

Testing the Bounds: Empirical Behavior of Target Zone Fundamentals

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Abstract

Standard target zone exchange rate models are based on nonlinear functions of unobserved economic fundamentals, which are assumed to be bounded, similarly to the target zone exchange rates themselves. Using a novel estimation and testing strategy, I show how this key but often overlooked assumption may be tested. Empirical results cast doubt on its validity in practice, providing a reason for well-documented empirical difficulties of these models in the literature.

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1 Introduction

As Sarno and Taylor (2001) emphasize, understanding how official intervention in the foreign exchange rate market works is of major policy importance. Greater comprehension of the implications of the established models of the effects of exchange rate intervention is essential in achieving this understanding. Nonlinearity is of course a key feature in many exchange rates models. Sarno (2003), for example, reviews nonlinear exchange rate models. Transaction costs may cause nonlinearities in real exchange rates (Sercu *et al.*, 1995; Michael *et al.*, 1997; Taylor *et al.*, 2001). Taylor and Peel (2000) model similar nonlinearities in nominal exchange rates. Other authors, such as Bessec (2003), Altavilla and De Grauwe (2005), and Crespo-Cuaresma *et al.* (2007), use regime-switching models to introduce nonlinearity into the relationship between an exchange rate and its fundamental.

In the target zone exchange rate literature (e.g., Krugman, 1991; Flood and Garber, 1991; Bertola and Caballero, 1992; Bertola and Svensson, 1993), nonlinearity due to exchange rate intervention is critical. Krugman's prototypical target zone model posits that exchange rates are driven by a nonlinear function of an unobserved economic fundamental. The Krugman model has not held up well to empirical tests in the literature. Subsequent modifications have been explicitly made for realignments (e.g., Bertola and Caballero, 1992; Bertola and Svensson, 1993), intramarginal interventions (e.g., Flood and Garber, 1991; Bartolini and Prati, 1999; Bessec, 2003), and other policy aberrations.

This paper provides a novel technique for testing an important but often overlooked assumption of the prototypical target zone model – that the fundamental is *bounded*. While the main innovation of the Krugman model was to illustrate a honeymoon effect in the adjustment process of target zone exchange rates, many additional target zone models have relied on the critical assumption that the fundamental has a random walk component, which may potentially be *unbounded*. These include theoretical models of Flood *et al.* (1990), Flood and Garber (1991), Svensson (1991), Bertola and Caballero (1993), Anthony and MacDonald (1998), and empirical models of de Jong (1994), Beetsma (1995), Iannizzotto and Taylor (1999), Taylor and Iannizzotto (2001), and surveys by Svensson (1992) and Taylor (1995). Determining the empirical relevance of the boundedness assumption is a needed contribution to the target zone literature.

I use a logistic functional approximation to the target zone model (Lundbergh and Teräsvirta, 2006; Miller and Park, 2008) that is robust to violations of the boundedness assumption. The unscented Kalman filter (Julier and Uhlmann, 1997; Julier *et al.*, 2000), a relatively new nonlinear filtering technique, provides estimates of the unobserved series (the fundamental) from a nonlinearly transformed series (the exchange rate). Because the economic fundamental follows a random walk if no intervention occurs (by assumption and with the support of empirical evidence), I conduct unit root tests to test the boundedness assumption for 16 fundamentals estimated from exchange rates during targeting episodes. I use both standard unit root tests (Phillips-Perron and KPSS) and non-standard unit root tests based on rescaled range tests, which are robust to bounded, nonlinear alternatives. Empirical evidence suggests that the assumption does not generally hold.

In the following section, I review the basic target zone model, and I explain the implications of an unbounded fundamental by showing precisely where the derivation of the

prototypical nonlinear target zone function relies on the boundedness assumption. I discuss respecification, estimation, and testing in Section 3. I present empirical findings in Section 4 and offer some concluding remarks in Section 5.

2 Model and Bounds

2.1 Basic Target Zone Model

A cornerstone of target zone models similar to Krugman's (1999), which has provided the basis for many subsequent target zone models in the literature, is an economic fundamental that drives the exchange rate. This fundamental X_t is defined by

$$X_t \equiv M_t + V_t,$$

where M_t represents the log of the domestic money stock, and V_t is an all-inclusive term representing exogenous velocity shocks. Krugman assumed that V_t follows Brownian motion with drift μ and constant diffusion σ and that M_t is a VF process.³ Empirical evidence for the Brownian assumption may be found in free-floating exchange rates (Meese and Rogoff, 1983). Subsequent authors (e.g., Svensson, 1991) expanded on the VF assumption to allow X_t to be regulated Brownian motion, such that $M_t = L_t - U_t$, where L_t and U_t are non-decreasing VF processes that regulate the lower and upper bounds respectively. (See Harrison, 1985, for detailed exposition on regulated Brownian motion.) Under this assumption,

$$X_t = X_0 + \mu t + \sigma W_t + L_t - U_t \quad (1)$$

where W_t is a standard Wiener process.

A basic present value model is assumed to hold, so that

$$S_t = X_t + \gamma \mathbf{E}_t(dS_t/dt) \quad (2)$$

or, alternatively,

$$S_t = \frac{1}{\gamma} \mathbf{E}_t \int_t^\infty e^{-(r-t)/\gamma} X_r dr \quad (3)$$

where γ is the interest rate semi-elasticity of money demand and \mathbf{E}_t denotes the expected value operator conditional on the natural Brownian filtration. These two equations – corresponding to equations (1) and (9) of Krugman (1991) – reflect that the exchange rate is simply the present discounted value of future changes in the fundamental up to a constant elasticity.

