frac{(2m+2)\,\gamma}{\eta}\left(\frac{\alpha}{c_D^k w}-1\right)\text{ and }n^j=\frac{(2m+2)\,\gamma}{\eta}\left(\frac{\alpha}{c_D^j w}-1\right) \tag{C.7}$$

Then

$$c_D^k w=\frac{(2m+2)\,\alpha\gamma}{\eta m f_E\left(c^M\right)^{-m}\left(L_k+\rho_1\sum_{h\neq k}L_h+\rho_2\sum_f L_f\right)\left(c_D^k\right)^m+(2m+2)\,\gamma} \tag{C.8}$$

The change in $c_D^k w$ is ambiguous. As in the benchmark, we can show that the Home CPI is

$$P_H=\sum_{k\in Home}\frac{L_k}{\sum_{h\in Home}L_h}\frac{2m^2+6m+3}{2\,(m+2)\,(m+3)}c_D^k w$$

In general, the effect on Home CPI from a decline in τ_1 is ambiguous.

The international wage parity is a special result based on the assumption that the entry cost (i) is proportional to the local wage, and (ii) the proportionality is identical across all regions. However, the underlying intuition for the RER effect is more general even when we relax those assumptions. As the internal trade cost falls, firms in region h face better opportunities to sell their products in other Home regions and abroad, and they may raise their outputs. This will produce two effects: (i) they lead to greater competition which lowers the local CPI, and (ii) they raise labor demand, hence resulting in a higher local wage rate. However, there is an offsetting force that puts a downward pressure on the local wage that comes from more firms from other Home regions entering the local market and crowding out some local firms.

At the same time, a reduction in the within-Home trade cost can also produce two opposite impacts on Foreign wage rate: i) a downward pressure from the fact that more Home firms export to Foreign markets which crowds out some Foreign firms, and ii) Foreign firms also find easier to export to Home, which raises the labor demand and hence wage rate. In this model, the net effects on the wage rates in the two countries are the same. Then, the increased competition effect on the price level in Home leads to a decline in Home's real exchange rate.

Now consider a special case in which Home is small (in the sense that N and $\sum_h L_h$ are much smaller than N^* and $\sum_f L_f$). By (C.3), we can show that, in any Home region h, w^h is proportional to the term $\rho_2 L_f \left(c_D^f\right)^{m+2}$. As in the previous analysis, we can easily show that, if N/N^* approaches zero, $\frac{dc_D^f}{d\tau_1}$ is close to zero. Notice that, if Home is small, ρ_2 is not sensititve to the change in τ_1, which implies that wages in Home w^h will not change much as the Home internal trading cost declines. A summary of all the results when Home is small is as follows. An improvement in Home's infrastructure i) does not change c_D^f much; ii) does not change w^h and w^f much (since we have shown $w^h = w^f$); however, iii) it lower c_D^h. As a result, Home CPI (which an increasing function of $c_D^h w^h$) will fall and Home's RER declines.

D Innovation (for online publication only)

In this section, we investigate how a decline in the trade cost will influence firms' innovation behaviors. As in Song et al. (2011), we assume that each firm hires a manager and delegates decision authority to the manager. Managers may adopt an innovation which can improve productivities with a positive possibility δ, which is an endogenous variable that can be optimally chosen by managers. Suppose managers and firms do not know the true productivity when making innovation decisions. Managers choose the probability of success in innovation δ by paying a cost $g(\delta)$, ($g' > 0$ and $g'' > 0$). After making an innovation decision, firms get a productivity draw as in our benchmark model. If the innovation succeeds, for a firm with marginal cost c from the original productivity draw, it can now produce the output with a new marginal cost λc ($\lambda < 1$). If the innovation fails, the firm's marginal cost remains the same from the original productivity draw c. After the realization of output, managers get paid. For those firms who cannot survive, they fire their managers without paying any salaries. The timeline for firms and managers' decisions is shown in Appendix Figure D1.

Since firms from the same region are ex ante the same, they will provide the same contract to managers. Managers from the same region are also ex ante the same, they make the same innovation decisions.

