The Efficiency of the Global Market for Capital Goods

Georg Strasser*

University of Pennsylvania

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Abstract

Despite integration of financial and goods markets, borders still impose considerable friction on the flow of goods. This paper quantifies these frictions by estimating the cost that borders impose on international flows of capital goods. It constructs a novel measure of the real exchange rate and estimates the border cost directly from nonlinearities in the real exchange rate process. During the sample period, 1974 to 2007, a relocation reduces the quantity of the relocated capital good by 35% for the median country pair. A transfer of consumption goods entails a loss of only 15%. This difference holds even after accounting for within-country costs, and indicates that border frictions in markets for capital goods are substantially higher than in markets for consumption goods.

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[*] Department of Economics, University of Pennsylvania, 3718 Locust Walk, Philadelphia, PA 19104-6297 (*georg@sas.upenn.edu*). I am grateful to Frank Diebold, Bernard Dumas, Urban Jermann, Karen Lewis, and Frank Schorfheide for valuable comments and suggestions.

1 Introduction

During the last three decades not only consumption goods, but also capital goods, have become increasingly mobile. Despite globalization of financial and goods markets, however, borders still impose considerable friction on flows of goods. These frictions may vary considerably between goods: For consumption goods, on the one hand, frictions may not exceed plain transportation. On the other hand, the relocation can be very complex if the good needs to be adapted to the local environment or if its use requires training. Differences in standards, culture, skill, and local technology levels bring about relocation costs that exceed the cost of transportation.

Previous studies of the market frictions embodied in borders focus on *consumption goods*. These goods are similarly useful in all countries and do not require localization, which is why we also refer to them as *unbundled goods*. Existing estimates of market frictions rely on trade flows (e.g. McCallum 1995, Anderson and van Wincoop 2003) and on the real exchange rate of consumer goods (e.g. Engel and Rogers 1996, Gorodnichenko and Tesar 2006). No estimates exist, however, of the relocation costs of more complex goods, such as *capital goods*. Capital goods comprise, for example, machinery, technology, and human capital embedded in the productive sector. Typically, a capital good combines several of these components in a unique way, which is why we will also refer to them as *bundled goods*.

Capital goods markets deserve particular attention today, as international cross-border consumption goods flows are largely liberalized. The cost of adjusting capital stock by means of investing, i.e. the cost of converting consumption goods into capital goods and vice versa, is considerable, and unbundling and rebundling of capital goods for the sole purpose of relocating them may thus be economically unfeasible. Thus the cost of *directly* relocating capital goods becomes decisive for the efficiency of the global allocation of capital goods. This allocation is a key determinant of relative output and ultimately of relative welfare. Unsurprisingly, it is an enduring core issue of international economics (Lucas 1990, Hsieh and Klenow 2007).

Several key questions emerge: How high is the border for capital goods? Does the height of this barrier differ, and if so, why? Because the damming effect of borders on capital goods reflects relocation cost, we can equivalently assess the efficiency of capital goods markets by asking: How costly is the relocation costs for capital goods? How do these relocation costs relate to the cost of transferring consumption goods? Answering these questions has direct implications for relative market efficiency and for determining which market would most benefit from additional effort to reduce these frictions.

A natural approach to these questions might start with data on goods' allocations among countries, which is available unfortunately only as a rough estimate, especially for capital goods. We therefore choose an indirect approach. In a classic contribution, Heckscher (1916) notes that under non-zero relocation cost large deviations from purchasing power parity (PPP) can be sustained. Dumas (1992), as well as Sercu, Uppal and van Hulle (1995), formally derive the link between relocation cost, allocations of goods and the real exchange rate.[1] Their fundamental insight allows us to analyze the real exchange rate in lieu of the allocation of goods across countries. In these models, relocation costs affect the real exchange rate in a unique way, which we exploit for estimating these costs.

Because conventional data of real exchange rates reflect the price index for unbundled goods, e.g. on the consumer (CPI) or wholesale price index (WPI), their behavior over time reflect the frictions in the market for unbundled goods. They contain no information on the market for capital goods. For this reason, we construct a novel measure of the real exchange rate based on capital goods. This new measure complements existing measures by focusing on a class of goods neglected so far, and thus allows us to compare capital goods with consumption goods.

An important innovation in our approach is the estimation of relocation cost directly from the time variation of the real exchange rate over time. Unlike previous studies, we do not exclusively rely on differences of price index levels between countries. Continuous time models of international finance predict more than just bounds on sustainable price differences between two countries. Rather, their solution provides the entire real exchange rate process, in particular the evolution of drift and diffusion over time. Our model, similar to Dumas (1992), predicts a nonlinear process for both conditional drift and diffusion, which we exploit in estimation. A very parsimonious approximation, which captures this nonlinearity, is the exponential smooth transition autoregressive (ESTAR) model. Accordingly, in our indirect inference framework, ESTAR serves as the auxiliary model, which allows us to attribute this nonlinearity to relocation costs.

We build on several strands of earlier literature. First, nonlinearity in real exchange rates is a well-documented phenomenon.[2] Prakash and Taylor (1997) and Obstfeld and

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[1] Costs of international trade have also been included in international business cycle models, e.g. Backus, Kehoe and Kydland (1992), Obstfeld and Rogoff (2000), Ravn and Mazzenga (2004).

[2] The importance of a nonlinear specification is highlighted by the weak support for mean-reversion achievable with linear models (Adler and Lehman 1983, Frankel and Rose 1996, Lothian and Taylor 1996, Rogoff, Froot and Kim 2001). Froot and Rogoff (1995) and Sarno (2005) provide useful surveys. These studies imply extremely slow speeds of mean reversion (Rogoff 1996, Murray and Papell 2005). Nonlinear models provide a natural explanation for both observations. The real exchange rate mean-reverts whenever it has wandered

Taylor (1997), for example, estimate a model with a hard cut-off between regimes.[3] Closer to our approach are studies that use a smooth transition between regimes, as in the ESTAR specification.[4] Michael, Nobay and Peel (1997), for example, use a sample of monthly WPI data of four countries in the 1920s and annual data for United Kingdom-France and United Kingdom-USA over 200 years. Taylor, Peel and Sarno (2001) work with monthly CPI data for five countries over the period 1973-1996. Modeling real exchange rates by an ESTAR model, Kilian and Taylor (2003) find predictability of the nominal exchange rate at horizons of two years or more. All these studies report strong support for a nonlinear specification, with a random walk dominating over short horizons. However, they do not make further use of this nonlinearity to quantify the border cost, nor do they provide any results applicable to capital goods.

Second, our work could be viewed as a particular way of studying mean reversion of international stock markets. Studies focusing on mean reversion of relative nominal international stock prices, such as Richards (1995) and Balvers, Wu and Gilliland (2000), find evidence of transitory country-specific effects in long-run relative stock returns. No one has yet explored the mean reversion of a real capital market-based measure, such as the real exchange rate for capital goods.

Third, Caselli and Feyrer (2007) show the importance of price and availability of complementary factors, such as technology (Eaton and Kortum 1999) or human capital (Lucas 1990), for differences in the marginal product of capital across countries. Because our definition of capital goods contains these complementary factors, our estimates of border cost shed light on the reasons for sustained country heterogeneity in stocks of these complementary factors.

The remainder of this paper is organized as follows. Section 2 introduces the methodology we use, including our measure, data and model. Section 3 describes the estimation and inference procedure. Section 4 presents the results, and section 5 concludes.

2 Methodology

In what follows we first discuss a model of endogenous capital accumulation with depreciation shocks and relocation cost, which captures key features of the real exchange rate data. We

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far away from parity, but follows a random walk when it is close to parity.

[3] This threshold autoregressive model was introduced by Tong (1990) and Balke and Fomby (1997).

[4] See Taylor (2005) for a survey. At the sectoral level, Imbs, Mumtaz, Ravn and Rey (2003) find nonlinearity for two thirds of the sectors in their sample.

then derive a novel measure of the real exchange rate of capital goods, and compare its properties with conventional real exchange rate series.

2.1 Modeling Real Exchange Rates with Frictions

We model an economy with complete financial markets, i.e. an economy where all necessary securities are available and international financial flows are unconstrained.[5] The counterpart of financial markets in the real economy, the market for goods, is subject to frictions. Relocating goods from one country to another entails a cost, $1 - r \in (0, 1)$, i.e. of every unit relocated only r percent arrive. This cost reflects first and foremost the cost of shipping an unbundled good. For capital goods it includes another component on top of the shipping cost – the cost of relocating organizational structures and knowledge necessary for operating the good. The overall cost for capital goods can therefore be much higher than for consumption goods, even though the shipping cost component for capital goods might be negligible.

Our model economy consists of two countries, which are separated by a border. There is only one good in our economy, but because any transfer of goods across the border entails an "iceberg" loss of $1 - r$, the good's location matters.[6] Accordingly, we mark parameters and quantities of the foreign country with an asterisk (*). The stock of goods, K, can be either consumed (c) or invested in a constant returns to scale production with productivity α. The stock of goods is subject to a zero-mean depreciation shock, $d\tilde{z}$. Further, the shocks in both countries have a joint covariance matrix Ω, and thus

$$\begin{pmatrix} d\tilde{z} \\ d\tilde{z}^* \end{pmatrix} = \Omega \begin{pmatrix} dz \\ dz^* \end{pmatrix} = \begin{pmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{12} & \sigma_{22} \end{pmatrix} \begin{pmatrix} dz \\ dz^* \end{pmatrix}, \tag{1}$$

where dz and dz^* are increments of a standard Brownian motion process.

Under this setup – perfect financial markets and imperfect markets for goods – the economy is always in equilibrium.[7] The marginal rates of substitution, however, differ between countries at almost every instance because of the cost of crossing the border. Since the relo-

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[5] Completeness seems an accurate description of the condition of financial markets among developed countries over the past 30 years, considering the immeasurable variety of financial instruments. Between developed countries, movements of financial capital were largely free from legal restrictions. See e.g. Allen and Gale (1994).

[6] On that account, there are two goods, indexed by their location, and a relocation technology, r.

[7] This setup differs from a class of finance models, where a "mispricing" of stocks or other assets constitutes an arbitrage opportunity that triggers e.g. foreign direct investment (Baker, Foley and Wurgler 2004) or investment (Polk and Sapienza 2004), or where imperfect capital markets cause foreign direct investment to be linked with e.g. currency movements (Froot and Stein 1991).

cation cost is the only friction hindering the movement of goods, this relocation cost bounds the possible valuation differences between countries from above. No relative valuation outside of the interval $[r; 1/r]$ can persist, because this would trigger immediate, risk-free, and profitable transfers of goods, dX, from a low-price to a high-price country, until the relative valuation has returned back into this interval.

Owing to the assumption of complete financial markets, the decentralized two-country problem is equivalent to the planner's problem:[8]

$$V(K, K^*) = \max_{\substack{c(t), c^*(t), \\ \Xi(r)}} E_t \int_0^\infty e^{-\rho(u-t)} \left(\frac{q}{\gamma} c(u)^\gamma + \frac{1-q}{\gamma} (c^*(u))^\gamma \right) du \tag{2}$$

s.t.

$$\begin{aligned} dK(t) &= (\alpha K(t) - c(t))\, dt + K(t) d\tilde{z}(t) - dX(t) + r dX^*(t) \\ dK^*(t) &= (\alpha^* K^*(t) - c^*(t))\, dt + K^*(t) d\tilde{z}^*(t) + r dX(t) - dX^*(t) \end{aligned} \tag{3}$$

where $K(0)$ and $K^*(0)$ are given, $c(t), c^*(t), K(t), K^*(t), X(t), X^*(t) \geq 0 \quad \forall t$, and where $\rho > 0$ denotes the discount rate, $1 - \gamma > 0$ the risk aversion and q the welfare weight of the home country. The relocation of goods is captured by $X(t)$, which is an adapted, nonnegative, right-continuous, nondecreasing stochastic process. Ξ denotes the open region in the (K, K^*) space in which no goods are transferred, i.e. where $dX = 0$ and $dX^* = 0$. Due to the homogeneity of the value function, Ξ is fully characterized by the minimal and maximal imbalance levels, $\underline{\omega}$ and $\overline{\omega}$.[9]

The symmetric version of this model has been developed by Dumas (1992).[10] We consider here, in addition, country heterogeneity in the ability to produce capital goods (Hsieh and Klenow 2007), which can result in persistent differences of prices between countries. This complication of the analytic and subsequent numerical solution becomes important when estimating this model, because only an asymmetric model can explain, for example, a nonzero unconditional mean of the drift of the real exchange rate.