Equations (2) and (3) theoretically hold for *any* exchange rate. In the case of a free-floating exchange rate, $L_t = U_t = 0$ and so $\mathbf{E}_t(dS_t/dt) = \mu$. There is thus a linear relationship between the exchange rate and fundamental. In the target zone case, the monetary authorities use unsterilized interventions in the domestic money market in order to try to

³Harrison (1985) defines a *VF function* Z as one for which the supremum over all finite partitions of $\sum_i |Y(t_i) - Y(t_{i-1})|$ are finite. A stochastic process Y satisfying this property is a *VF process*. An important characteristic of VF processes from the point of view of Ito calculus is that their quadratic variation is zero.

maintain the zone. As markets anticipate these interventions, this relationship becomes nonlinear as $\mathbf{E}_t(dS_t/dt) < 0$ near the upper bound and $\mathbf{E}_t(dS_t/dt) > 0$ near the lower bound. Krugman and subsequent authors postulated a nonlinear relationship

$$S_t = s(X_t) \quad (4)$$

between the exchange rate and fundamental.⁴

2.2 Formulation of the Differential Equation to Determine $s(X)$

For some general VF processes L and U in (1), the Ito Lemma gives

$$ds(X) = \sigma s'(X) dW + \Gamma s(X) dt + s'(X) dL - s'(X) dU$$

for $\Gamma s \equiv \sigma^2 s''/2 + \mu s'$. Using the integration by parts formula (Harrison, 1985, pg. 73),

$$\begin{aligned} e^{-T/\gamma} s(X_T) &= s(X_t) + \int_t^T e^{-(r-t)/\gamma} ds(X) - \frac{1}{\gamma} \int_t^T e^{-(r-t)/\gamma} s(X) dr \\ &= s(X_t) + M_T - \int_t^T e^{-(r-t)/\gamma} \left(\frac{1}{\gamma} s(X) - \Gamma s(X) \right) dr \\ &\quad + \int_t^T e^{-(r-t)/\gamma} s'(X) dL - \int_t^T e^{-(r-t)/\gamma} s'(X) dU \end{aligned}$$

where $M_T \equiv \sigma \int_t^T e^{-(r-t)/\gamma} s'(X) dW$ is an Ito integral. Taking conditional expectations and limits as $T \rightarrow \infty$,

$$\begin{aligned} s(X_t) &= \mathbf{E}_t \int_t^\infty e^{-(r-t)/\gamma} \left(\frac{1}{\gamma} s(X) - \Gamma s(X) \right) dr \\ &\quad - \mathbf{E}_t \int_t^\infty e^{-(r-t)/\gamma} s'(X) dL + \mathbf{E}_t \int_t^\infty e^{-(r-t)/\gamma} s'(X) dU \end{aligned} \quad (5)$$

This expression is similar to Harrison's (1985, pg. 83, line 5), but with a critical difference. Nothing special has yet been assumed about L and U other than that they are VF.

Defining $z^+ \equiv \max(z, 0)$ and $z^- \equiv \min(z, 0)$, so that $z = z^+ + z^-$, the mean value theorem allows

$$s'(X) dL = s'(\underline{X}) dL + s''(\underline{X}^*)(X - \underline{X})^+ dL + s''(\underline{X}^*)(X - \underline{X})^- dL \quad (6)$$

and

$$s'(X) dU = s'(\bar{X}) dU + s''(\bar{X}^*)(X - \bar{X})^- dU + s''(\bar{X}^*)(X - \bar{X})^+ dU \quad (7)$$

for $\underline{X}^* \in (\min(\underline{X}, X), \max(\underline{X}, X))$ and $\bar{X}^* \in (\min(X, \bar{X}), \max(X, \bar{X}))$.

⁴An error term (ε_t) is often added (Meese and Rose, 1990; Flood *et al.*, 1990; *inter alia*) to allow for estimation error and idiosyncratic deviations from the target zone.

2.3 Solution in Special Cases

There are two important special cases. If X is Brownian motion with drift and without regulators, then $dL = dU = 0$. In this case, the second and third terms of (5) are zero.

If X is regulated Brownian motion with regulators dL and dU such that X is bounded on the interval $[\underline{X}, \overline{X}]$, then $(X - \underline{X})^-$ and $(X - \overline{X})^+$ are zero due to the bounds. If the regulators act as in Harrison (1985) and Krugman (1991) – in particular, no intramarginal interventions – then $dL = 0$ when $(X - \underline{X})^+ > 0$ and $dU = 0$ when $(X - \overline{X})^- > 0$. In other words, no intervention occurs unless the fundamental is exactly at one of the bounds. Under boundedness and no intramarginal interventions, (6) and (7) reduce to $s'(\underline{X})dL$ and $s'(\overline{X})dU$. At \underline{X} and \overline{X} , s' is assumed to be known constants c_1 and c_2 (equal to zero, in particular).

In both special cases, the second and third terms of (5) are known. Problems of the type

$$s(X_t) = \mathbf{E}_t \int_t^\infty e^{-(r-t)/\gamma} (\mu(X)dr - c_1dL + c_2dU) \quad (8)$$

for known function μ may be solved by solving the second-order differential equation

$$\frac{1}{\gamma}s(X) - \Gamma s(X) = \mu(X)$$

or

$$s''(X) + \frac{2\mu}{\sigma^2}s'(X) - \frac{2}{\gamma\sigma^2}s(X) + \frac{2}{\sigma^2}\mu(X) = 0$$

with boundary conditions given by $s'(\underline{X}) = c_1$ and $s'(\overline{X}) = c_2$. The solution (see Harrison, pg. 86) is given by

$$s_0(X_t) = \mathbf{E}_t \int_t^\infty e^{-(r-t)/\gamma} \mu(X)dr + B_1 \exp(\rho_1 X_t) + B_2 \exp(\rho_2 X_t)$$

where

$$\rho_{1,2} \equiv -\frac{\mu}{\sigma^2} \left(1 \pm \sqrt{1 + \frac{2\sigma^2}{\mu^2\gamma}} \right)$$

with $\rho_1 < 0$ and $\rho_2 > 0$.

In Krugman's model (1988, pg. 676), $\mu(X) = X/\gamma$, so that

$$\mathbf{E}_t \int_t^\infty e^{-(r-t)/\gamma} \mu(X)dr = \frac{1}{\gamma} \int_t^\infty e^{-(r-t)/\gamma} (\mu(r-t) + X_t)dr = \gamma\mu + X_t$$

and

$$s_0(X_t) = \gamma\mu + X_t + B_1(\underline{X}, \overline{X}) \exp(\rho_1 X_t) + B_2(\underline{X}, \overline{X}) \exp(\rho_2 X_t) \quad (9)$$

is the solution, up to constants $B_1(\underline{X}, \overline{X})$ and $B_2(\underline{X}, \overline{X})$. The boundary conditions give constants of

$$B_1(\underline{X}, \overline{X}) = \frac{\gamma\sigma^2\rho_2 \exp(\rho_2 \underline{X})(1 - c_2) - \exp(\rho_2 \overline{X})(1 - c_1)}{2 \exp(\rho_1 \overline{X} + \rho_2 \underline{X}) - \exp(\rho_1 \underline{X} + \rho_2 \overline{X})}$$

and

$$B_2(\underline{X}, \overline{X}) = \frac{\gamma\sigma^2\rho_1 \exp(\rho_1\overline{X})(1-c_1) - \exp(\rho_1\underline{X})(1-c_2)}{2 \exp(\rho_1\overline{X} + \rho_2\underline{X}) - \exp(\rho_1\underline{X} + \rho_2\overline{X})}$$

for general c_1, c_2 .