We assume the similar assumption as in Song et al (2011) that, managers can steal $\psi < 1$ of output. For a representative firm i from Home region k, the incentive constraint implies that

$$w_t^m \geq \psi \left(\sum_{h \in Home} \pi_{kh}^i + \sum_{f \in Foreign} \pi_{kf}^i \right)$$

The optimal contract implies that the incentive constraint is binding:

$$w_t^m = \psi \left(\sum_{h \in Home} \pi_{kh}^i + \sum_{f \in Foreign} \pi_{kf}^i \right)$$

Then firms can only receive $1 - \psi$ of the total profit, which implies the entry condition for firms from Home region k in the following:

$$(1-\psi) \left(\begin{array}{c} \sum_{h \in Home} \int_0^{\frac{c_D^h}{\tau_{kh}}} \left[\left(1-\delta^k\right) \pi_{kh}(c) + \delta^k \pi_{kh}(\lambda c) \right] dG(c) \\ + \sum_{f \in Foreign} \int_0^{\frac{c_D^f}{\tau_{kf}}} \left[\left(1-\delta^k\right) \pi_{kf}(c) + \delta^k \pi_{kf}(\lambda c) \right] dG(c) \end{array} \right) = f_E \tag{D.1}$$

where c_D^h and c_D^f are the similar highest prices defined in the benchmark in Home region h and Foreign region f, respectively.

The utility for a representative manager is

$$U^m = q_0^{c,m} + \alpha \int_{i \in \Omega} q_i^{c,m} di - \frac{1}{2}\gamma \int_{i \in \Omega} \left(q_i^{c,m}\right)^2 di - \frac{1}{2}\eta \left(\int_{i \in \Omega} q_i^{c,m} di \right)^2 - g(\delta) - l^m$$

which consists of two parts: i) the same quasi-linear utility on consumptions as workers, and ii) the extra loss to managers if they get fired by firms. The loss l^m takes value

$$l^m = \begin{cases} l & \text{if managers are fired by firms} \\ 0 & \text{otherwise} \end{cases}$$

where $l > 0$. We may understand such a loss as the extra effort the fired managers have to exert in finding a new job.

Managers will optimally choose consumptions and the effort on innovation to maximize their expected utilities. We define $\overline{c_D}^k$ as the threshold below which firms from Home region k will at least operate in some markets,

$$\overline{c_D}^k = \max\left[c_D^k, c_D^h/\tau_1, c_D^f/\tau_2\right], \text{ where } h \neq k$$

Then, the probability of a manager from Home region k getting fired is $\delta^k\left(1-\left(\frac{\overline{c_D}^k}{\lambda c^M}\right)^m\right)+\left(1-\delta^k\right)\left(1-\left(\frac{\overline{c_D}^k}{c^M}\right)^m\right)$. The expected utility for a manager from Home region k is

$$\begin{aligned} EU^m &= E\left[q_0^{c,m}+\alpha\int_{i\in\Omega}q_i^{c,m}di-\frac{1}{2}\gamma\int_{i\in\Omega}\left(q_i^{c,m}\right)^2di-\frac{1}{2}\eta\left(\int_{i\in\Omega}q_i^{c,m}di\right)^2\right]-g\left(\delta^k\right) \\ &\quad -l\left[\delta^k\left(1-\left(\frac{\overline{c_D}^k}{\lambda c^M}\right)^m\right)+\left(1-\delta^k\right)\left(1-\left(\frac{\overline{c_D}^k}{c^M}\right)^m\right)\right] \end{aligned}$$

Due to the quasi-linear utility on consumptions, the demand curve for a differentiated good will remain the same as in the benchmark. The first order condition with respect to p is

$$\frac{\partial\left[\psi\left(\begin{array}{c}\sum_{h\in Home}\int_0^{\frac{c_D^h}{\tau_{kh}}}\left[\left(1-\delta^k\right)\pi_{kh}(c)+\delta^k\pi_{kh}(\lambda c)\right]dG(c) \\ +\sum_{f\in Foreign}\int_0^{\frac{c_D^f}{\tau_{kf}}}\left[\left(1-\delta^k\right)\pi_{kf}(c)+\delta^k\pi_{kf}(\lambda c)\right]dG(c)\end{array}\right)\right]}{\partial p}-g'=l\left(\frac{\overline{c_D}^k}{c^M}\right)^m\left(\frac{1}{\lambda^m}-1\right)$$

By the firm's profit function and (D.1), the first order condition above can be re-written as

$$\frac{\psi}{1-\psi}\frac{fm\left(1-\lambda\right)\left(\frac{2}{m+1}-\frac{1+\lambda}{m+2}\right)}{1-\frac{2m}{m+1}\left(1-\delta^k+\delta^k\lambda\right)+\frac{m}{m+2}\left(1-\delta^k+\delta^k\lambda^2\right)}-g'=l\left(\frac{\overline{c_D}^k}{c^M}\right)^m\left(\frac{1}{\lambda^m}-1\right) \qquad \text{(D.2)}$$

Since $(1-\lambda)\left(\frac{2}{m+1}-\frac{1+\lambda}{m+2}\right)>0$, the left hand side of (D.2) is decreasing in δ^k. This means that, if markets become tougher, i.e., $\overline{c_D}^k$ decreases, managers will choose a greater effort in innovations.