We define the *imbalance* of goods as $\omega = K/K^*$. Substituting $V(K, K^*) = K^{*\gamma} I(\omega)$, and

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[8] Basak and Croitoru (2007) show that a decentralized economy with country-specific bonds and a claim on the dividend flow of one country can equivalently be solved by (2).

[9] The technical appendix, which is available upon request, provides detailed calculation and discussion of many of the results presented in this subsection.

[10] The models of Sercu et al. (1995) and O'Connel and Wei (2002) predict a no-arbitrage band as well. Versions of this model are used by e.g. Uppal (1993) to analyze the effect of home bias in consumption on portfolio choice, and by Dumas and Uppal (2001) to assess the benefit of international financial integration.

using the homogeneity property of the value function, we obtain a second order ordinary differential equation, which governs the imbalance process in periods of no relocations.

$$\begin{aligned} 0 &= \left(\frac{1}{\gamma q} - q^{\frac{1}{1-\gamma}}\right) I'(\omega)^{\frac{\gamma}{\gamma-1}} + \left(\frac{1}{\gamma(1-q)} - (1-q)^{\frac{1}{1-\gamma}}\right) \left(\gamma I(\omega) - \omega I'(\omega)\right)^{\frac{\gamma}{\gamma-1}} \\ &+ \left(\alpha^* \gamma - \rho + \frac{1}{2}\left(\sigma_{12}^2 + \sigma_{22}^2\right)\gamma(\gamma-1)\right) I(\omega) \\ &+ \left[\alpha - \alpha^* + (\gamma-1)(-\sigma_{22}^2 - \sigma_{12}^2 + \sigma_{12}(\sigma_{11}+\sigma_{22}))\right] \omega I'(\omega) \\ &+ \left(\frac{1}{2}\left(\sigma_{11}^2 + \sigma_{12}^2\right) + \frac{1}{2}\left(\sigma_{22}^2 + \sigma_{12}^2\right) - \sigma_{12}(\sigma_{11}+\sigma_{22})\right) \omega^2 I''(\omega) \end{aligned} \tag{4}$$

By optimal choice of the boundary of Ξ, the unknown function $I(\omega)$ must satisfy value matching and smooth pasting conditions at both boundaries at all times. The value matching condition requires equalization of marginal values of the good at the moment of relocation, e.g. for the upper boundary, $\overline{\omega}$[11]

$$V_K(K, K^*) = r V_{K^*}(K, K^*). \tag{5}$$

The smooth pasting conditions require

$$V_{KK}(K, K^*) = r V_{KK^*}(K, K^*), \tag{6}$$

and

$$V_{K^*K}(K, K^*) = r V_{K^*K^*}(K, K^*). \tag{7}$$

Substituting for the value function we can express these conditions in terms of the unknown functional $I(\omega)$.

$$\frac{I'(\overline{\omega})}{\gamma I(\overline{\omega})} = \frac{r}{1 + r\overline{\omega}} \tag{8}$$

$$\frac{I''(\overline{\omega})}{\gamma I(\overline{\omega})} = \frac{r^2(\gamma-1)}{(1 + r\overline{\omega})^2} \tag{9}$$

The differential equation (4) with boundary conditions (8) and (9) and the analogous conditions for the lower boundary must be solved numerically for the function $I(\omega)$. We determine the optimal boundaries by guessing values for $\underline{\omega}$ and $\overline{\omega}$ and iterating both forward toward some intermediate imbalance level $\omega_0 \in (\underline{\omega}, \overline{\omega})$ using the embedded fifth-order Runge-

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[11] The conditions for the lower boundary are analogous.

Kutta method of Cash and Karp (1990).[12] If $\overline{I'(\omega_0)} = \underline{I'(\omega_0)}$ and $\overline{I''(\omega_0)} = \underline{I''(\omega_0)}$ then a solution has been found. Otherwise we retry with a new guess for the pair of boundaries.

[Table 1 about here.]

[Table 2 about here.]

Table 1 reports the maximum sustainable imbalance as a function of risk and risk aversion for modest relocation cost ($r = 0.82$) in a symmetric world. The imbalances are the larger, the lower the risk aversion and the higher the risk. Table 2 shows that a higher relocation cost ($r = 0.66$) implies larger sustainable imbalances for any level of risk aversion and risk.

[Table 3 about here.]

If the countries differ in their productivity, then, as shown in table 3, the sustainable abundance of goods increases in the highly productive country, and decreases in the less productive country; however, this difference shrinks quickly as risk aversion increases. Given a degree of risk aversion, the maximum sustainable imbalance approaches an asymptote as risk grows to infinity. For risk aversion larger than unity there exists a maximum risk level, beyond which the differential equation has no solution.

We are now able to define the *real exchange rate*, p, as the ratio of the marginal values of the good in two countries, i.e.

$$p(\omega) = \frac{V_K(K, K^*)}{V_{K^*}(K, K^*)} = \frac{I'(\omega)}{\gamma I(\omega) - \omega I'(\omega)}. \tag{10}$$

Note that the real exchange rate depends only on the capital goods imbalance, ω, but not on the stock levels, K and K^*, of the good. Therefore, the real exchange rate tracks the relative scarcity of goods – a scarcity due to the frictions in the goods market, which underlines the strong impact of relative productivity on the real exchange rate.

Using Ito's lemma, drift and diffusion of natural logarithm of the real exchange rate process

$$dln(p) = \mu_p(p)dt + \sigma_p(p)dz \tag{11}$$

can be written as a function of ω, $I(\omega)$, $I'(\omega)$, $I''(\omega)$.

The drift of $ln(p)$ is at the upper boundary

$$\mu_p(\omega = \overline{\omega}) = \alpha^* - \alpha + \frac{\overline{\omega} - 1/r}{\overline{\omega} + 1/r}(1-\gamma)\sigma^2, \tag{12}$$

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[12] This procedure is described in detail in Press, Teukolsky, Vetterling and Flannery (2001, p.710).

and at the lower boundary

$$\mu_p(\omega = \underline{\omega}) = \alpha^* - \alpha + \frac{\underline{\omega} - r}{\underline{\omega} + r}(1 - \gamma)\sigma^2. \tag{13}$$

For realistic parameter values the mean reversion at the boundary gains in strength with shock diffusion, σ^2, and with risk aversion, $1 - \gamma$.[13]

[Figure 1 about here.]

A key feature of our model is that drift and diffusion of the the real exchange rate vary systematically with its level. The upper panel of figure 1 shows the drift of two real exchange rate processes with different relocation costs. The process represented by the solid line results from high relocation cost ($r = 0.66$), whereas the process represented by the dashed line reflects low relocation cost ($r = 0.82$). Both processes share the property that a deviation from parity entails a drift of opposite sign. The diffusion, shown in the lower panel, decreases as real exchange rate deviations from parity become large. The real exchange rate process is therefore mean reverting at the boundaries of Ξ, but indistinguishable from a random walk close to parity. Clearly, increases in relocation cost not only widen the range of sustainable deviations from PPP, but also lower the drift at all real exchange rate levels. Likewise, they increase diffusion at all real exchange rate levels.

[Figure 2 about here.]

We now take a closer look at the high relocation cost scenario. Figure 2 compares the drift of the real exchange rate in a symmetric world, in which productivities are equal ($\alpha = \alpha^*$, solid line), with the drift in an asymmetric world, in which productivities differ ($\alpha < \alpha^*$, dashed line). The dashed line shows that small differences in growth rates can shift the reversion target level away from PPP ($ln(p) = 0$) to a considerably different level ($ln(p) \approx 0.1$). If the productivity gap between two countries is wide, then the drift can have the same sign at almost all real exchange rate levels.[14] In this case the real exchange rate process is therefore divergent for half of its support, although it is still bounded by Ξ.

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[13] The necessary condition for this to hold is $\underline{\omega} < r$ and $\overline{\omega} > 1/r$. Tables 1 and 2 show that this is always satisfied except for very small σ in combination with $\gamma < 0$.

[14] An example for this extreme case is shown in figure 11.

2.2 Measuring Real Exchange Rates

The model described in the previous section helps us estimate the relocation cost directly from real exchange rate data. Typically the real exchange rate is calculated for consumption goods, and based on the CPI, WPI, or deflators of the gross domestic product (GDP). Each of these excludes a large share of the capital goods required for production, in particular immaterial goods. To compare the border effect of consumption goods with that of capital goods, we need one real exchange rate series for each.

For consumption goods we use the commonly used real exchange rate based on the WPI, which captures the bulkiness and business-to-business nature of these goods in international transactions.

Unfortunately for capital goods, no appropriate real exchange rate is readily available. We therefore construct a novel real exchange rate series tailored to capture the valuation differences of capital goods between countries. Capital goods are factors in operation in the productive sector of the economy. They are typically owned by a firm, need to be combined with other capital goods in order to be fully useful,[15] and are often intangible (e.g. in the form of patents and knowhow). Clearly, none of the aforementioned real exchange rates focuses on capital goods, and for the most part they do not contain any capital goods at all.

To understand more clearly what data we need, let us rewrite (10) by raising the fraction to higher terms using the world market price of an uninvested capital good, V_G.

$$p(\omega) = \frac{V_K(K, K^*)K/(V_G K)}{V_{K^*}(K, K^*)K^*/(V_G K^*)} \tag{14}$$

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[15] A major share of capital goods, except machinery, can be considered complementary factors. In the case of information technology investment, for example, only about one third of expenditures are invested in hardware and prepackaged software, whereas the rest is spent for complementary capital such as training, support, and custom software, which is a necessary requirement for the hardware to be useful within the productive sector (Basu, Fernald, Oulton and Srinivasan 2003, Kiley 1999). The work of Caselli and Feyrer (2007) highlights the importance of these complementary factors for understanding global capital goods allocations. They find that under a narrow definition of capital stocks (i.e. machinery only) the marginal product of capital across countries does not differ by much, and thus border frictions for these goods are small. It is the other, complementary capital goods needed in the production process, such as human capital and technology, that explain the difference in the marginal product of capital. They point out that the scarcity of complementary capital goods, which are included in the capital goods definition employed in this paper, and the higher cost of capital goods explain the low capital flows into these countries. Our model predicts a similar link between high cost of capital and low new investment. Without relocations, the less productive country is short of capital goods. Because relocation costs hinder a complete equalization of this imbalance, the price of capital goods in the less productive country is higher. The model predictions match therefore the empirical observation of Caselli and Feyrer (2007), but the causality is reversed.

Notice that the market value of all capital goods in a given country can be written as

$$M = V_K\left(K(t), K^*(t)\right)K(t)e(t), \tag{15}$$

where $e(t)$ is the nominal exchange rate to a numeraire currency. Likewise, book values of all capital goods in a given country are

$$B = V_G K(t)e(t)\varphi, \tag{16}$$

where φ denotes a time-invariant, country-specific accounting constant. The real exchange rate (14) can therefore be written in terms of (inflation-adjusted) market-to-book ratios, M/B, i.e.

$$p(\omega) = \frac{M/B}{M^*/B^*}\frac{\varphi}{\varphi^*}. \tag{17}$$

Stock indices measure the total market value of capital goods of firms included in this stock index. The corresponding quantity of capital goods is captured by the aggregate book values, after adjusting it for the effect of inflation. Normalizing the stock indices by adjusted book values removes the effect of nominal exchange rates and of quantity changes via e.g. retained earnings or international relocation of capital goods, and thus provides us with a measure of the relative value of one unit of capital good. For countries with identical accounting standards the real exchange rate of capital goods is thus simply the ratio of market-to-book values. When countries differ in accounting standards or leverage levels, $p(\omega)$ can be corrected for the constant factor $\frac{\varphi}{\varphi^*}$ by setting midrange of $log(p(\omega))$ to zero.