In the prototypical target zone model, $c_1 = c_2 = 0$ (See Iannizzotto and Taylor, 2001, e.g.), giving the target zone model its standard ‘‘S’’ shape. Alternatively, if the derivatives are set equal to 1 at $\underline{X}, \overline{X}$, then $B_1 = B_2 = 0$ and the linear case is obtained.

2.4 A Closer Look at the Bounds

What if the fundamental is allowed to exceed its bounds $(\underline{X}, \overline{X})$? If no monetary policy action is taken, then $dL = dU = 0$. The linear case is obtained. On the other hand, if the targeting policy is maintained,

$$\lim_{\underline{X} \rightarrow -\infty} B_1(\underline{X}, \overline{X}) = 0 \quad \text{and} \quad \lim_{\overline{X} \rightarrow \infty} B_2(\underline{X}, \overline{X}) = 0$$

as the bounds are extended. This result holds for any $c_1, c_2 < \infty$. These are extreme cases.

In general, if the band is nominally maintained, but empirically exceeded, the third terms of (6) and (7) become non-zero. That is, $(X - \underline{X})^- < 0$ and $(X - \overline{X})^+ > 0$.

Consider the lower bound. The second term of (5) becomes

$$\mathbf{E}_t \int_t^\infty e^{-(r-t)/\gamma} s'(X) dL = \mathbf{E}_t \int_t^\infty e^{-(r-t)/\gamma} c_1 dL + \mathbf{E}_t \int_t^\infty e^{-(r-t)/\gamma} s''(\underline{X}^*)(X - \underline{X})^- dL$$

which involves the unknown function s . Since this term involves s , the solution for $s(X_t)$ given above *does not generally hold*. The only cases in which this problem is quickly remedied are (i) $dL = 0$, the target zone policy is dropped; (ii) $s''(\underline{X}^*) = 0$ for unknown \underline{X}^* ; or (iii) $\underline{X} \rightarrow -\infty$ so that $(X - \underline{X})^- \rightarrow 0$.

If there is a *de facto* lower bound $\underline{\underline{X}}$ such that $\underline{\underline{X}} < \underline{X}$, then the mean value theorem allows

$$s'(X) dL = s'(\underline{\underline{X}})dL + s''(\underline{\underline{X}}^*)(X - \underline{\underline{X}})^+ dL + s''(\underline{\underline{X}}^*)(X - \underline{\underline{X}})^- dL + s''(\underline{\underline{X}}^*)(\underline{X} - \underline{\underline{X}})dL$$

In this case, for $s'(\underline{\underline{X}}) = c_3$, the second term of (5) becomes

$$\mathbf{E}_t \int_t^\infty e^{-(r-t)/\gamma} s'(X) dL = \mathbf{E}_t \int_t^\infty e^{-(r-t)/\gamma} c_3 dL + \mathbf{E}_t \int_t^\infty e^{-(r-t)/\gamma} s''(\underline{\underline{X}}^*)(X - \underline{\underline{X}})dL \quad (10)$$

since $\min(X - \underline{\underline{X}}, 0) + (\underline{X} - \underline{\underline{X}}) = X - \underline{\underline{X}}$. Note that the second term of (10) is not zero, because $\mathbf{E}_t dL > 0$ when $\underline{\underline{X}} \leq X \leq \underline{X}$. The solution above (with c_3 instead of c_1) applies if the new lower bound $\underline{\underline{X}}$ is *expected*, in which case $\mathbf{E}_t dL = 0$ when $(X - \underline{\underline{X}}) > 0$, or if there is no longer a lower bound, so that $s' = 1$ and $s'' = 0$. The same logic applies for the upper bound.

The prototypical target zone model of Krugman (1991) therefore relies heavily on an assumption that either (i) X is bounded with known bound, or (ii) there is no bound, in which case the exchange rate floats. The latter case no longer describes a target zone model.

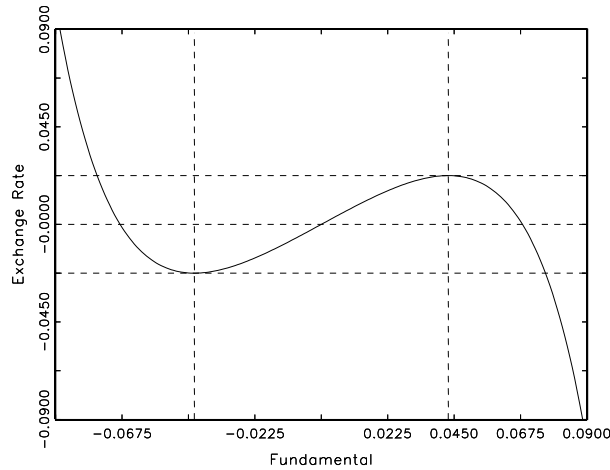


Figure 1: Krugman target zone function with explicit target zone (horizontal lines) and implicit fundamental bounds (vertical lines).

2.5 A Graphical Interpretation

Figure 1 illustrates the Krugman function given by (9). As long as the fundamental stays within (\bar{X}, \underline{X}) , delineated by the two vertical lines, the familiar “S”-shaped function maps an exchange rate within the explicit target zone, given by the three horizontal lines. (The central horizontal line in this and subsequent figures represents the exchange rate target or central parity, while the outer lines represent the edges of the target zone.) To avoid confusion, I henceforth refer to the vertical band as the *fundamental band* defined by *fundamental bounds* \bar{X} and \underline{X} , while the horizontal band is the usual *target zone* or *exchange rate band*.