If there is no extra utility loss for failed managers, i.e., $l=0$, δ^k is a constant which can be solved from (D.2). Then (D.1) becomes

$$L_k\left(c_D^i\right)^{m+2}+\sum_{h\neq k}L_h\rho_{kh}\left(c_D^h\right)^{m+2}+\sum_f L_f\rho_{kf}\left(c_D^f\right)^{m+2}=\frac{4\gamma\left(c^M\right)^m f_E}{1-\psi}\frac{1}{A\left(\delta^k\right)} \qquad \text{(D.3)}$$

where

$$A\left(\delta^k\right)=1-\frac{2m}{m+1}\left(1-\delta^k+\delta^k\lambda\right)+\frac{m}{m+2}\left(1-\delta^k+\delta^k\lambda^2\right)$$

The right hand side term of equation (D.3) is a constant. In this case, all benchmark results will hold.

In this section, we consider another case that $l>0$. We assume two assumptions in this extension: i) Home and Foreign are initially identical in everything, and ii) all regions in Home (Foreign) are symmetric. However, Home has experienced a faster development in its infrastructure, as a result, τ_1

falls. By Appendix C, we can obtain that, for any Home region k

$$c_D^k = \left(\frac{4\gamma \left(c^M\right)^m f_E}{(1-\psi) L_k} \frac{1}{A\left(\delta^k\right)} \frac{\left[\begin{array}{c} (1+(N-2)\rho_1)(1+(N^*-1)\rho_1^*) - \sum_f \frac{A(\delta^k)}{A(\delta^f)} \rho_2 (1-\rho_1) \\ -(N-1) N^* \rho_2 \rho_2^* - \sum_{h \neq k} \frac{A(\delta^k)}{A(\delta^h)} \left[\rho_1 \left(1 + (N^*-1)\rho_1^*\right) - N^* \rho_2 \rho_2^*\right] \end{array} \right]}{(1-\rho_1)\left[(1+(N-1)\rho_1)(1+(N^*-1)\rho_1^*) - NN^* \rho_2 \rho_2^*\right]} \right)^{\frac{1}{m+2}}$$

For any Foreign region j,

$$c_D^j = \left(\frac{4\gamma \left(c^M\right)^m f_E}{(1-\psi) L_f} \frac{1}{A\left(\delta^j\right)} \frac{\left[\begin{array}{c} (1+(N^*-2)\rho_1^*)(1+(N-1)\rho_1) - \sum_h \frac{A(\delta^j)}{A(\delta^h)} \rho_2^* (1-\rho_1^*) \\ -(N^*-1) N \rho_2 \rho_2^* - \sum_{f \neq j} \frac{A(\delta^j)}{A(\delta^f)} \left[\rho_1^* \left(1 + (N-1)\rho_1\right) - N \rho_2 \rho_2^*\right] \end{array} \right]}{(1-\rho_1)\left[(1+(N-1)\rho_1)(1+(N^*-1)\rho_1^*) - NN^* \rho_2 \rho_2^*\right]} \right)^{\frac{1}{m+2}}$$

In general, a decline in τ_1 has ambiguous impacts on c_D^k and c_D^j. However, under some sufficient conditions, for instance, λ is not far from one or l is small enough, considering small changes in τ_1, $A\left(\delta^k\right)/A\left(\delta^j\right)$ is always close to one, we can show that

$$\begin{aligned} & \frac{\left[\begin{array}{c} (1+(N-2)\rho_1)(1+(N^*-1)\rho_1^*) - \sum_f \frac{A(\delta^k)}{A(\delta^f)} \rho_2 (1-\rho_1) \\ -(N-1) N^* \rho_2 \rho_2^* - \sum_{h \neq k} \frac{A(\delta^k)}{A(\delta^h)} \left[\rho_1 \left(1 + (N^*-1)\rho_1^*\right) - N^* \rho_2 \rho_2^*\right] \end{array} \right]}{(1-\rho_1)\left[(1+(N-1)\rho_1)(1+(N^*-1)\rho_1^*) - NN^* \rho_2 \rho_2^*\right]} \\ \cong \; & \frac{1-\rho_2 + (N^*-1)(\rho_1^* - \rho_2)}{(1+(N-1)\rho_1)(1+(N^*-1)\rho_1^*) - NN^* \rho_2 \rho_2^*} \end{aligned}$$