Our use of market-to-book ratios differs from their interpretation in standard q-theory (Hayashi 1982). Our aim of dividing market by book values is normalizing market values to one unit of capital goods, and because the value of capital goods changes over time, the market-to-book ratio must change as well. In contrast, Tobin's q in our model is always unity, because it does not explicitly consider adjustment cost of investment within a given country.[16] In our setup the market-to-book ratio of a single country's stock index has therefore no economic meaning in isolation, but is informative relative to other countries' market-to-book ratios. The ratio of two countries' market-to-book ratios measures the relative price

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[16] Market-to-book values measure the ratio of the market value of equity relative to the book value of equity, i.e. the denominator includes the book value of all capital goods (including goodwill) minus the book value of debt. Our model does not distinguish between equity and debt. As long as within any given country the debt level is a fixed proportion of equity, dividing by book values provides the desired quantity correction.

of one unit of capital goods between the two countries. Despite the different interpretation, high relative market-to-book ratios between two countries influence future relative returns – similar to the stylized fact that market-to-book ratios are inversely related to future equity returns (Fama and French 1992, Fama and French 1998, Pontiff and Schall 1998).

Our concept of the real exchange rate based on capital goods has multiple advantages. Firstly, it allows us to study properties of the market for capital goods in isolation from markets for other goods, which has not been done previously due to lack of data. In combination with our estimation approach, it enables us to estimate relocation costs of capital goods from macroeconomic data. This is important, because microeconomic data on the cost of relocating capital goods across borders on a per-project basis is not publicly available.[17]

Secondly, because one component of market-to-book ratios is determined in financial markets, it responds quickly to new information. In contrast, accounting regulations (Nexia International 1993) restrict the revaluation of book values of stocks of capital goods. The rare value adjustments of book values paired with frequent quantity adjustments, which makes book values inappropriate as a measure of value, is a virtue for our purposes. It makes, properly adjusted, book values a measure of the quantity of capital goods operating in an economy. Our approach mitigates problems with CPI and WPI data, which are subject to aggregation bias (Imbs, Mumtaz, Ravn and Rey 2005) and non-synchronous sampling (Taylor 2001). In particular, the valuation component of our real exchange rate, the market values, are synchronously sampled worldwide in centralized markets in a standardized and automated manner. It is collected in real time, and not subject to revisions. Further, aggregation to a country stock index is transparent and largely internationally comparable.

Our approach differs in important ways from the study of Engel and Rogers (1996) on the “width of the border”, addressing many concerns pointed out by Gorodnichenko and Tesar (2006). For example, we do not rely on the unconditional variance of the real exchange rate as dependent variable. Our estimates are identified by time variation, not by within-country cross-section variation, and are therefore unaffected by differences in within-country price dispersion. Further, the real exchange rate for capital goods is – by virtue of the speed of financial markets – less persistent than a real exchanges rate based on the CPI, and by its definition immune to pure nominal exchange rate changes.

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[17] Available data, such as data on FDI, which might be used to identify frictions between countries, measures only financial flows, but not the underlying flow of capital goods.

2.3 Data

We collect data from various editions of Capital International Perspective (1975-2007). This dataset from Morgan Stanley Capital International contains monthly nominal exchange rates, stock price indices and consistently calculated market-to-book ratios for these indices of 18 developed countries for the period December 1974 to June 2007.

[Figure 3 about here.]

The market-to-book ratios vary substantially over time. The solid line in figure 3 shows that the equal-weighted average market-to-book ratio trended upward over the last 30 years, with large transitory upward bursts. The variation across countries does not show any trend during the same period. In periods of a high market-to-book ratio average, however, the variation increases temporarily. This indicates that not all countries participate in these transitory upward bursts. Because variation after a few years returns back to the long-term level, this foreshadows mean reversion of relative market-to-book values between countries, and thus of the real exchange rate for capital goods.

We correct book values for the effect of inflation, using WPI and CPI data provided by the International Monetary Fund's (IMF) International Financial Statistics database.[18] Figure 4 plots the effect of the book value correction for Germany. In the high inflation periods of the 1970s this correction adjusts the original bookvalues (dashed line) upwards, as shown by the solid line, to match the overall inflation reflected in the market values.

[Figure 4 about here.]

We calculate the real exchange rate for consumption goods based on the monthly WPI from the IMF International Financial Statistics database for the same countries and time period.

[Figure 5 about here.]

Figure 5 compares our two measures of the real exchange rate. The real exchange rate based on capital goods, represented by the solid line, moves less steadily than the real exchange rate for consumption goods, represented by the dashed line. Quite striking is

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[18] Inflation adjustment is based on the firm investment cycle. We assume a degressive depreciation schedule at a depreciation rate δ of 10%, i.e. $B_t = \sum_{i=0}^{\infty} \delta^i I_{t-i}$, which lets us calculate the approximate path of investment over time, $I_t = B_t - \delta B_{t-1}$. Adjusted bookvalues are therefore $\tilde{B}_t = \sum_{i=0}^{\infty} \delta^i I_{t-i} \Pi_{t-i}^t$, where Π_{t-i}^t denotes the WPI price deflator between period t and $t-i$.

the difference in evolution of the real exchange rate of capital goods during and after the new-economy boom. Canadian capital goods, shown in the upper left panel, reached their 30-year low in value relative to the USA shortly before the peak of the new economy boom, reflecting the delayed growth of this sector in Canada. In contrast, German capital goods in the upper right panel reached their all-time low in the after-new-economy recession, which suggests that the recent recession had freed up more capital goods in Germany than in the USA.

Our model predicts a nonlinear relationship between returns and current levels of the real exchange rate. This kind of relationship is known to exist for consumption goods, as revealed for instance by the study of Michael et al. (1997). For capital goods we find a similar relationship. We test the real exchange rate series of each of the 153 possible country pairs for ESTAR-type nonlinearity, using a Granger and Teräsvirta (1993)-type test. This test is based on a second-order Taylor approximation of the ESTAR functional form around $\theta = 0$.[19] As expected, real exchange rates based on capital goods of most country pairs follow a nonlinear process as well. 52% of country pairs reject linearity at the 5% level, and 76% at the 10% level in favor of ESTAR-type nonlinearity. As illustration, figure 6 plots two-year changes in the real exchange rate of capital goods against the initial levels. Both country pairs shown feature random walk behavior close to the parity level and strong mean reversion away from parity. Visual inspection thus already indicates nonlinearity with two regimes.[20]

[Figure 6 about here.]

3 Estimation via Indirect Inference

Our model has no closed form solution. Drift and diffusion are time-varying and functions of the unobserved imbalance, ω. In principle the coefficients on $I'(\omega)^{\frac{\gamma}{\gamma-1}}$, $(\gamma I(\omega) - \omega I'(\omega))^{\frac{\gamma}{\gamma-1}}$, $I(\omega)$, $\omega I'(\omega)$, and $\omega^2 I''(\omega)$ of differential equation (4) can be estimated by maximum likelihood (Brown and Hewitt 1975) after solving the nonlinear filtering problem of $\omega(t)$ based on the observations $p(t)$ (Bensoussan 1992). However, because the differential equation for p is not available in closed form, this calculation of ω_0 from $p(\omega_0)$ is computationally very

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[19] The test as well as detailed results are part of the technical appendix, which is available upon request.

[20] Further, the variance appears higher in the center than in the outer regime, in line with the predictions of our model. This may, however, be an effect of the relatively small number of observations in the outer regime.

costly and practically infeasible. Further, even after filtering and obtaining the series of ω, the closed from of the density of the conditional likelihood is not available because of the discreteness of the data. In contrast going in the opposite direction, i.e. calculating $p(\omega_0)$ from ω_0 by (10), is a simple task, because the functional's value at ω_0, $I(\omega_0)$, is a by-product of calculating ω_0 via (4). More productive is therefore a method that does not require calculating the conditional distribution of p_t given p_{t-1} directly from the original model.

This estimation problem ideally suits the indirect inference procedure, introduced by Smith (1993), Gouriéroux, Monfort and Renault (1993) and Gallant and Tauchen (1996). Indirect inference replaces the hard-to-evaluate likelihood function of the original model with the likelihood function of an auxiliary model which is easier to estimate. Importantly, the auxiliary model must pick up the key features of interest of the data, in particular nonlinearity in drift and diffusion. One can then generate independent simulated data sets from the structural model for various parameters, estimate the auxiliary model with these simulated data, and repeat this procedure until parameters are found for which the estimates of the auxiliary model based on the simulated data are close by some metric to the estimates based on the actual data. Further, indirect inference does not require the calculation of the unobservable ω from the observed p. It allows us to solve and simulate the model for ω, and calculate then the implied real exchange rate, $p(\omega)$.

3.1 Auxiliary Model

The most crucial decision in indirect inference is choosing an appropriate auxiliary model. For the problem at hand, a natural auxiliary model is the ESTAR model of Haggan and Ozaki (1981) and Teräsvirta (1994). Whereas the process of the real exchange rate, p, implied by our structural model is complicated and not available in closed form, its key feature, the smooth transition from a divergent to a mean reverting regime, can parsimoniously be modeled by the ESTAR specification. The ESTAR model has the following standard form:

$$\begin{aligned} p_t - p_{t-1} &= (1-\Phi(\theta; p_{t-d}-\mu))\left(\beta_0 + (\beta_1 - 1)p_{t-1} + \sum_{j=1}^{m} \beta_j p_{t-j}\right) + \\ &+ (\Phi(\theta; p_{t-d}-\mu))\left(\beta_0^* + (\beta_1^* - 1)p_{t-1} + \sum_{j=1}^{m} \beta_j^* p_{t-j}\right) + \epsilon_t \qquad (18) \\ \epsilon_t &\sim N(0, \sigma_t^2) \end{aligned}$$

[Figure 7 about here.]

The transition function $\Phi\left(\theta; p_{t-d} - \mu\right)$, parametrized by the transition lag d and the transition parameter $\theta \geq 0$, governs the smooth transition between the inner autoregressive process with parameters β and the outer autoregressive process with parameters β^*:

$$\Phi\left(\theta; p_{t-d} - \mu\right) \;=\; 1 - exp\left(-\theta\left(p_{t-d} - \mu\right)^2\right) \tag{19}$$

Figure 7 plots a typical ESTAR transition function.[21] Unfortunately, the standard ESTAR model does not address conditional variance dynamics which our structural model (2) predicts. Instead, the conditional variance, σ_t, is assumed to be the same for any p. Here, we generalize the standard ESTAR to allow for a time-varying conditional variance. Our specification uses a second transition function $\tilde{\Phi}\left(\tilde{\theta}; p_{t-d} - \mu\right)$, which smoothly moves between an inner regime variance σ_1^2 and an outer regime variance σ_2^2.[22]

$$\begin{aligned} \sigma_t^2 &= \left(1 - \tilde{\Phi}(\tilde{\theta}; p_{t-d} - \mu)\right)\sigma_1^2 + \left(\tilde{\Phi}(\tilde{\theta}; p_{t-d} - \mu)\right)\sigma_2^2 && (20) \\ \tilde{\Phi}\left(\tilde{\theta}; p_{t-d} - \mu\right) &= 1 - exp\left(-\tilde{\theta}\left(p_{t-d} - \mu\right)^2\right) && (21) \end{aligned}$$

We follow Teräsvirta (1994) in specifying the transition lag, d, and number of autoregressive terms, m, based on the nonlinearity test of Granger and Teräsvirta (1993), where we restrict $d \leq 12$ and $m \leq 3$. Estimation of the ESTAR model is straightforward. Numerical difficulties arise only for country pairs, whose real exchange rate varies relatively little. For these countries the likelihood function has two local maxima, one "reasonable" maximum and one maximum combining very weak nonlinearity with an oscillating, nonstationary, outer regime.[23] For illustration of the ESTAR model given by (18)–(21) we present here some results for the country pair Germany-USA. The conditional mean dynamics for Germany-USA are highly sensitive to deviations from parity. As the upper panel of figure 8 shows, at relatively small deviations the process fully transits to the mean reverting outer

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[21] The particular transition function shown is the estimate for the real exchange rate based on capital goods for the country pair Germany–USA and the time period 1974:12 – 2007:06.