The fundamental bounds are critical to the derivation of the model, as discussed above. If the model is taken literally, out of context of the solution to the stochastic differential equation above, the fundamental bounds are still critical. The economic intuition of the model breaks down when the fundamental exceeds these bounds if the model is taken literally. Beyond the bounds, either a new solution – and therefore new model – must be considered, or else the predicted exchange rate begins to move in the opposite direction of the fundamental. Even for moderate deviations, the predicted exchange rate deviates from the target zone in the *opposite direction*.

The exogenous velocity shocks will exceed the fundamental bounds eventually (both by assumption and from empirical evidence). The log of the money stock must therefore increase or decrease – potentially without bound – in order to counteract velocity shocks beyond the fundamental bounds, and thus to bound the fundamental and therefore also the exchange rate. A test of the boundedness of the fundamental therefore amounts a test of the target zone policy itself.

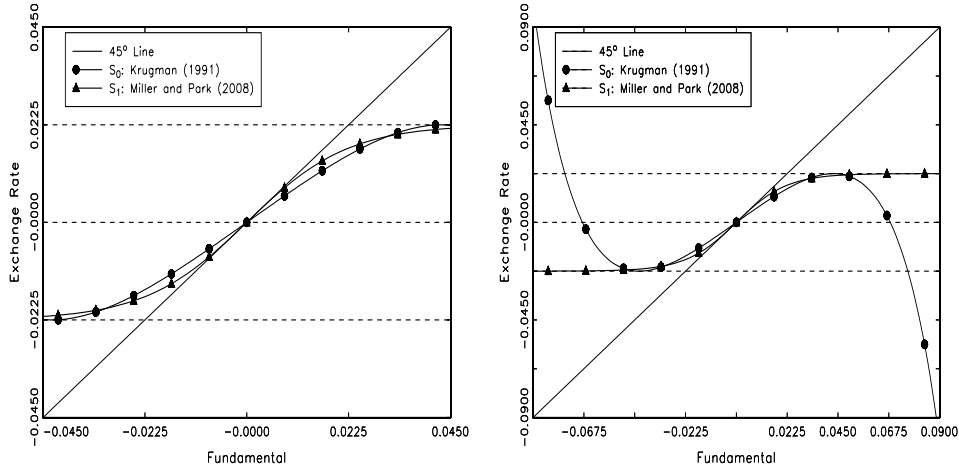


Figure 2: Comparison of s_0 and s_1 (a) within the band, and (b) beyond the band.

3 Specification and Testing

3.1 Specification

Estimation of the unobserved fundamental may be accomplished by viewing (4) as a state-space model. Consistently with Meese and Rose (1990) and Flood *et al.* (1990), I add an error term to allow for estimation error and idiosyncratic deviations from the target zone. I consider the discrete-time model

$$s_t = s(x_t) + \varepsilon_t, \quad (11)$$

so the error sequence (ε_t) also allows discretization error. I subsequently use lower case letters for discrete-time processes, which replace the continuous-time process denoted with capital letters above.

For the purposes of estimation, I assume a state equation of $x_t = x_{t-1} + \eta_t$. Although it may appear otherwise, this state equation does *not* impose a random walk structure on the estimated series (\hat{x}_t). If s were linear, Chang *et al.* (2009) showed that the estimated series (\hat{x}_t) from the linear Kalman filter would be a linear process constructed from (x_t) with *absolutely summable* coefficients. The summability means that (\hat{x}_t) would inherit persistence from (x_t). In other words, if (x_t) were stationary, then (\hat{x}_t) would be stationary, but if (x_t) were a random walk, then (\hat{x}_t) would have a unit root. Any nonlinear filter is of course much more complicated than the linear Kalman filter. However, many nonlinear filters (such as the one used in this research) use linear updating equations. The persistence properties of (\hat{x}_t) should be inherited from (x_t), as in the linear case.

Identification of this model is problematic. As seen in Figure 1 and Figure 2(b), the function in (9) maps three different values of the fundamental to each exchange rate within the target zone. A filtering strategy based on (9) must deal with this problem.

Previous authors (de Jong, 1994; Beetsma, 1995; Iannizzotto and Taylor, 1999; Taylor and Iannizzotto, 2001; *inter alia*), whose focus has generally been on the model parameters

rather than the fundamental, solved this problem by simply enforcing the bounds. These authors in particular use the method of simulated moments to estimate the function. The fundamental may be estimated subsequently by inverting the exchange rate function *after* the functional parameters have been estimated. This approach necessitates distributional assumptions that explicitly bound the simulated fundamental. Imposing the restriction in estimation is problematic for subsequent tests of the restriction – at least for the type of tests considered here, which aim to test the time series behavior of the fundamental, rather than the comparative fit of different models or techniques.

An alternative would be flatten the function beyond the fundamental bounds, so that all fundamentals beyond these bounds are mapped exactly to the respective exchange rate bounds. This strategy would allow the fundamental to exceed the bounds, which would be appropriate for subsequent testing. However, identification in estimation would be impossible.

In order to allow identification but also allow fundamentals beyond the bounds to map to reasonable exchange rates within the target zone band (up to idiosyncratic error), a monotone increasing function may be used. Lundbergh and Teräsvirta (2006) and Miller and Park (2008) used logistic functions for target zone exchange rates. Specifically, consider

$$s_1(x_t) = \nu - h/2 + h / (1 + \exp(-(x_t - \nu)/\beta)), \quad (12)$$

where $\exp \nu$ is the central parity, $2(\exp h/2 - 1)$ is the bandwidth, and β is a slope parameter. Although this function does not explicitly solve the continuous time model, it approximates the solution within the band, as illustrated in Figure 2(a), while allowing identification of the fundamental within and outside of the band. As is clear from Figure 2(b), s_1 is robust to potentially unbounded fundamentals, since large fundamentals are still mapped inside the band. Moreover, the fundamental is identified up to the error term (ε_t). Essentially, s_1 replaces the smooth pasting requirements used to derive s_0 with the requirement of monotonicity for identification.

All empirical results below use (11) with s given by s_1 in (12), estimated using the unscented Kalman filter (Julier and Uhlmann, 1997; Julier *et al.*, 2000) with smoothing,⁵ a nonlinear filter that is more robust to biases inherent in the more well-known extended Kalman filter. As above, estimates of the fundamental are denoted by (\hat{x}_t) .⁶

3.2 Testing the Bounds

Standard linear unit root tests, such as the Phillips-Perron tests, may not have high power against bounded, nonlinear alternatives. In the specific context of target zone exchange

⁵Following Julier *et al.* (2000), I set the tuning parameter $\theta = 2$, since (x_t) is univariate, and do not use additional tuning parameters.

