Non-Linear Exchange Rate Dynamics in Target Zones: A Bumpy Road Towards A Honeymoon

Some Evidence from the ERM, ERM2 and Selected New EU Member States

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Some Evidence from the ERM, ERM2 and Selected New EU Member States

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Abstract

This study investigates exchange rate movements in the Exchange Rate Mechanism (ERM) of the European Monetary System (EMS) and in the Exchange Rate Mechanism II (ERM-II). On the basis of Bessec (2003), we set up a three-regime self-exciting threshold autoregressive model (SETAR) with a non-stationary central band and explicit modelling of the conditional variance. This modelling framework is employed to model daily DM-based and median currency-based bilateral exchange rates of countries participating in the original ERM and also for exchange rates of the Czech Republic, Hungary, Poland and Slovakia from 1999 to 2004. Our results confirm the presence of strong non-linearities and asymmetries in the ERM period, which, however, seem to differ across countries and diminish during the last stage of the run-up to the euro. Important non-linear adjustments are also detected for Denmark in ERM-2 and for our group of four CEE economies.

Keywords: target zone, ERM, non-linearity, SETAR.

JEL: F31, G15, O10

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1. Introduction

The seminal paper of Krugman (1991) focused on explaining the exchange rate behaviour of a currency with a central parity rate and upper and lower exchange rate bands, the so called target zone model. The existence of the Exchange Rate Mechanism (ERM) of the European Monetary System (EMS) provided researchers with an ideal opportunity to test the target zone model because it provided ample data for empirical analysis. Since the early 1990s, numerous papers have been written on the period preceding the ERM crisis of 1993[1], while the period in the run-up to the euro has received less attention.[2] However, further analysis of the post-1993 experience would appear to be fruitful for, at least, two reasons. First, Flood, Rose and Mathieson (1990) and Rose and Svensson (1995) reported only limited non-linearity in the period prior to 1993. However, the widening of the fluctuation bands from $\pm 2.25\%$ to $\pm 15\%$ in the post-1993 period may have introduced additional non-linear behaviour into exchange rate behaviour. Second, the recent enlargement of the European Union to 25 countries implies that the New Member States would participate, at some point in time, in an ERM-2 arrangement, prior to their adoption of the euro. For them, there may be useful information contained in the behaviour of ERM currencies prior to the introduction of the euro in 1999.

The empirical literature on target zones suffers from a number of problems. First, most studies use monthly or weekly frequencies, which may ‘aggregate out’ the true dynamics of the exchange rate process. Second, the frequent jumps in the central parity in the ERM are not adequately accounted for in the pre-1993 period. Finally, either the mean[3] or variance equation[4] is investigated in a more sophisticated way instead of modelling them jointly.

The aim of this study is to shed additional light on exchange rate behaviour in ERM, ERM-2 and CEE countries. Our modelling framework is based on the target zone models set out in Bartolini and Prati (1999) and Bessec (2003). These models predict the presence of soft bands within the officially announced large bands. More specifically, these models assume that the monetary authorities do not intervene in the proximity of the central parity. In this area, the

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[1] Examples are Anthony and MacDonald (1998), Bessec (2003), Bekaert and Gray (1998), Chung and Tauchen (2001), Rose and Svensson (1995).

[2] See, for example, Anthony and MacDonald (1999), Bessec (2003) and Brandner and Grech (2002).

[3] For example, Bessec (2003) models the mean equation using a SETAR model.

[4] Brandner and Grech (2002) use a simple AR process for the mean equation and use different GARCHG models for the variance equation.

exchange rate behaves like a random walk. However, the monetary authorities take policy action when the exchange rate is about to leave this corridor. Thus, the exchange rate exhibits mean reversion towards the soft band. However, it should be noted that, in reality, such band mean reversion could be the outcome of a number of factors, such as direct and indirect central bank interventions, moral persuasion, communication with the markets, stabilisation of market expectations, in the face of increased credibility of the monetary authorities, or because of an increased stability of the underlying fundamentals. This type of behaviour is best captured by a three-regime SETAR model in which we model conditional variance by means of a GARCH(1,1). The application of this model for daily data from the post-1993 ERM and ERM-2 does not only indicate the presence of a three-regime threshold model but also considerable asymmetries for the detected upper and lower bounds that delimit the soft band within the announced target zone.

The remainder of the paper is structured as follows: Section 2 overviews the target zone literature and summarizes the principal features of this class of models. Section 3 sets out the econometric framework. Section 4 provides the description and a first analysis of the data used in the paper. Section 5 analyses the empirical results and Section 6 provides some concluding remarks.

2. Target Zone Models

2.1. The Krugman Model: Perfect Credibility with Marginal Interventions

The baseline target zone model presented in Krugman (1991) is based on a continuous-time representation of the flexible-price monetary model in which the exchange rate (e) is assumed to be a linear function of a set of fundamental variables (f) and the expected change of the exchange rate ($E(de)/dt$):[5]

$$e = f + \gamma E(de)/dt \qquad (1)$$

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[5] Recall that under the assumption of uncovered interest parity, the standard discrete-time form of the monetary model can be written as: $e_t = m_t - m_t* - \alpha(y_t - y_t*) + \beta\Delta e^e_{t+1}$ with $\alpha, \beta > 0$, m and $m*$ denoting domestic and foreign money supply, y and $y*$ standing for domestic and foreign output and Δe^e_{t+1} representing the expected change in the nominal exchange rate in period t for period t+1.