[22] Studies that allow for time-varying conditional variance in an ESTAR setup are scarce. A notable exception are Lundbergh and Teräsvirta (2006), who augment an ESTAR-type model with a GARCH variance process. For the *nominal* exchange rate of the Swedish krona and the Norwegian krone against a currency basket in the 1980s they find only a very weak decline of the conditional variance at the boundaries of the target zone set by the central bank.

[23] For about one fourth of country pairs ESTAR has two pronounced local maxima. In about one half of these cases, the "reasonable" local maximum is the global maximum. The technical appendix discusses ESTAR estimation and results in more detail.

regime. Only close the parity the inner, non-stationary regime dominates. The lower panel reveals that the conditional variance is less sensitive.

[Figure 8 about here.]

[Figure 9 about here.]

From Michael et al. (1997) we already know that real exchange rates based on CPI can be modeled by an ESTAR process. The same applies to real exchange rates based on capital goods. For most country pairs this real exchange rate follows a nonstationary inner regime (figure 9, left panel) and a stationary outer regime (figure 9, right panel). The last row of table 4 shows that after accounting for the maximum weight put on the outer regime, all but one country pair follow a stationary outer regime. However, the individual coefficients of the mean equation are often insignificant. Conversely, the coefficient estimates of the variance equation are typically significant, but often with a higher variance in the outer regime.

[Table 4 about here.]

3.2 Discretization, Simulation and Optimization

Although the ESTAR estimates reveal nonlinearity in the data, they unfortunately do not provide a natural interpretation of the autoregressive coefficients. Furthermore, they lack a natural benchmark for the transition parameter, θ. Estimating the structural model described earlier allows us to ask whether θ is "big" or "small". In our indirect inference framework ESTAR assumes then the role of the auxiliary model.

Inspection of the estimation equations (4) with (8) and (9) reveals that in a country-by-country estimation not all parameters can be identified. Importantly, however, the real exchange rate process may be asymmetric, reflecting differences in productivity between countries. For example, the real exchange rate process may be close to one boundary most of the time, and hardly ever reach the other. To allow for this possibility we keep the productivity differential as a parameter to be estimated. Instead we assume equal variance $\sigma_{11} = \sigma_{22}$, and fix the discount rate at $\rho = 0.05$ and the covariance at $\sigma_{12} = 0.2$.

The estimation requires the efficient simulation of many discrete trajectories of p for a given parameter set. We first simulate the ω process, which can be done with high precision because the diffusion of this process is constant. Wagner and Platen (1978) and Platen (1981) introduced an Itô-Taylor scheme which strongly converges at rate 1.5. This convergence excels the rate of 1.0 achieved by the well-known Milstein (1974) scheme. Using the fact that the noise in our model is additive and the diffusion is constant, this scheme can be written as

$$\begin{aligned}\omega_{t+1} &= \omega_t + \mu_\omega(\omega_t)\Delta + \sigma_\omega \Delta z_t + \mu'_\omega(\omega_t)\sigma_\omega \Delta y_t \\ &+ \frac{1}{2}\left(\mu_\omega(\omega_t)\mu'_\omega(\omega_t) + \frac{1}{2}\sigma^2_\omega \mu''_\omega(\omega_t)\right)\Delta^2, \end{aligned} \tag{22}$$

where $\Delta z_t = \sqrt{\Delta} u_1$, $\Delta y_t = \frac{1}{2}\Delta^{3/2}\left(u_1 + \frac{1}{\sqrt{3}}u_2\right)$, and $u_1 \sim N(0,1)$ and $u_2 \sim N(0,1)$ are independent.[24]

Next, we calculate the process of the real exchange rate from the process of imbalances, using the interim results $(I(\omega), I'(\omega))$ obtained in the calculation of the imbalance process. If numerical issues prohibit a successful Itô-Taylor step, we replace the Itô-Taylor step with a Milstein (1974) step.

We can now proceed with inference in the following way:

1. Estimate the ESTAR specification based on actual data by quasi maximum likelihood. Denote the set of parameter estimates by $A_0 = \left\{\theta, \tilde{\theta}, \beta_i, \beta_i^*, \mu, \sigma_1, \sigma_2\right\}$.
2. Pick starting values for the parameters of the structural model, $B = \{\gamma, r, \alpha, \alpha^*, \sigma, q\}$.
3. Solve the differential equation for optimal boundaries, $\overline{\omega}$ and $\underline{\omega}$, using the Cash-Karp Runge-Kutta algorithm of order 5.
4. Simulate S=30 paths of the imbalance process, ω_t, by the Itô-Taylor scheme (Platen 1981) for $T = 391$ periods based on the structural model.
5. Calculate the price process, $p(\omega_t)$, from the imbalance process.
6. Compute the indirect inference estimate of B by minimizing the distance between the data-based and the simulation-based estimate, measured by the score criterion

$$\hat{B} = \underset{B}{\operatorname{argmin}} \left[\sum_{s=1}^{S}\sum_{t=1}^{T} \frac{\partial \ln f^{ESTAR}}{\partial A}\left(p_t^s(B) | p_{t-1}^s, A_0\right)\right]'$$

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[24] See also Kloeden and Platen (1999, p.351). Another class of simulation schemes with a convergence rate of 1.0, the so-called Runge-Kutta methods (Kloeden and Platen 1999), do not require the calculation of explicit derivatives of drift and diffusion. In our case, however, all components of these derivatives must already be evaluated for the calculation of the drift and diffusion itself. Thus, nothing is saved by replacing differentials with differences.

$$\times \quad \Omega \times \left[\sum_{s=1}^{S} \sum_{t=1}^{T} \frac{\partial \ln f^{ESTAR}}{\partial A} \left(p_t^s(B) | p_{t-1}^s, A_0 \right) \right], \tag{23}$$

where Ω is a nonnegative, symmetric weighting matrix.

4 Empirical Results

We apply our estimation procedure to the real exchange rates of both consumption goods and capital goods. For France, Germany, Japan, the United Kingdom (UK) and the USA table 5 shows the estimation results for consumption goods, and table 6 the corresponding results for capital goods.

The estimated transfer cost for consumption goods in table 5 ranges from 13% for France-UK up to 33% for Japan-UK. It is smallest between France, Germany and the UK, and highest in country pairs involving Japan on one side, in particular Japan - USA, Japan - UK, and France - Japan. Only between Germany and Japan a transfer seems to be less costly. An outlier is the country pair France - USA, where transfer costs are of similar magnitude as in the Japan country pairs.

With one exception, the preferences are estimated to be slightly more risk averse than logarithmic preferences. The estimated productivity differentials provide a transitive ranking if Japan is excluded. The UK is most productive, followed by the USA, Germany and France. The shock variance is similar between country pairs, only for consumption goods between Germany and France it is particularly low. However, the productivities of and shocks to capital stocks, α and σ, vary too much across countries to be economically meaningful.

[Table 5 about here.]

The picture changes dramatically when we shift the focus from consumption goods to capital goods. The second column of table 6 reports for all countries much larger relocation costs of capital goods than transfer costs of consumption goods, and a higher variation across countries. But there are similarities as well. As with consumption goods, Japan country pairs have also the highest relocation cost for capital goods. Up to 58 % of the relocated quantity is lost between e.g. Japan–UK and Japan-USA. And as with consumption goods, again a relocation of capital goods between Germany and Japan is relatively less costly. Relocating capital goods to and from Germany seems to be easier to Japan and the USA, than to the neighboring European countries. Overall, relocation costs are lowest between France, UK and USA with a relocation loss of around 30%.

Risk aversion, $1-\gamma$, is again generally slightly higher than in logarithmic preferences. The estimated productivities for capital goods do not allow a transitive ordering of countries. The shock variance is somewhat higher for capital goods than for consumption goods. Subject to a particularly volatile stock of capital goods is the pair UK-USA, which may reflect the high speed at which these economies generate and scrap business concepts.

[Table 6 about here.]

The transfer and relocation costs, r, which are our key parameter of interest, have the smallest standard error. This is not surprising, because the main aim of our estimation strategy was to capture this nonlinearity. For all country pairs the transfer and relocation discounts are significantly different from zero and unity. That is, for both real exchange rates we reject both of the extremes random walk ($r = 0$) and constant ($r = 1$).

Our parameter estimates allow us now to graphically compare the drift and diffusion processes. As an example, we discuss here the real exchange rates of Germany–USA. The dashed line in the upper panel of figure 10 shows that the drift of the real exchange rate for capital goods at parity is positive, which is an effect of the lower productivity of Germany relative to the USA and the, as a result, relative scarcity of capital goods in Germany. Only a large abundance of capital goods in the USA, i.e. a large p, triggers a relocation of capital goods from the USA to Germany, because Germany itself reproduces capital goods a lower rate.

Figure 10 also emphasizes the very different heights of the border for consumption goods and of the border for capital goods. The real exchange rate process for consumption goods, shown by the solid line, follows a much narrower band with lower diffusion than the process for capital goods. The nonlinearity, i.e. the maximum drift, however, is similar for both types of goods.

[Figure 10 about here.]

Figures 11 and 12 compare the real exchange rate process for capital goods of Germany–USA, shown as dashed line, with other countries.

[Figure 11 about here.]

As indicated earlier, the process for Japan-USA in figure 11 is hardly mean reverting at all for $ln(p) > 0$, due to the high relocation cost and large productivity differential. It is nevertheless stationary, because the possible real exchange rate levels are always bounded by the possibility of relocation.

[Figure 12 about here.]

In contrast, the solid line in figure 12 displays a country pair with very strong mean reversion and a narrow real exchange rate band. The country pair shown is UK-USA, which is among the country pairs with the lowest relocation costs for capital goods.

Table 7 compares the transfer cost of consumption goods with the relocation cost of capital goods directly. Relocation cost for capital goods among these five countries exceed transfer cost of consumption goods by 6 to 200 percent. For example Germany's borders, although among the least hindering for consumption goods, are as hindering for capital goods as are borders between other countries. In contrast, moving any good across the UK-US border is relatively cheap.

[Table 7 about here.]

Looking at a larger set of country pairs we find a positive correlation of about 0.7 between relocation costs for capital goods and for consumption goods (figure 13).

[Figure 13 about here.]

[Table 8 about here.]

The left half of table 8 ranks all countries in our sample by their cost of transferring consumption goods to and from the USA. By far the lowest border is the one between the USA and Canada. Less than 7% of the quantity of consumption goods crossing this border is lost in the form of iceberg costs. On the other extreme, a transfer of consumption goods from France to the USA incurs a cost of more than 30%. Small European countries have the smallest transfer costs of consumption goods to and from the USA.

We compare our estimates with the ratio of cost-insurance-freight (cif) and free-on-board (fob) prices provided by the IMF's International Financial Statistics database for a few countries. For countries in our sample both cif and fob values of imports are available for Australia, France, Germany, UK, and USA. The average civ/fob ratio for these countries fell from approximately 6% in 1975 to approximately 4.5% today. All transfer cost estimates exceed this level. This emphasizes that transfer cost consist of more than just insurance and freight costs. Other expenses, such as e.g. administration, customs, distribution, and market access costs devour another 1% (Canada) to 30% (France) of the transferred quantity. This border cost estimate is somewhat smaller than the average estimate in the literature, which

Anderson and van Wincoop (2004) in a comprehensive survey fix at a transfer cost equivalent of 43% for a representative rich country.

The right three columns of table 8 rank the same countries again, but now by their cost of relocating capital goods to and from the USA. Despite the high correlation, this reshuffles the ordering quite heavily. Asian economies form the group of countries with the highest relocation costs, each of them incurring a loss of more than 50%. Some countries with relatively high transfer costs of consumption goods, such as Italy and UK, have very low relocation costs of capital goods. Conversely, some smaller economies with low transfer costs of consumption goods, such as Canada and Austria, have high relocation costs of capital goods. Particularly open European countries, however, such as the Netherlands, Switzerland, and UK, have low relocation costs of less than 25%. Nevertheless, this is still more than the transfer cost of consumption goods. Perhaps surprisingly, the Italian-US border seems to be less of an obstacle for capital goods than for consumption goods – only 14% of capital goods are lost in transit.