⁶The fundamental is often defined explicitly based on assumptions of the flexible price monetary model. See, for example, Meese and Rose (1990), Flood *et al.* (1990), Svensson (1991). In principle, we may use this definition to incorporate income, money stock, and other covariates directly into the model. Such an approach has at least two serious drawbacks: (a) Lower frequency data for these series lead to very small sample sizes, and (b) assumptions about purchasing power parity and uncovered interest parity must be addressed. Pursuing this approach for the first five exchange rates below (with time periods over which sufficiently monthly data are available) yielded qualitatively similar test results to those reported below.

rates, this lack of power has been noted by Taylor and Iannizzotto (2001), Taylor *et al.* (2001), and Cavaliere (2005) for nominal exchange rates and by Kapetanios *et al.* (2003) for real exchange rates. Such tests are consequently not appropriate for testing boundedness of the target zone exchange rates themselves.

However, linear unit root tests may still be appropriate for an estimated fundamental series. Recall that the fundamental is defined as Brownian motion (with possible drift) with the log of the domestic money stock M_t playing the role of the regulators $L_t - U_t$ to keep the fundamental bounded. Under a hypothesis of no bounds (or poorly defined bounds), M_t plays little role in moderating the persistence of the fundamental. In this case, the unit root hypothesis (in discrete time) is appropriate.

On the other hand, if M_t is an effective regulator, then X_t will be bounded. Although the bound does not imply covariance stationarity, the discrete-time analog of the linear combination $M_t + V_t$ may be approximately cointegrating in a loose sense, so that the fundamental is strongly mean-reverting.

I construct KPSS tests for the exchange rates themselves, but not for the fundamentals. Although the covariance stationary null would be convenient to reject the boundedness assumption, the fundamental is composed of a random walk plus a nonlinear function of the same random walk. Although the fundamental may be bounded, these bounds are not sufficient for covariance stationarity.

For both exchange rate and fundamental, I construct Phillips-Perron Z_c (coefficient test) and Z_t (t-test) statistics. The I(1) nulls may provide evidence against the boundedness of the fundamentals. On the other hand, since the fundamental is not directly observed and estimation is explicitly nonlinear, a testing strategy robust to nonlinear, bounded alternatives may be more appropriate. Cavaliere (2005) used variations of the rescaled range statistic (Hurst, 1951; Mandelbrot and Wallis, 1969; Lo, 1991) to test boundedness of the exchange rates themselves. Similarly to Cavaliere (2005), I use test statistics

$$\begin{aligned} R &\equiv n^{-1/2}(\max_{t=1,\dots,n}(\hat{x}_t) - \min_{t=1,\dots,n}(\hat{x}_t))/\hat{\omega}_n \\ \Lambda &\equiv -n^{-1/2} \min_{t=1,\dots,n}(\hat{x}_t - \bar{x}_n)/\hat{\omega}_n \\ \Upsilon &\equiv n^{-1/2} \max_{t=1,\dots,n}(\hat{x}_t - \bar{x}_n)/\hat{\omega}_n \end{aligned}$$

where \bar{x}_n is the sample mean of \hat{x}_t and $\hat{\omega}_n$ is a consistent estimator of the limiting variance of $n^{-1/2} \sum_{t=1}^n \hat{\eta}_t$. Under the null, $(\hat{x}_t) \sim I(1)$. If the *de facto* bounds of the data – given by the range and the upper and lower bounds – increase with the sample size, these tests point to the absence of bounds. If they do not increase with the sample size, then the series may be bounded.

4 Data and Empirical Results

Empirical results focus on ten exchange rate mechanism (ERM) I exchange rates, five ERM II exchange rates, and one US dollar peg.

Many empirical estimates of target zone models – whether favorable or unfavorable – have used data from the ERM I period. The ERM crisis of the early 1990's resulted

	Dates	Band (\pm)	Dates	Band (\pm)
Belgian franc (BEF/DEM)	04/02/91-08/02/93	2.25%	08/03/93-12/31/98	15%
French franc (FRF/DEM)	04/02/91-08/02/93	2.25%	08/03/93-12/31/98	15%
Dutch guilder (NLG/DEM)	04/02/91-12/31/98	2.25%		
Danish krone (DKK/DEM)	01/04/91-08/02/93	2.25%	08/03/93-12/31/98	15%
Danish krone (DKK/EUR)	01/04/99-09/28/07	2.25%		
Irish pound (IEP/DEM)	08/02/93-12/31/98	15%		
Austrian schilling (ATS/DEM)	01/09/95-12/31/98	15%		
Spanish peseta (ESP/DEM)	03/06/95-12/31/98	15%		
Portuguese escudo (PTE/DEM)	03/06/95-12/31/98	15%		
Finnish markka (FIM/DEM)	10/14/96-12/31/98	15%		
Italian lira (ITL/DEM)	11/25/96-12/31/98	15%		
Greek drachma (GRD/EUR)	01/04/99-12/29/00	15%		
Slovenian tolar (SIT/EUR)	06/28/04-12/29/06	15%		
Cyprus pound (CYP/EUR)	05/02/05-12/31/07	15%		
Latvian lats (LVL/EUR)	05/02/05-12/31/07	1%		
Saudi riyal (SAR/USD)	08/24/98-12/31/07	1%		

Table 1: Exchange rates, time periods, and bandwidths.

in a widening of the target zones for many ERM I rates. The bands were so wide, in fact, that one could argue that exchange rates were almost floating during this period. As illustrated in Figure 3, the persistence and volatility of the Belgian franc, French franc, and Danish krone increased immediately after the bands were widened. This change is consistent with a regime shift either to a float or to a wider band. However, since a target policy was maintained and since the empirical characteristics do not suggest a random walk (which would be characteristic of a float), an expanded model similar to the discussion of \underline{X} above is appropriate for this period. Moreover, since especially volatile fundamentals that exceeded the theoretical fundamental bounds may be estimated during this period, tests may shed light on some of the rejections of target zone models during this period. In order to estimate the fundamental for these three rates, I explicitly model the (known) change in the bandwidth and allow for a contemporaneous structural break in estimation of the (unknown) slope parameter β .