which is increasing in τ_1. Since Home and Foreign are initially identical, for small changes in τ_1, we still obtain $\overline{c_D}^k = c_D^k$. Then we can show by contradiction that a decline in τ_1 will lead to a rise in δ^k and yield a lower c_D^k. Suppose not, a decline in τ_1 leads to a higher c_D^k, by (D.2), this implies a lower δ^k. Since $A\left(\delta^k\right)$ is increasing in δ^k, we can show that, as τ_1 declines, c_D^k falls. Contradiction! Therefore, as the within-country trade cost declines, c_D^k falls. By (D.2), managers hired by Home firms will increase their effort in innovations, which further lowers the regional price level.

Similar to the benchmark model, Home CPI is

$$P_H = \sum_{k \in Home} \frac{L_k}{\sum_{h \in Home} L_h} P_k = \frac{1}{2} \sum_{k \in Home} \frac{L_k}{\sum_{h \in Home} L_h} B\left(\delta^k\right) c_D^k$$

where

$$B\left(\delta^k\right) = \frac{1 + \frac{m}{m+1}\left(1 - \delta^k + \delta^k \lambda\right) - \frac{m}{m+2}\left(1 - \delta^k + \delta^k \lambda^2\right) - \frac{m}{m+3}\left(1 - \delta^k + \delta^k \lambda^3\right)}{1 - \frac{m}{m+2}\left(1 - \delta^k + \delta^k \lambda^2\right)}$$

Under the same assumptions in Proposition 1 and that λ is not far from one or l is small enough, $B\left(\delta^k\right)$ is decreasing in δ^k. Then, as τ_1 falls, Home CPI will decline. In addition to the markup adjustment channel we have discussed in the benchmark, there is another effect from a decline in the within-Home trade cost on the Home CPI. As the within-Home trade cost falls, Home firms are facing increasing competition in each region. Managers hired by Home firms are facing a greater possibility of being fired. To avoid this situation, managers will choose a greater effort in innovations which boosts firms' productivities and reduces the cost of production. As a result, prices will fall.

As for the real exchange rate,

$$RER_H = \frac{P_H}{P_F} = \frac{\sum_{k \in Home} \frac{L_k}{\sum_{h \in Home} L_h} B\left(\delta^k\right) c_D^k}{\sum_{j \in Foreign} \frac{L_j}{\sum_{h \in Foreign} L_f} B\left(\delta^j\right) c_D^j}$$

Similar to the previous analysis, we can show that, for any home region k and foreign region j, c_D^k / c_D^j falls as τ_1 declines. Since Home and Foreign are initially identical in everything, this implies that $\delta^k > \delta^j$. Therefore, $\left(B\left(\delta^k\right) c_D^k\right) / \left(B\left(\delta^j\right) c_D^j\right)$ falls, Home's real exchange rate depreciates as the within-Home trade cost falls.

E Traded input (for online publication only)

In this section, we consider another channel where an improvement in infrastructure can affect the real exchange rate. For simplicity, we consider a small open economy model. There are N regions within the country. For a representative consumer from region i, she/he consumes a final good c_i to obtain utility, where c_i consists of three types of goods: internationally tradable good (c_{IT}), domestically tradable but internationally nontradable good (c_{DT}) and domestically nontradable good (c_{NT})

$$c_i = \frac{c_{IT}^{\alpha} c_{DT}^{\beta} c_{NT}^{1-\alpha-\beta}}{\alpha^{\alpha} \beta^{\beta} \left(1 - \alpha - \beta\right)^{1-\alpha-\beta}},\ \alpha, \beta \in (0, 1) \text{ and } \alpha + \beta < 1 \tag{E.1}$$

We assume the same trade cost assumptions as in the benchmark model: i) within-country trade cost τ_1 is identical across regions; ii) all firms from the country face the same international trade cost τ_2 if they export; and iii) the import trade cost from the rest of world is τ_2^*. For a representative firm in region i, it uses labor (l_i) and a trade input (z_i) to produce

$$y_j^i = \frac{A_j^i z_j^{\theta_j} l_j^{1-\theta_j}}{\theta_j^{\theta_j} (1-\theta_j)^{1-\theta_j}},\ j = IT, DT, NT,\ \theta_j \in (0,1)$$

where A_j^i is the total factor productivity. For simplicity, we assume that the trade input z_i and the final consumption good c_i have the same composite over the three types of goods.