In order to put our estimates into perspective, we compare them with estimates of adjustment costs. The adjustment cost of capital goods within a country, i.e. the difference between the capital good's value as part of a firm and the proceeds from selling the dismantled capital good, provide an upper bound on how large relocation costs of capital goods within a country can be. In a setup similar to Abel and Eberly (1994) and Abel and Eberly (1996), where the only form of adjustment cost is a gap between buying and selling prices of capital goods, Cooper and Haltiwanger (2006) find for the USA an adjustment loss of about 20%. For the aerospace industry, Ramey and Shapiro (2001) find costs of 40% and more. These intra-US adjustment losses are very close to our estimates for relocation costs between small European countries and the USA. For these countries, in particular Italy, Switzerland and the UK, the border effect toward the USA is thus negligible, whereas for the other countries the border imposes considerable additional friction.

Until now we have derived a new measure for the height of the border, and found it to be much larger for capital goods than for consumption goods. But what are the underlying causes that raise a border? To answer this question, we regress the natural logarithm of our border cost measures on factors commonly used in international trade. The independent variables are distance in 10000 kilometers, the 2003 GDP of the larger country in trillion US dollars (USD) at PPP, the sum of the 2003 GDP of both countries in trillion USD at PPP, a dummy for common language, a dummy for countries located in Continental Europe, and the number of cross-border mergers in 2003.

[Table 9 about here.]

Regression specification (1) in table 9 reveals that relative economic size strongly affects border height for both consumption goods and capital goods. The smaller a country is, the smaller are, ceteris paribus, its border costs with large trade partners. Mergers, which may reflect information flows between a country pair, are marginally significant for capital goods, but this may in fact be the result of endogeneity. Once we use instruments for the number of mergers its coefficient becomes insignificant.

Dropping two insignificant variables in the consumption good regression, we arrive at specification (2). The coefficients of both distance and small country GDP are highly significant. Every additional 1000 kilometers of geographic distance increases the transfer cost of consumption goods by approximately 0.9%. But as McCallum (1995) and Engel and Rogers (1996) have pointed out, there is more to a border than just geographic distance. Whereas a common language does not significantly change the border effect, the GDP of the smaller country does. That is, the more two countries differ in economic size, the narrower is the border between them. For every trillion USD of small country GDP the transfer costs increase by approximately 5.2%. It might be that economies of smaller size adapt regulations and standards of the economically larger countries. This reduces the need for localization and thus may make the relocation of capital goods to and from economically large countries less costly.

The results for consumption goods are robust to adding a dummy for Continental Europe. For capital goods, however, the dummy for Continental Europe is significant. As reported in specification (3) for $log(r_{CAP})$, a relocation of capital goods to and from Continental Europe incurs approximately 29% extra cost. Relocation cost for capital goods also increases with distance, more strongly than transfer cost for consumption goods. Every 1000 kilometers of geographic distance increase relocation costs by approximately 2.3%.

The intercept reflects the border effect, that obtains even if both countries are neighbors and one country economically dominates the other. In this case the mere existence of a border leads to a transfer cost coefficient of $r_{WPI} = 0.94$ and a relocation cost coefficient of $r_{CAP} = 0.80$. For a typical country with $r_{WPI} = 0.85$ and $r_{CAP} = 0.65$, distance, relative size and region increase border cost by two thirds for both types of goods.

Even though we have already established mean reversion as a property of the real exchange rate, we have no notion yet of how long full mean reversion to the parity level will take. We therefore calculate the time that it takes the real exchange rate process on average to hit a boundary when started at parity, and the time it takes to revert to parity if started at either boundary. Despite mean reversion, these so-called hittimes are quite long, or, in the words of Rogoff (1996) “glacial”. Table 10 lists the hittimes for the example Germany–USA. The real exchange rate of consumption goods takes about 5 years from the boundary to the center and vice versa. For capital goods this time interval is more than twice that long.

[Table 10 about here.]

The hittime distribution itself is very skewed (figures 14 and 15). Furthermore, due to the wide range of transfer and in particular relocation costs, the expected hittimes vary considerably between countries. Taking both variations together may explain the inconclusiveness of the data about halftimes of mean reversion documented by Kilian and Zha (2002).

[Figure 14 about here.]

[Figure 15 about here.]

In summary, relocation costs of capital goods are larger than transfer costs of consumption goods. Border height for capital goods varies substantially across countries, much more than for consumption goods. The most hampering borders are between Western and Asian countries. As expected, geographic distance increases the height of the border, but relative economic size seems to matter as well. That is, a large country economically dominating a smaller country seems to facilitate the relocation of capital goods. Within Continental Europe, the relocation costs for capital goods are high compared to the rest of the world, even though transfer costs of consumption goods are not significantly different. The time from a maximum imbalance to a balanced position is about 5 years for consumption goods for a typical country pair, and more than 10 years for capital goods. These long time spans obtain despite the real exchange rate process clearly does not follow a random walk. Overall, the market for capital goods is less efficient than market for consumption goods and still far from perfect integration.

5 Conclusion and Directions for Further Research

In this paper we have implemented a novel approach to estimating border cost directly from the real exchange rate series. We have found the border to be considerably higher for capital goods than for consumption goods. This indicates that markets for capital goods and consumption goods are at different stages of integration.

Considering the high relocation cost estimates for capital goods, we suggest that the market for capital goods would benefit from additional effort at reducing border frictions. The World *Trade* Organization's (WTO) focus on trade liberalization alone distracts from harvesting some lower hanging fruits. Considering the stalled Doha negotiations, it might be rewarding to shift some policy attention and negotiation time from consumption goods to the relocation cost of capital goods and to think about ways to reduce the embedded border effect.

Furthermore, we found that alternative real exchange rate measures, which are not based on CPI, and nonlinearities in the real exchange rate process carry useful additional market information. This insight allowed us to provide additional evidence that the real exchange rate follows an overall stationary, nonlinear process, which is indistinguishable from a random walk close to parity. As further integration of the world economy continues to shrink the barriers imposed to trade by borders, the range of values assumed by the real exchange rate will shrink as well. No matter how easily crossed borders eventually become, however, random walk behavior in the inner regime will ensure that reversion to PPP will continue to be slow.

Our work has three important implications for the forecasting of real exchange rates. First, it supports long-run predictability in line with Kilian and Taylor (2003) despite short-run random walk behavior. Second, border cost and its determining factors affect the drift and can therefore help in forecasting real exchange rates. Third, and importantly, this work emphasizes that the definition of the real exchange rate must be chosen carefully to fit the forecasting situation at hand.

The ultimate aim of this line of research is internally consistent estimates of adjustment, transfer and relocation cost across countries and types of goods. This paper has made an important step in this direction, but more work is needed, especially in expanding the set of country pairs included in the study. Our approach readily extends to estimating several countries jointly in a system, which will then allow one to impose cross-country restrictions. Last not least, the role of regions and of relative country size warrants investigation of the effect of regulation and common standards.

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Table 1: Maximum Sustainable Imbalance ($\overline{\omega}$) as a Function of Risk and Risk Aversion for Low Relocation Cost ($r = 0.82$)

Risk av.	Risk ($\sigma_{11} = \sigma_{22}$)					
$(1-\gamma)$	0^+	0.02	0.1	0.5	1	∞
0	∞	∞	∞	∞	∞	∞
0.1	7.31	8.89	12.99	19.10	19.96	20.26
0.2	2.70	3.36	5.27	8.15	8.50	8.63
0.5	1.49	1.91	3.16	4.53	4.65	4.69
1	1.22	1.60	2.60	3.39	3.44	3.46
1.5	1.14	1.50	2.38	2.95	n.a.	2.97^*
2	1.10	1.46	2.26	n.a.	n.a.	2.70^{**}
3	1.07	1.42	2.11	n.a.	n.a.	2.41^{***}

parameter values $r = 1/1.22$, $\rho = 0.05$, $\alpha = \alpha^* = 0.05$, $q = 0.5$, $\sigma_{12} = 0$

(* reported for $\sigma_{max} = 0.584$, ** reported for $\sigma_{max} = 0.418$, *** reported for $\sigma_{max} = 0.301$)

Table 2: Maximum Sustainable Imbalance ($\overline{\omega}$) as a Function of Risk and Risk Aversion for High Relocation Cost ($r = 0.66$)

Risk av.	Risk ($\sigma_{11} = \sigma_{22}$)					
$(1-\gamma)$	0^+	0.02	0.1	0.5	1	∞
0	∞	∞	∞	∞	∞	∞
0.1	57.67	69.44	97.58	134.46	139.42	140.94
0.2	7.59	9.27	13.71	20.94	22.05	22.49
0.5	2.25	2.85	4.71	7.76	8.15	8.31
1	1.50	1.96	3.39	5.28	5.47	5.54
1.5	1.31	1.75	3.01	4.46	n.a	4.50^*
2	1.23	1.66	2.83	n.a.	n.a.	3.97^{**}
3	1.14	1.59	2.62	n.a.	n.a.	3.41^{***}

parameter values $r = 2/3$, $\rho = 0.05$, $\alpha = \alpha^* = 0.05$, $q = 0.5$, $\sigma_{12} = 0$

(* reported for $\sigma_{max} = 0.566$, ** reported for $\sigma_{max} = 0.408$, *** reported for $\sigma_{max} = 0.295$)

Table 3: Maximum Sustainable Imbalance in Asymmetric World as a Function of Risk Aversion for High Relocation Cost ($r = 0.66$)

Risk av. $(1-\gamma)$	$\alpha = \alpha^*$=0.05 $\overline{\omega}$	$\alpha = 0.04 < \alpha^* = 0.06$ $\overline{\omega}$	$1/\underline{\omega}$
0.1	134.46	19.78	894.77
0.2	20.94	9.97	47.32
0.5	7.76	5.51	11.06
1	5.28	4.35	6.43
1.5	4.46	3.89	5.12

parameter values $r = 2/3$, $\rho = 0.05$, $q = 0.5$, $\sigma_{11} = \sigma_{22} = 0.5$, $\sigma_{12} = 0$

Table 4: ESTAR Estimation Result

	inner regime		total
outer regime	stationary	nonstationary	153
stationary (AR)	36	98	134
nonstationary (AR)	5	14	19
stationary (AR $\times\Phi$)	40	112	152

Table 5: Indirect Inference Estimates, Real Exchange Rate based on WPI, Selected Countries

		γ	r	α	α^*	σ	q
France	Germany	-0.030	**0.855**	0.113	0.118	0.290	0.524
		(0.029)	**(0.024)**	(0.004)	(0.000)	(0.001)	(0.000)
France	Japan	-0.475	**0.765**	0.089	0.089	0.509	0.503
		(0.035)	**(0.031)**	(0.002)	(0.000)	(0.034)	(30.548)
France	UK	-0.043	**0.870**	0.018	0.073	0.629	0.670
		(1.843)	**(0.016)**	(0.060)	(0.466)	(0.531)	(1.649)
France	USA	0.394	**0.697**	0.042	0.110	0.558	0.573
		(0.486)	**(0.087)**	(0.037)	(0.037)	(0.045)	(0.336)
Germany	Japan	-0.639	**0.845**	0.456	0.383	0.638	0.537
		(1.207)	**(0.005)**	(0.660)	(0.823)	(0.263)	(0.159)
Germany	UK	-0.440	**0.861**	0.164	0.169	0.517	0.558
		(1.271)	**(0.005)**	(0.084)	(0.141)	(0.159)	(0.438)
Germany	USA	-0.495	**0.847**	0.112	0.121	0.504	0.499
		(0.020)	**(0.001)**	(0.004)	(0.005)	(0.019)	(0.004)
Japan	UK	-0.513	**0.664**	0.126	0.083	0.488	0.337
		(0.013)	**(0.032)**	(0.260)	(0.456)	(0.211)	(0.146)
Japan	USA	-0.126	**0.730**	0.010	0.010	0.532	0.801
		(1.476)	**(0.041)**	(0.107)	(0.256)	(0.370)	(0.661)
UK	USA	-0.282	**0.844**	0.060	0.048	0.590	0.520
		(0.899)	**(0.005)**	(0.459)	(0.593)	(0.236)	(0.679)

Inflation-adjusted bookvalues, demeaned, 1974:12–2007:06. ESTAR as auxiliary model with $p \leq 3$ and $d \leq 12$ chosen by nonlinearity test. Standard errors in parentheses.