ERM II exchange rates provide insights into more contemporary target zone arrangements, since several non-euro EU members are still bound by the ERM II, as of this writing. Saudi Arabia has pegged the Riyal to the US dollar, unofficially since 1986 and officially since 2003. The Riyal is allowed to fluctuate within a narrow $\pm 1\%$ band around this peg. Maintaining the peg became a controversial issue for Saudi Arabia in 2007, as a weak dollar drove other oil-exporting countries to drop their pegs.

Table 1 details the exchange rates used in this research, with sample periods and target zone characteristics. All European rates were obtained from EuroStat and Saudi rates were obtained from the Pacific Exchange Rate Service (University of British Columbia). The

beginnings of most series coincide either with the last realignment of the respective central rates or with entrance of the country into the ERM. The central parity for the drachma rate was realigned roughly halfway through its two-year target zone period. Since this realignment was small in percentage terms and relative to the bandwidth of the zone and the actual fluctuations of the exchange rate, I do not model it explicitly.

Figure 3 shows the exchange rates and estimated fundamentals. The fundamentals exhibit stochastic trends, straying from their mean when the respective exchange rates near the edge of their band. Since any potential fundamental bounds do not coincide with the bounds imposed on the exchange rate, boundedness of these stochastic trends is an open question. Note that most of the ERM I and ERM II exchange rates and fundamentals appear to converge to their targets leading up to the adoption of the euro.⁷ Interestingly, the krone/mark rate also seems to show convergence, even though Denmark did not adopt the euro. The last two exchange rates, which were sampled through 2007, show pressure to move outside of their respective bands. Clearly, Latvia has struggled throughout this period against pressure to appreciate the lats. Saudi Arabia began to face similar pressure to maintain its peg to the dollar in the face of US rate cuts. Saudi Arabia has not dropped the dollar peg (as of this writing) as Kuwait did in 2007.

Test results for the exchange rates are shown in Table 2, with significance at the 5% level indicated. The KPSS test fails to reject the $I(0)$ null for most of the exchange rates, and the $I(1)$ null is rejected by at least one of the other unit root tests for eleven exchange rates, at least two tests for eight rates, at least three tests for six rates, and all five tests reject the null for the Saudi riyal. The tests suggest many of the exchange rates themselves are bounded.

In order to evaluate unit root test statistics for the estimated fundamentals, I use both standard and bootstrapped critical values. Although the fundamental is filtered with error, the nonstationarity of the fundamental may asymptotically dominate the error, so that standard critical values may be asymptotically valid. As this is a conjecture, it is natural to consider bootstrapping to take into account the nonlinearity of the filter.

In constructing the bootstrap, I randomly draw (with replacement) from the estimated residuals ($\hat{\varepsilon}_t$) and increments of the estimated fundamental ($\hat{\eta}_t$). Note that even if (\hat{x}_t) is stationary, sums of randomly drawn increments are still unit root processes, so critical values for unit root nulls are legitimate. Each bootstrapped critical value is constructed from 10,000 bootstrap repetitions.

I do not re-estimate the parameters of s in the bootstrap. Rather, I apply the nonlinear filter to the bootstrapped exchange rates with originally estimated parameters for the respective rates. Based on a comparison using the krone/euro rate (the longest series) with a smaller number of bootstraps, I found that critical values from bootstrapping using the same parameters and using re-estimated parameters were very similar. As re-estimation

⁷As von Hagen and Traistaru (2005) noted, markets reacted to expected convergence of the exchange rates to their central parities as early as September 1997. An alternative model might feature a gradual narrowing of the implicit band described by the function – i.e., a time-varying band parameter h_t – or by a gradual tightening of expectations around the parity – i.e., a time-varying slope parameter β_t . The empirical result of tightening bands would be to increase the volatility of the fundamental during this period. Since the tests are not well-equipped to deal with changing volatility, I maintained the announced bands throughout.