Assume that all markets are perfectly competitive, and we normalize the price for internationally tradable good (net of trade cost) to be one. Let P_i denote the local CPI in region i. Then, for a internationally tradable good producer in region i, the profit maximization condition implies

$$\frac{1}{\tau_2} = \frac{P_i^{\theta_{IT}} w_i^{1-\theta_{IT}}}{A_{IT}^i} \tag{E.2}$$

where w_i is the wage rate in region i. Similarly, for a representative domestically tradable but internationally nontradable good producer in region i,

$$\frac{P_{DT}}{\tau_1} = \frac{P_i^{\theta_{DT}} w_i^{1-\theta_{DT}}}{A_{DT}^i} \tag{E.3}$$

and for a representative domestically nontradable good producer

$$P_{NT}(i) = \frac{P_i^{\theta_{NT}} w_i^{1-\theta_{NT}}}{A_{NT}^i} \tag{E.4}$$

By (E.1), we can obtain

$$P_i = (\tau_2^*)^{\alpha} P_{DT}^{\beta} P_{NT}(i)^{1-\alpha-\beta} \tag{E.5}$$

By (E.2), (E.3), (E.4) and (E.5),

$$P_i = (\tau_2^*)^{\zeta_1} \left(\frac{\tau_1}{A_{DT}^i}\right)^{\zeta_2} \left(\frac{\tau_2}{A_{IT}^i}\right)^{-\zeta_3} \left(\frac{1}{A_{NT}^i}\right)^{\zeta_4} \tag{E.6}$$

where

$$\begin{aligned}
\zeta_1 &= \frac{\alpha(1-\theta_{IT})}{1-\alpha\theta_{IT}-\beta\theta_{DT}-(1-\alpha-\beta)\theta_{NT}} \\
\zeta_2 &= \frac{\beta(1-\theta_{IT})}{1-\alpha\theta_{IT}-\beta\theta_{DT}-(1-\alpha-\beta)\theta_{NT}} \\
\zeta_3 &= \frac{\beta(1-\theta_{DT})+(1-\alpha-\beta)(1-\theta_{NT})}{1-\alpha\theta_{IT}-\beta\theta_{DT}-(1-\alpha-\beta)\theta_{NT}} \\
\zeta_4 &= \frac{(1-\alpha-\beta)(1-\theta_{IT})}{1-\alpha\theta_{IT}-\beta\theta_{DT}-(1-\alpha-\beta)\theta_{NT}}
\end{aligned}$$

are all positive.

The country's CPI and real exchange rate are

$$P = \sum \frac{L_i}{L} P_i \text{ and } RER = \sum \frac{L_i}{L} \frac{P_i}{P^*}$$

where L_i and L denote the population in region i and total population in the country, respectively. P^* is the CPI index in the rest of world (which is a constant in this small open economy model).

Now it is easy to show that

$$\begin{aligned} \frac{dP}{d\tau_1} &= \sum \frac{L_i}{L} \frac{P_i}{\tau_1} \left(\zeta_1 \frac{d\tau_2^*}{d\tau_1} \frac{\tau_1}{\tau_2^*} + \zeta_2 - \zeta_3 \frac{d\tau_2}{d\tau_1} \frac{\tau_1}{\tau_2} \right) \\ \frac{dRER}{d\tau_1} &= \sum \frac{L_i}{L} \frac{P_i}{P^* \tau_1} \left(\zeta_1 \frac{d\tau_2^*}{d\tau_1} \frac{\tau_1}{\tau_2^*} + \zeta_2 - \zeta_3 \frac{d\tau_2}{d\tau_1} \frac{\tau_1}{\tau_2} \right) \end{aligned}$$

Under a sufficient condition that

$$\frac{d\tau_2}{d\tau_1} \frac{\tau_1}{\tau_2} \leq \frac{\beta (1 - \theta_{IT})}{\beta (1 - \theta_{DT}) + (1 - \alpha - \beta)(1 - \theta_{NT})} \tag{E.7}$$

we can show that

$$\frac{dP}{d\tau_1} > 0 \text{ and } \frac{dRER}{d\tau_1} > 0$$

As within-country trade cost τ_1 falls, the CPI and the real exchange rate of the country will fall.

Similar to the benchmark, if Home is small, then Home-to-Foreign trade cost mainly depends on the border cost and/or within-Foreign trade cost. The elasticity of Home-to-Foreign trade cost with respect to within-Home trade cost, $\frac{d\tau_2}{d\tau_1} \frac{\tau_1}{\tau_2}$, is small. Then our sufficient condition easily holds.