Table 6: Indirect Inference Estimates, Real Exchange Rate based on Capital Goods, Selected Countries

Country	Country	Structural Parameter					
		γ	r	α	α^*	σ	q
France	Germany	-0.501	**0.526**	0.095	0.101	0.503	0.468
		(0.056)	**(0.000)**	(0.088)	(0.130)	(0.000)	(5.420)
France	Japan	-0.496	**0.497**	0.098	0.094	0.506	0.507
		(0.009)	**(0.028)**	(0.002)	(0.004)	(0.007)	(51.275)
France	UK	-0.208	**0.734**	0.069	0.054	0.665	0.505
		(0.020)	**(0.022)**	(0.011)	(0.001)	(0.012)	(0.014)
France	USA	-0.514	**0.681**	0.145	0.120	0.493	0.519
		(0.602)	**(0.010)**	(0.022)	(0.017)	(0.019)	(0.036)
Germany	Japan	-0.396	**0.620**	0.194	0.152	0.586	0.495
		(0.014)	**(0.017)**	(0.008)	(0.008)	(0.006)	(0.020)
Germany	UK	-0.597	**0.571**	0.135	0.144	0.473	0.917
		(0.494)	**(0.020)**	(0.006)	(0.009)	(0.002)	(0.778)
Germany	USA	-0.417	**0.638**	0.078	0.091	0.508	0.411
		(0.024)	**(0.018)**	(0.006)	(0.006)	(0.016)	(1.909)
Japan	UK	0.137	**0.427**	0.211	0.135	0.648	0.178
		(0.096)	**(0.017)**	(0.058)	(0.081)	(0.177)	(0.136)
Japan	USA	-0.020	**0.439**	0.140	0.180	0.421	0.667
		(0.005)	**(0.006)**	(0.009)	(0.001)	(0.003)	(0.004)
UK	USA	-0.205	**0.771**	0.139	0.116	0.765	0.252
		(0.067)	**(0.012)**	(0.014)	(0.021)	(0.021)	(4.586)

Inflation-adjusted bookvalues, demeaned, 1974:12–2007:06. ESTAR as auxiliary model with $p \leq 3$ and $d \leq 12$ chosen by nonlinearity test. Standard errors in parentheses.

Table 7: Border Effect, Comparison of Consumption Goods with Capital Goods

		r_{WPI}	r_{CAP}	$\frac{1-r_{CAP}}{1-r_{WPI}}$
France	Germany	0.855	0.526	3.27
		(0.024)	(0.000)	
France	Japan	0.765	0.497	2.14
		(0.031)	(0.028)	
France	UK	0.870	0.734	2.05
		(0.016)	(0.022)	
France	USA	0.697	0.681	1.06
		(0.087)	(0.010)	
Germany	Japan	0.845	0.620	2.45
		(0.005)	(0.017)	
Germany	UK	0.861	0.571	3.09
		(0.005)	(0.020)	
Germany	USA	0.847	0.638	2.37
		(0.001)	(0.018)	
Japan	UK	0.664	0.427	1.71
		(0.032)	(0.017)	
Japan	USA	0.730	0.439	2.08
		(0.041)	(0.006)	
UK	USA	0.844	0.771	1.47
		(0.005)	(0.012)	

Inflation-adjusted bookvalues, demeaned, 1974:12–2007:06. ESTAR as auxiliary model with $p \leq 3$ and $d \leq 12$ chosen by nonlinearity test. Standard errors in parentheses.

Table 8: Border Cost vs. USA

Consumption Goods			Capital Goods		
	γ	r		γ	r
Canada	0.268	0.938	Italy	-0.498	0.858
	(0.023)	(0.002)		(0.003)	(0.001)
Belgium	-0.191	0.922	Switzerland	-0.500	0.846
	(0.000)	(0.010)		(0.043)	(0.005)
Austria	-0.233	0.903	**UK**	-0.205	0.771
	(0.087)	(0.008)		(0.067)	(0.012)
Denmark	-0.185	0.899	Netherlands	-0.263	0.752
	(0.606)	(0.011)		(0.004)	(0.009)
Switzerland	-0.031	0.874	Norway	-0.593	0.738
	(0.570)	(0.010)		(0.053)	(0.036)
Singapore	0.110	0.873	Belgium	-0.255	0.732
	(0.288)	(0.023)		(0.072)	(0.010)
Australia	-0.237	0.862	Denmark	-0.498	0.719
	(1.562)	(0.007)		(0.029)	(0.011)
Norway	-0.010	0.861	France	-0.514	0.681
	(0.488)	(0.007)		(0.602)	(0.010)
Germany	-0.495	0.847	Sweden	-0.014	0.645
	(0.020)	(0.001)		(0.118)	(0.084)
Netherlands	-0.218	0.845	**Germany**	-0.417	0.638
	(0.352)	(0.010)		(0.024)	(0.018)
UK	-0.282	0.844	**Canada**	0.768	0.631
	(0.899)	(0.005)		(0.062)	(0.003)
Sweden	-0.077	0.835	Australia	-0.255	0.613
	(1.073)	(0.037)		(0.223)	(0.030)
Spain	0.326	0.813	Austria	-0.192	0.561
	(3.184)	(0.016)		(0.198)	(0.033)
Hongkong	-0.146	0.786	Spain	-0.549	0.501
	(0.014)	(0.018)		(0.018)	(0.031)
Italy	0.143	0.750	Hongkong	-0.207	0.498
	(0.693)	(0.025)		(0.027)	(0.008)
Japan	-0.126	0.730	**Japan**	-0.020	0.439
	(1.476)	(0.041)		(0.005)	(0.006)
France	0.394	0.697	Singapore	-0.270	0.372
	(0.486)	(0.087)		(0.018)	(0.027)

Inflation-adjusted bookvalues, demeaned, 1974:12–2007:06. ESTAR as auxiliary model with $p \leq 3$ and $d \leq 12$ chosen by nonlinearity test. Standard errors in parentheses.

Table 9: Components of Relocation Cost

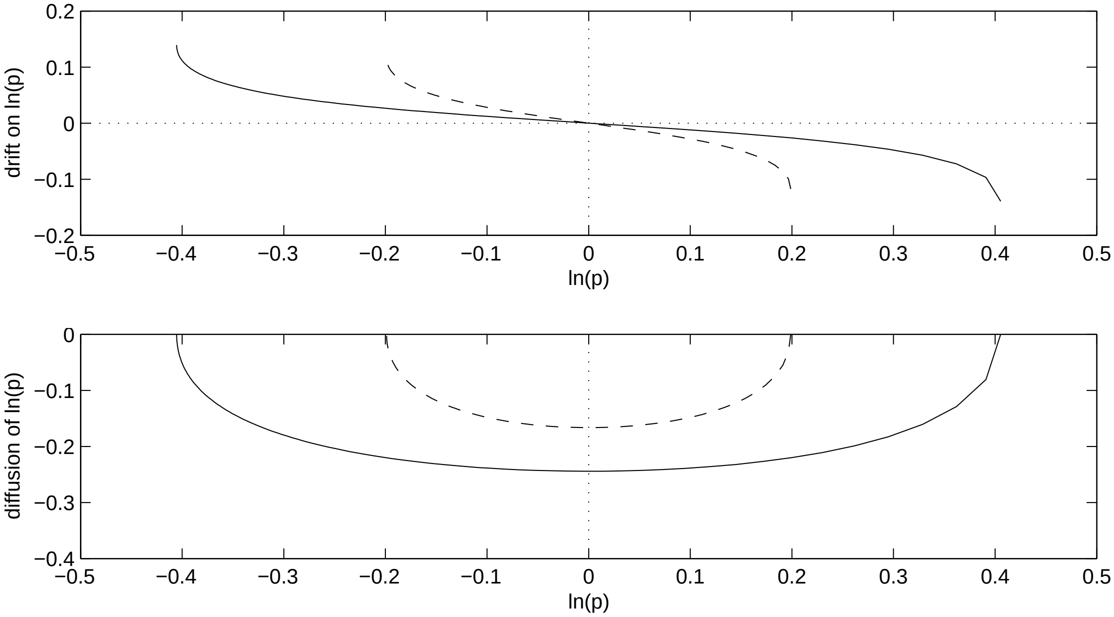
	$log(r_{WPI})$			$log(r_{CAP})$	
	(1)	(2)	(3)	(1)	(3)
Distance	-0.077	-0.098***	-0.079*	0.022	-0.237**
	(0.053)	(0.035)	(0.040)	(0.117)	(0.115)
Small country GDP	-0.059***	-0.054***	-0.056***	-0.082	-0.057
	(0.019)	(0.016)	(0.016)	(0.052)	(0.044)
Large country GDP	-0.001			0.012	
	(0.004)			(0.012)	
Common language	0.023	0.046		-0.241*	
	(0.060)	(0.036)		(0.129)	
# Mergers	1.78e-5			1.58e-4*	
	(3.33e-5)			(0.81e-4)	
Europe ex. UK			0.016		-0.344***
			(0.060)		(0.125)
Constant	-0.062	-0.058	-0.062	-0.572***	-0.229*
	(0.047)	(0.035)	(0.043)	(0.081)	(0.122)
Adj. R^2	0.334	0.385	0.341	0.127	0.135
N	26	26	26	32	32

Dependent variable: $ln(r)$, independent variables: distance (in 10000 km), GDP of the larger country (trillion USD at PPP, 2003), sum of GDP of both countries (trillion USD at PPP, 2003), number of mergers between firms located in either of the two countries in 2003. Standard errors in parentheses. (* significant at the 10% level, ** at 5% level, *** at 1% level)

Table 10: "Glacial" hittimes, Example Germany-USA

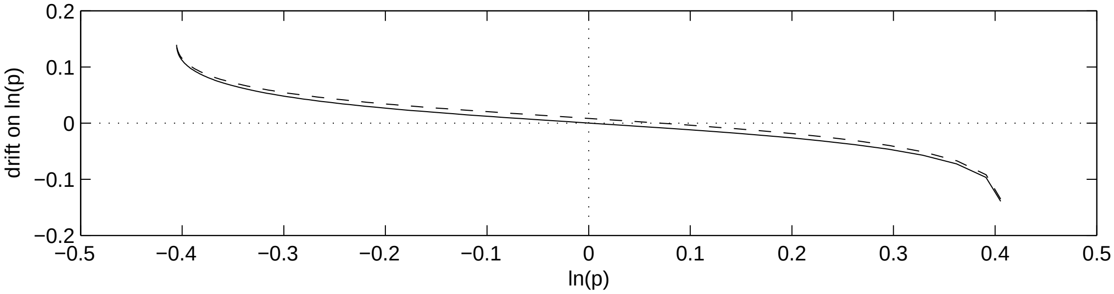
	consumption goods	capital goods
Hit of a boundary starting at parity	5.1 years	13.7 years
Hit of parity starting at $\overline{\omega}$	4.8 years	11.2 years
Hit of parity starting at $\underline{\omega}$	7.3 years	20.8 years

Figure 1: Drift and Diffusion of Price Process, Effect of Relocation Cost



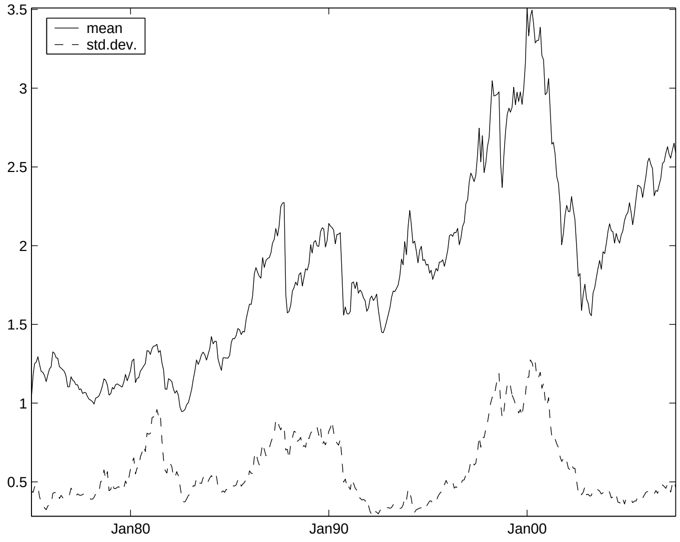
The upper panel shows the drift of the natural logarithm of the real exchange rate process as a function of the natural logarithm of the current real exchange rate, $ln(p)$. The lower panel shows the corresponding (signed) diffusion (coefficient). It compares the process for a high relocation cost ($r = 0.66$, solid line) with the process for a low relocation cost ($r = 0.82$, dashed line). The other parameter values used for this graph are $\gamma = 0$, $\rho = 0.05$, $q = 0.5$, $\sigma_{11} = 0.5$, $\sigma_{12} = 0$, and $\sigma_{22} = 0.5$.