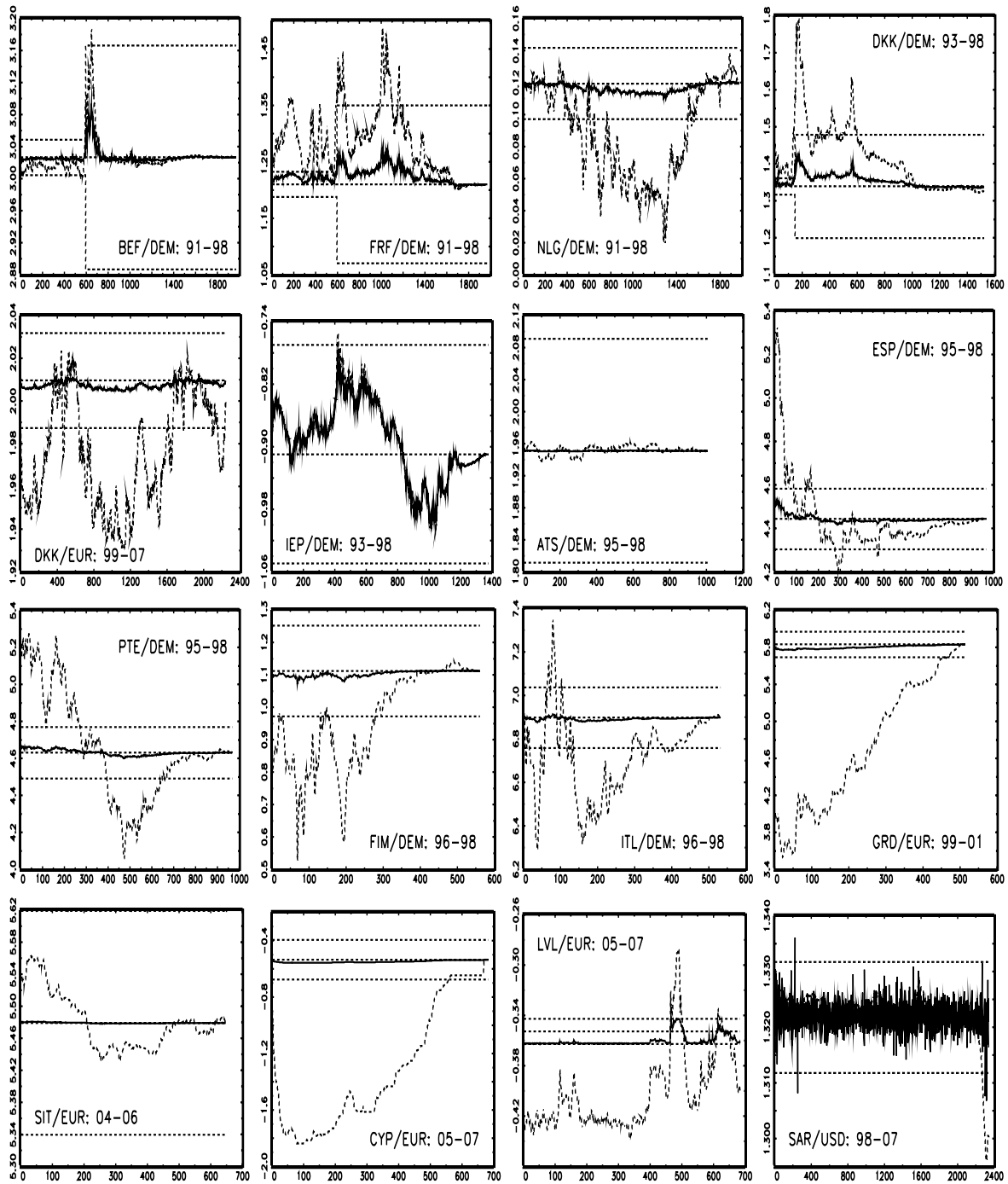


Figure 3: Target zone exchange rates (solid lines) and estimated fundamentals (dashed lines). Horizontal lines represent the target and target zone (not the fundamental band).

	KPSS	Z_c	Z_t	R	Λ	Y
BEF/DEM	0.46	-14.10	-2.86	0.97	0.46	0.46
04/02/91-12/31/98	0.09	-20.86 **	-3.12 **	1.35	0.13 **	1.22
FRF/DEM	0.46	-14.10	-2.86	0.97	0.46	0.46
04/02/91-12/31/98	0.16	-14.20 **	-2.64	0.91 **	0.24 **	0.68
NLG/DEM	0.46	-14.10	-2.86	0.97	0.46	0.46
04/02/91-12/31/98	0.11	-9.29	-2.23	0.96 **	0.57	0.39 **
DKK/DEM	0.46	-14.10	-2.86	0.97	0.46	0.46
01/04/93-12/31/98	0.30	-8.97	-1.92	1.28	0.26 **	1.02
DKK/EUR	0.46	-14.10	-2.86	0.97	0.46	0.46
01/04/99-09/28/07	0.15	-9.86	-2.35	0.78 **	0.37 **	0.41 **
IEP/DEM	0.46	-14.10	-2.86	0.97	0.46	0.46
08/02/93-12/31/98	0.30	-4.48	-1.42	1.57	0.77	0.79
ATS/DEM	0.46	-14.10	-2.86	0.97	0.46	0.46
01/09/95-12/31/98	0.26	-37.45 **	-2.80	0.97	0.49	0.49
ESP/DEM	0.46	-14.10	-2.86	0.97	0.46	0.46
03/06/95-12/31/98	0.26	-15.88 **	-3.79 **	1.77	0.40 **	1.36
PTE/DEM	0.46	-14.10	-2.86	0.97	0.46	0.46
03/06/95-12/31/98	0.25	-5.66	-1.92	1.85	0.91	0.94
FIM/DEM	0.46	-14.10	-2.86	0.97	0.46	0.46
10/14/96-12/31/98	0.41	-14.09	-2.23	1.12	0.84	0.28 **
ITL/DEM	0.46	-14.10	-2.86	0.97	0.46	0.46
11/25/96-12/31/98	0.17	-20.44 **	-3.03 **	1.03	0.44 **	0.59
GRD/EUR	0.46	-14.10	-2.86	0.97	0.46	0.46
01/04/99-12/29/00	279.6 **	0.04	0.14	2.55	1.34	1.21
SIT/EUR	0.46	-14.10	-2.86	0.97	0.46	0.46
06/28/04-12/29/06	0.23	-10.20	-1.61	1.57	0.60	0.97
CYP/EUR	0.46	-14.10	-2.86	0.97	0.46	0.46
05/02/05-12/31/07	3.07 **	0.63	0.20	2.43	0.98	1.45
LVL/EUR	0.46	-14.10	-2.86	0.97	0.46	0.46
05/02/05-12/31/07	0.36	-11.83	-2.50	0.89 **	0.12 **	0.77
SAR/USD	0.46	-14.10	-2.86	0.97	0.46	0.46
08/24/98-12/31/07	2.29 **	-1971 **	-9.02 **	0.76 **	0.39 **	0.37 **

Table 2: Test results for original exchange rates. ** denotes significance of test test statistics at the 5% level. No other significance levels are noted.