Figure 2: Drift and Diffusion of Price Process, Countries Differing by Productivity Mean



The graph shows the drift of the natural logarithm of the real exchange rate process as a function of the natural logarithm of the current real exchange rate, $ln(p)$. The solid line shows the process for the case when both countries are identical ($\alpha = 0.05$, $\alpha^* = 0.05$). The dashed line obtains if country 2 has a higher productivity than country 1 ($\alpha = 0.04$, $\alpha^* = 0.06$). The other parameter values used for this graph are $\gamma = 0.5$, $\rho = 0.05$, $r = 0.66$, $\sigma_{11} = 0.5$, $\sigma_{12} = 0$, and $\sigma_{22} = 0.5$.

Figure 3: Average and Standard Deviation of Market-to-Book Ratios Across Countries



The graph shows the cross-section equal-weight mean and standard deviation of the market-to-book value for all 153 country pairs for the period 1974:12-2007:06.

Figure 4: Book Value Correction, Germany (local currency)

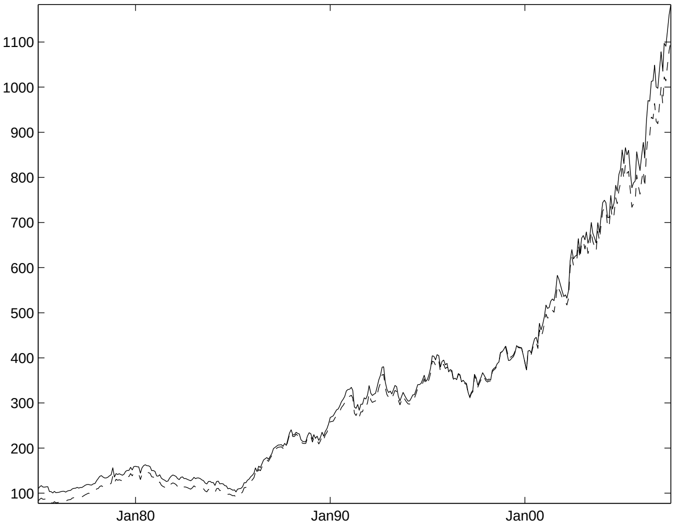
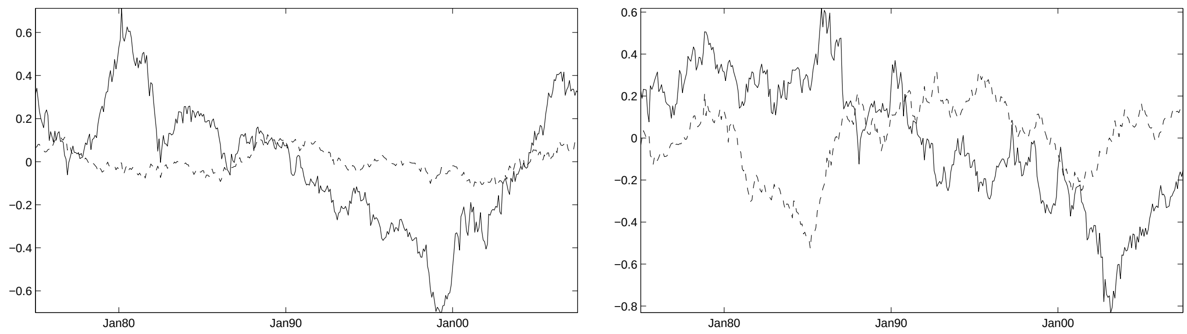
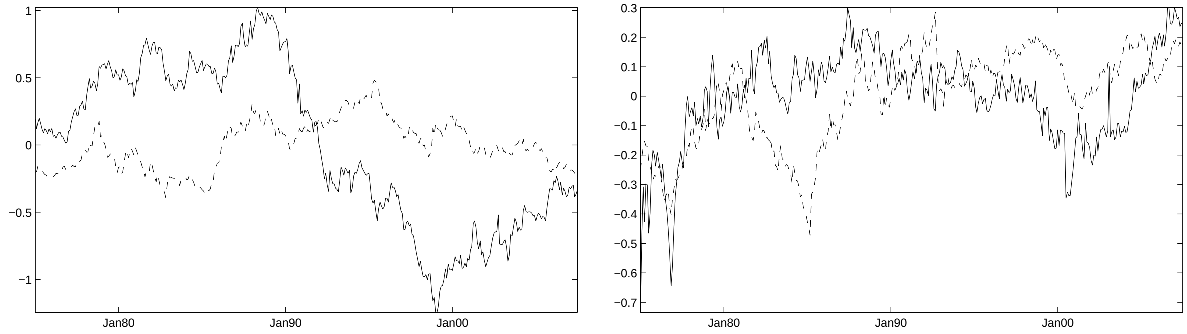


Figure 5: Real Exchange Rates, 1974:12–2007:6


(a) Canada–USA

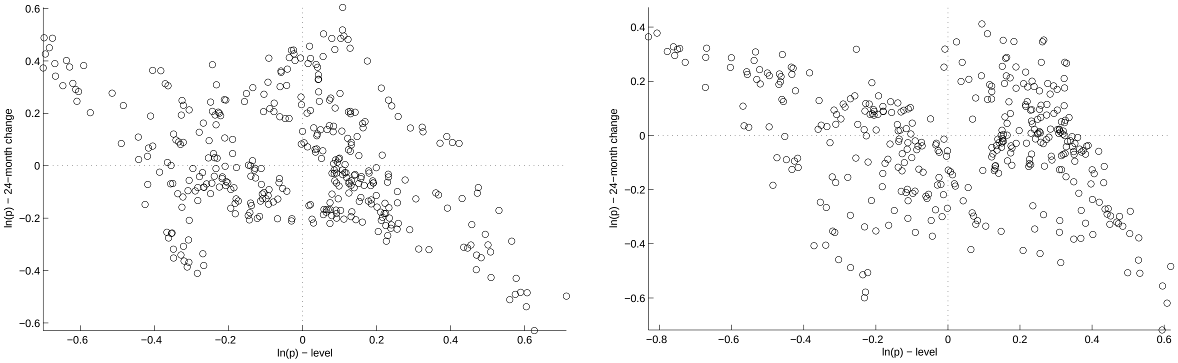
(b) Germany–USA


(c) Japan–USA

(d) UK–USA

The graph shows the natural logarithm of the real exchange rate for capital goods (solid line), and for consumption goods (dashed line).

Figure 6: 24-month Changes in Real Exchange Rate of Capital Goods vs. Initial Levels


(a) Canada–USA

(b) Germany–USA

Figure 7: Transition Function of Mean, Germany – USA

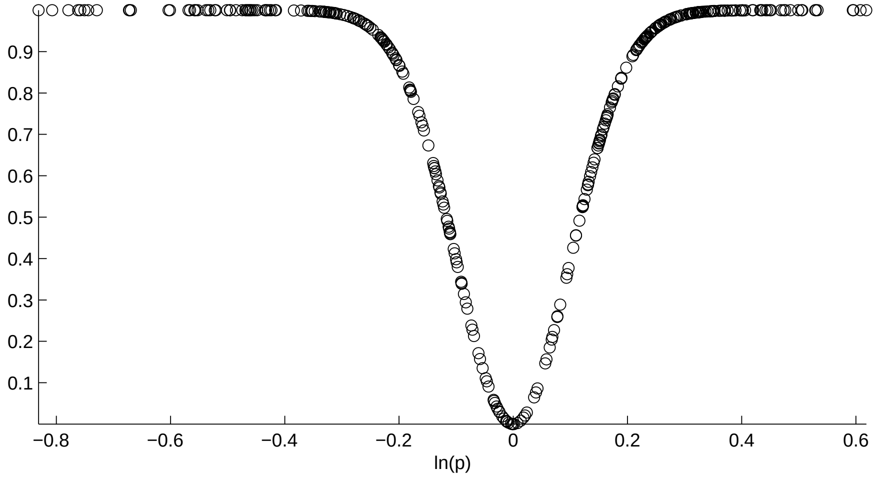
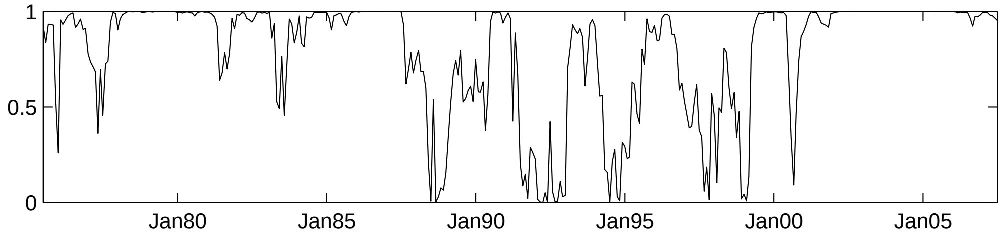
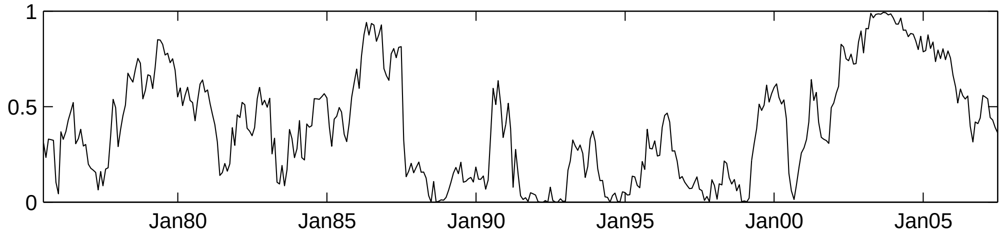


Figure 8: Time Variation of Transition Functions, Germany – USA

(a) Transition Function of Conditional Mean

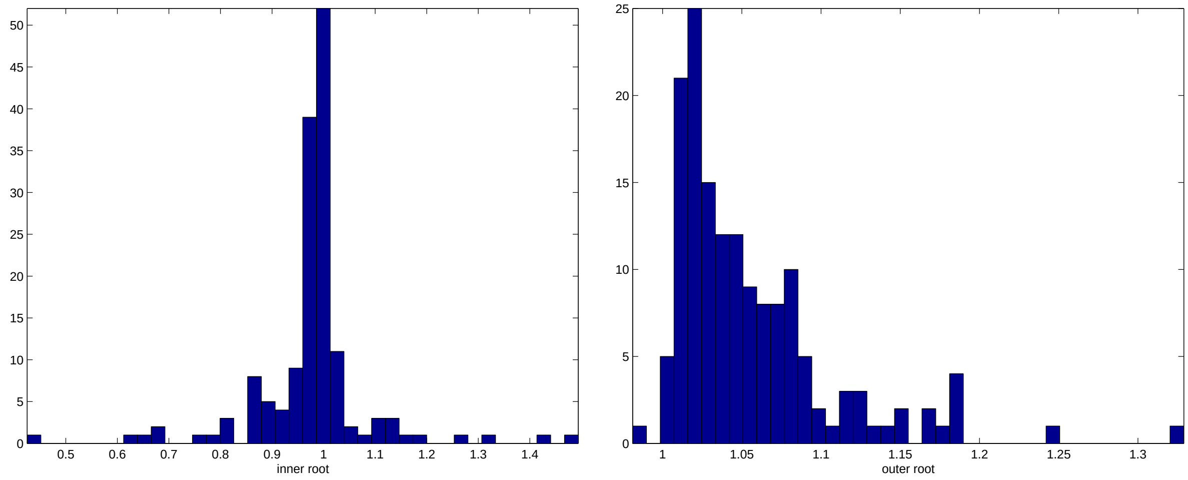


(b) Transition Function of Conditional Variance



The graph plots the values the ESTAR transition function of the conditional mean (upper panel) and of the conditional variance (lower panel) for the country pair Germany–USA during the period 1974:12–2007:6.

Figure 9: Frequency Distribution of Root

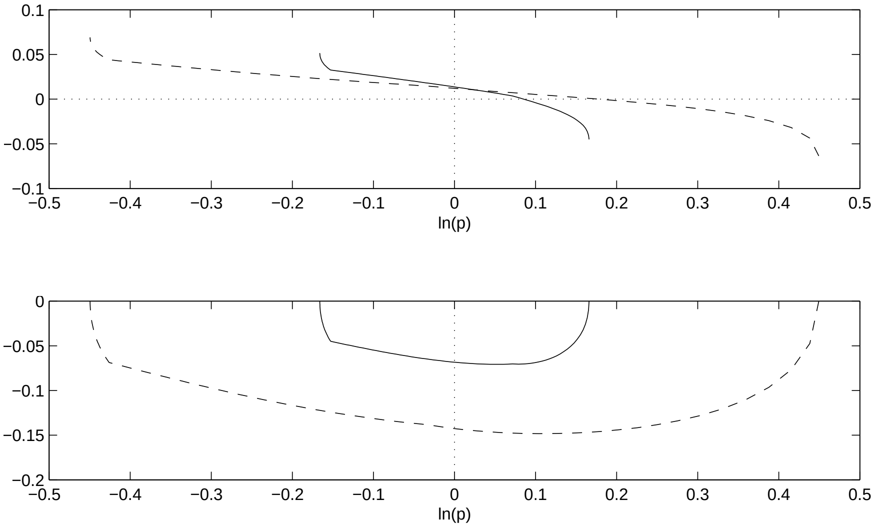


(a) of Inner Regime

(b) of Outer Regime

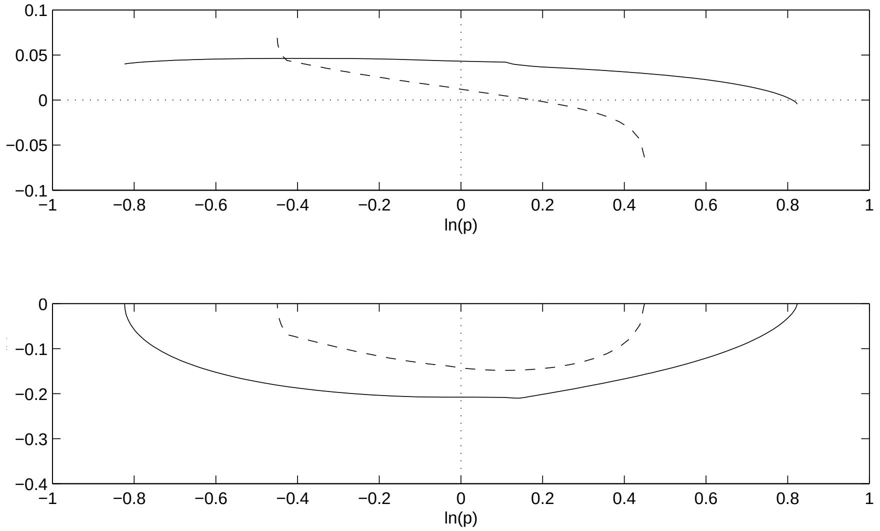
The histogram shows the frequency distribution of the root of the inner regime (left panel) and outer regime (right panel) based on ESTAR estimates for all 153 country pairs during the period 1974:12–2007:6.

Figure 10: Germany – USA, Estimated Drift and Diffusion, Consumption Goods vs. Capital Goods



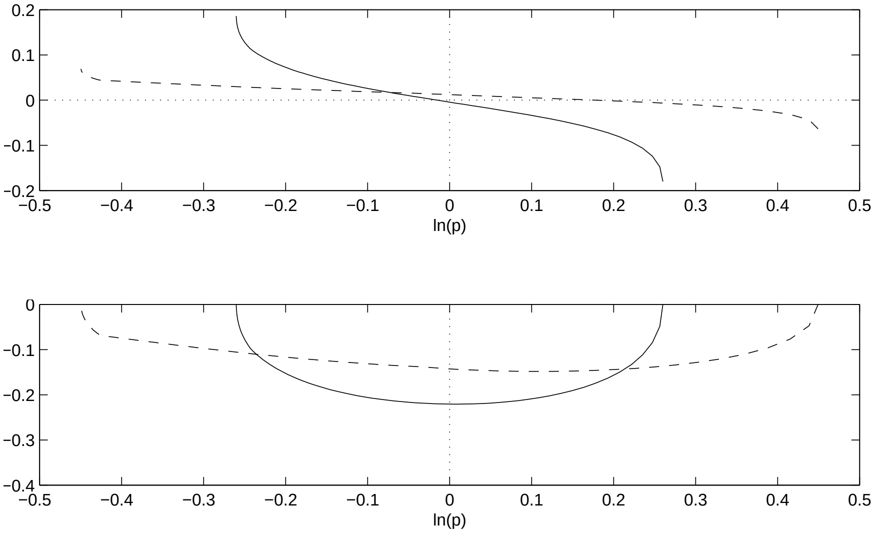
The graph plots the estimated drift and diffusion of the real exchange rate process, based on consumption goods (solid line) and based on capital goods (dashed line), for the pair Germany-USA during the period 1974:12–2007:6. Parameter values are taken from tables 5 and 6. The range of sustainable imbalances for consumption goods is $\omega \in [0.37; 2.23]$, and for capital goods $\omega \in [0.17; 3.81]$.

Figure 11: Japan – USA, Drift and Diffusion of Real Exchange Rate based on Capital Goods



The solid line is the estimated drift and diffusion of the real exchange rate of capital goods for the country pair Japan – USA during the period 1974:12–2007:6. The dashed line plots the same for Germany-USA. Parameter values are taken from tables 5 and 6. The range of sustainable imbalances is $\omega \in [0.02; 2.27]$.

Figure 12: UK – USA, Drift and Diffusion of Real Exchange Rate based on Capital Goods



The solid line is the estimated drift and diffusion of the real exchange rate for capital goods for the country pair UK-USA during the period 1974:12–2007:6. The dashed line plots the same for Germany-USA. Parameter values are taken from tables 5 and 6. The range of sustainable imbalances is $\omega \in [0.32; 4.39]$.

Figure 13: Transfer Costs of Consumption Goods vs. Relocation Costs of Capital Goods

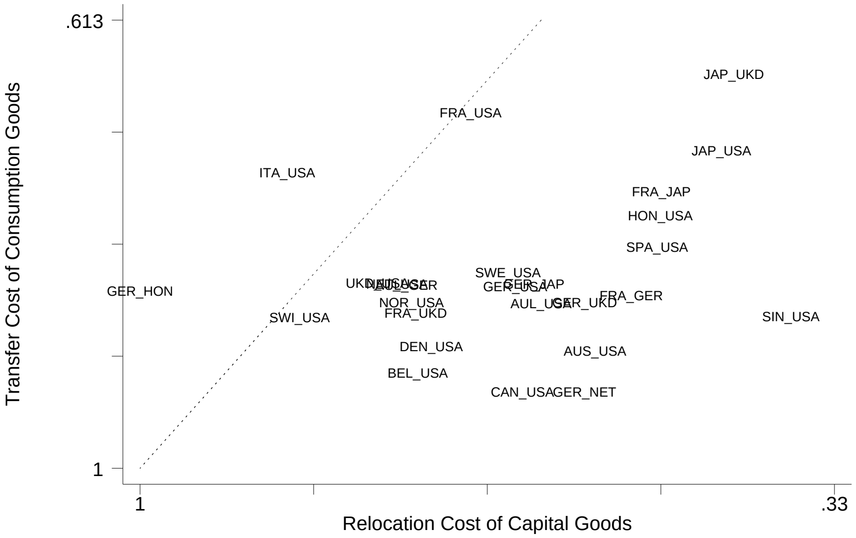
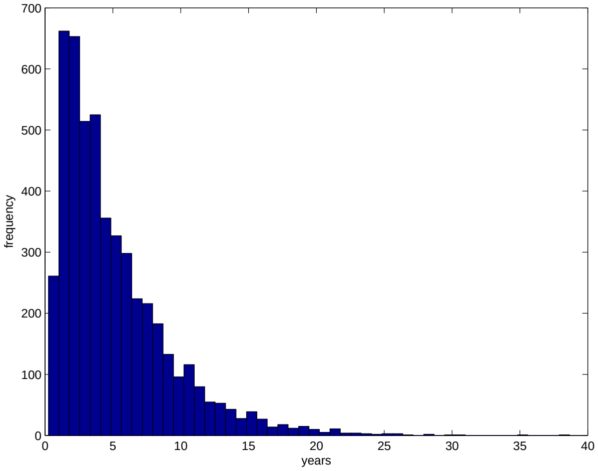
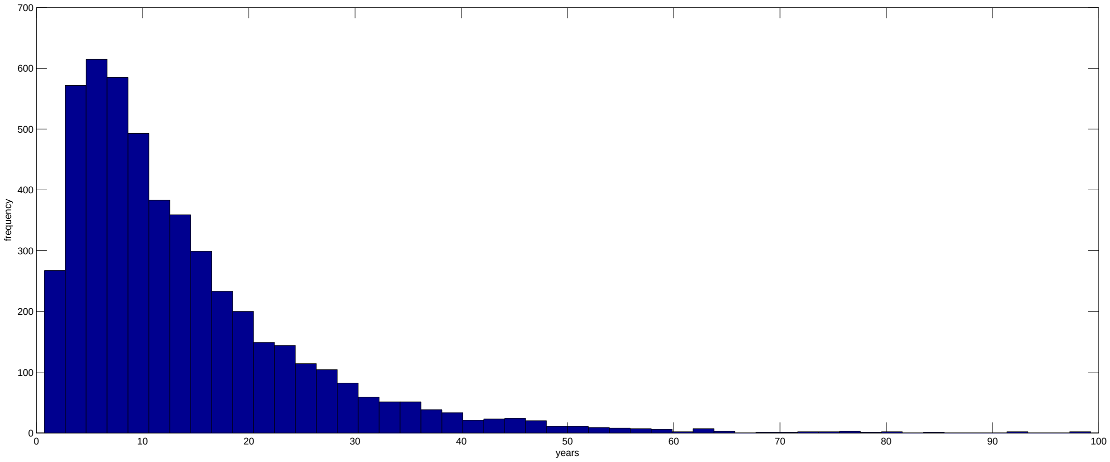


Figure 14: Hittime Distribution for Consumption Goods, Germany–USA



The histogram shows the distribution of the time span until the real exchange rate process for consumption goods hits one of the boundaries for the first time, when the process starts from a balanced position ($p(0) = 0$). The histogram is based on 5000 simulated sample paths with parameter values taken from table 5.

Figure 15: Hittime Distribution for Capital Goods, Germany–USA



The histogram shows the distribution of the time span until the real exchange rate process for capital goods hits one of the boundaries for the first time, when the process starts from a balanced position ($p(0) = 0$). The histogram is based on 5000 simulated sample paths with the parameter values taken from table 6.