	Z_c	CV_0	CV_B	CV_{B^*}	Z_t	CV_0	CV_B	CV_{B^*}	R	CV_0	CV_B	CV_{B^*}	Λ	CV_0	CV_B	CV_{B^*}	Y	CV_0	CV_B	CV_{B^*}
BEF/DEM		-14.10	-6.25		-2.86	-2.82			0.97	0.95			0.46	0.44			0.46	0.44		
04/02/91-12/31/98	-5.58				-2.86	**			1.50				0.21	**	**		1.29			
FRF/DEM		-14.10	-5.47		-2.86	-2.78			0.97	0.96			0.46	0.45			0.46	0.45		
04/02/91-12/31/98	-3.92				-2.56				0.88	**	**		0.25	**	**		0.63			
NLG/DEM		-14.10	-5.60		-2.86	-2.80			0.97	0.95			0.46	0.44			0.46	0.45		
04/02/91-12/31/98	-3.30				-1.95				1.07				0.63				0.44	**	**	
DKK/DEM		-14.10	-4.71		-2.86	-2.70			0.97	0.96			0.46	0.45			0.46	0.45		
01/04/93-12/31/98	-1.34				-2.10				1.19				0.24	**	**		0.95			
DKK/EUR		-14.10	-5.69		-2.86	-2.81			0.97	0.96			0.46	0.45			0.46	0.45		
01/04/99-09/28/07	-3.35				-2.32				0.76	**	**		0.37	**	**		0.39	**	**	
IEP/DEM		-14.10	-5.06		-2.86	-2.75			0.97	0.96			0.46	0.45			0.46	0.45		
08/02/93-12/31/98	-1.13				-1.50				1.57				0.71				0.86			
ATS/DEM		-14.10	-5.61		-2.86	-2.75			0.97	0.95			0.46	0.45			0.46	0.44		
01/09/95-12/31/98	-3.73				-2.91	**	**		0.76	**	**		0.44	**	**		0.32	**	**	
ESP/DEM		-14.10	-3.38	-7.67	-2.86	-2.67	-2.88		0.97	1.76	0.96		0.46	0.78	0.44		0.46	0.81	0.45	
03/06/95-12/31/98	-13.34		**	**	-5.23	**	**	**	2.02				0.42	**	**	**	1.59			
PTE/DEM		-14.10	-4.83		-2.86	-2.70			0.97	1.10			0.46	0.52			0.46	0.52		
03/06/95-12/31/98	-2.72				-1.97				1.89				0.93				0.96			
FIM/DEM		-14.10	-5.10		-2.86	-2.68			0.97	0.98			0.46	0.46			0.46	0.46		
10/14/96-12/31/98	-2.47				-1.64				1.28				0.91				0.37	**	**	
ITL/DEM		-14.10	-5.58		-2.86	-2.74			0.97	0.93			0.46	0.44			0.46	0.44		
11/25/96-12/31/98	-5.93		**		-2.70				1.07				0.44	**			0.62			
GRD/EUR		-14.10	-2.58	-11.66	-2.86	-2.86	-3.40		0.97	2.90	0.95		0.46	1.45	0.45		0.46	1.23	0.43	
01/04/99-12/29/00	0.37				-0.13				2.69	**			1.43	**			1.26			
SIT/EUR		-14.10	-4.80		-2.86	-2.60			0.97	1.08			0.46	0.51			0.46	0.51		
06/28/04-12/29/06	-1.57				-1.54				1.85				0.69				1.16			
CYP/EUR		-14.10	-4.68		-2.86	-2.60			0.97	1.02			0.46	0.49			0.46	0.48		
05/02/05-12/31/07	0.96				-0.13				1.82				0.74				1.08			
LVL/EUR		-14.10	-16.50		-2.86	-4.16			0.97	0.81			0.46	0.15			0.46	0.22		
05/02/05-12/31/07	-5.02				-2.06				1.24				0.29	**			0.95			
SAR/USD		-14.10	-0.93	-3.49	-2.86	-1.36	-3.77		0.97	1.92	0.65		0.46	0.93	0.30		0.46	0.91	0.30	
08/24/98-12/31/07	12.98				0.04				1.47	**			1.22				0.25	**	**	**

Table 3: Test results for estimated fundamentals. CV_0 denotes critical values from the standard distributions, CV_B denotes critical values from the bootstrapped distribution, and CV_{B^*} denotes critical values from the bootstrapped distribution with random signs. ** denotes significance of test statistics at the 5% level. No other significance levels are noted.

requires numerical optimization of a highly nonlinear function, estimation may take an inordinate length of time to converge or may not converge at all. The high marginal cost of numerical optimization does not outweigh the low marginal benefit of a very small gain in precision. Moreover, the main benefit of the bootstrap lies in accounting for nonlinear filtering rather than for estimation.

The results are shown in Table 3 for Z_c , Z_t , R , Λ and Υ . The test statistics appear in the first column under each of these labels. The second column contains standard critical values with bootstrapped critical values following.

Notice that the bootstrapped critical values for Z_t and all of the range-based tests are remarkably close to the standard critical values for most of the exchange rates. This observation provides some empirical evidence in favor of the robustness of the range tests in particular to lower-order nonlinearity from estimation error. In contrast, the Z_c critical values are substantially different.

For several of the exchange rates, the range-based critical values appear unusually large. Consider the drachma, with a bootstrap critical value of 2.90 compared to 0.97. Notice that the estimated fundamental contains many more increases than decreases over the sample period. Redrawing from the empirical distribution of its increments creates a range too large relative to \sqrt{n} . While such an estimated fundamental provides evidence *against* the boundedness assumption, redrawing from its increments makes it easier to reject the unit root to find evidence *for* boundedness. In order to balance this small-sample problem, I apply a random sign change to the bootstrapped increments for the drachma, and also for the peseta and the riyal. The resulting critical values are shown in the fourth column for each test statistic.

The empirical results are mixed. Using the bootstrapped critical values, six rates (the Irish pound, escudo, drachma, tolar, Cyprus pound, and lats) show no evidence that the respective estimated fundamentals are bounded. Another five rates (the guilder, krone/mark, markka, lira, and riyal) show evidence with only one test. For all of these five except the lira, the evidence points to a bound in one direction only. For the Belgian and French franc rates, the evidence is more mixed. From Figure 3, it appears that the boundedness assumption for the Belgian franc fundamental is reasonable over most of the sample period (except during the ERM crisis of the early 1990's). For the remaining three rates (the krone/euro, schilling, and peseta), the evidence clearly supports the boundedness assumption. Clearly, the fundamental bands for the krone and peseta must be much wider than the exchange rate bands shown in the figure.

It is instructive to examine differences between the tests on the estimated fundamentals and those on the exchange rates themselves. The most striking are the lira and riyal rates. For both of these, the evidence strongly favors bounded exchange rates but much less so for the estimated fundamentals.

5 Concluding Remarks

The empirical test results raise doubts about the fundamental bounds, a key assumption of the Krugman and many subsequent target zone models. These findings support an apparent

skepticism of these models in the literature. A new and specific explanation for possible model failure is offered by examining these bounds.

A new paradigm for structural modeling of target zone exchange rates is needed. While reduced form approaches in the literature – approaches by Bessec (2003), Crespo-Cuaresma, *et al.* (2005), Lundbergh and Teräsvirta (2006), *inter alia* – provide greater modeling flexibility by requiring only lagged exchange rate data, they do not allow for inference about some of the structural macroeconomic parameters of interest.

A recent approach by Bauer *et al.* (2009), building on work by Frankel and Froot (1986), Brock and Hommes (1998), and De Grauwe and Grimaldi (2005, 2006), using a heterogeneous agent structure, shows promise in the direction of developing an alternative approach to modeling target zone exchange rates. They derive a model in which the fundamental is driven by a nonlinear stochastic differential equation, which they show through simulations may generate exchange rate behavior more consistent with target zone exchange rate data.

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