The fundamentals explicitly considered by Krugman (1991) are money supply and velocity. Money supply is controlled by the monetary authorities, whereas velocity is exogenous. First, it is assumed that the announced fluctuation band around the central parity is perceived by market participants as fully credible. Perfect credibility implies that neither the fluctuation bands nor the central parity would be altered and that the exchange rate would remain inside the fluctuation band. Second, it is assumed that the monetary authorities only intervene when the exchange rate hits the upper or lower bound of the officially announced fluctuation band. The implication of the second assumption is that the exchange rate behaves within the fluctuation band as under a free float. Because velocity is assumed to follow a standard Wiener, or Brownian motion, process without drift[6] and because the money supply is considered constant under a free float (with the expected change in the exchange rate being equal to zero) the nominal exchange rate also follows a Brownian motion and depends proportionally on the fundamentals, i.e. velocity.

Under the assumptions sketched out above, the general solution of the model becomes the following:

$$e = f + A \cdot exp(\mu \cdot f) + B \cdot exp(-\mu \cdot f) \tag{2}$$

where A and B are constants, $\mu = \sqrt{2/\lambda \cdot \sigma_f^2}$, σ_f is the standard deviation of the fundamentals and λ denotes the elasticity of real money supply to the interest rate in the structural form of the monetary model. Equation (2) is composed of a linear and a non-linear part. The linear part, f, represents the solution for a free-float. However, the main results of the model, which came to be known as the *honeymoon effect* and *smooth pasting* are reflected in the non-linear part, $A \cdot exp(\mu \cdot f) + B \cdot exp(-\mu \cdot f)$. The honeymoon effect refers to the phenomenon that if the exchange rate is close to the weaker (stronger) edge of the band, the probability increases that the exchange rate will hit the edge, which automatically leads to interventions by the monetary authorities. As a consequence, the probability that the exchange rate appreciates (depreciates) is higher than the probability that it depreciates (appreciates). This is depicted in Figure 1. From this it follows that the exchange rate will be less depreciated (appreciated) given by the line TT than the level that would be given by the fundamentals alone (linear component of equation (2)) under a free float (45-degree line FF). Thus, this type of target zone model stabilises the

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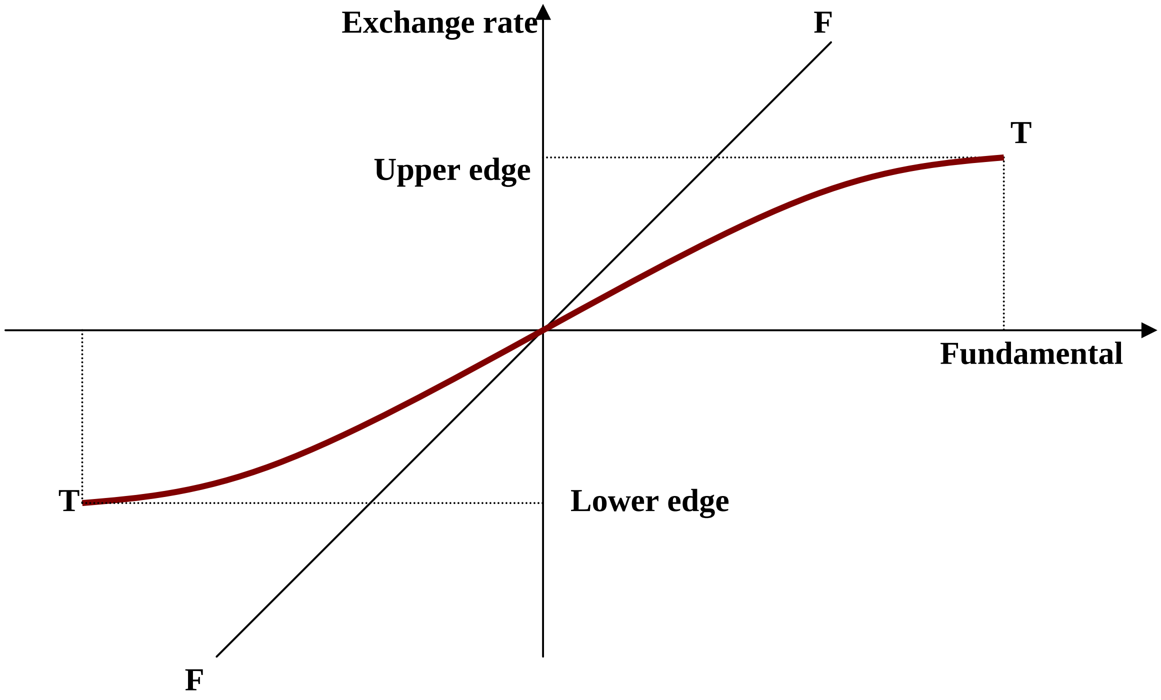
[6] This is indeed the continuous-time representation of a random walk.

exchange rate relative to its fundamentals within the fluctuation band. *Smooth pasting* refers to the phenomenon that the path of the exchange rate smoothes out on its way to the boundaries of the band and its slope becomes zero when it eventually hits the edge.

Figure 1. The Krugman Model



A crucial implication of the baseline Krugman model is that the exchange rate will spend more time close to the boundaries than inside the target zone. Consequently, the distribution of the exchange rate will be U-shaped between the upper and lower bounds. Lundbergh and Teräsvirta (2003) demonstrate for the case of Norway from 1986 to 1988 that provided the two main assumptions are satisfied, i.e. the target zone is perfectly credible and the monetary authorities intervene only at the edges of the target zone, the Krugman model is able to describe surprisingly well the exchange rate behaviour in Norway in the period considered.

2.2. Extensions of the Krugman Model[7]

Target zone exchange rate regimes may not be fully credible because the central parity may be realigned and the fluctuation bands widened. If realignment causes a shift in the band which does not overlap with the previous band, the exchange rate will jump. This may or may not be the case if there is an overlap between the old and new bands. Numerous realignments

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[7] For a very detailed presentation of the extensions, see e.g. Svensson (1992) and Kempa and Nelles (1999).

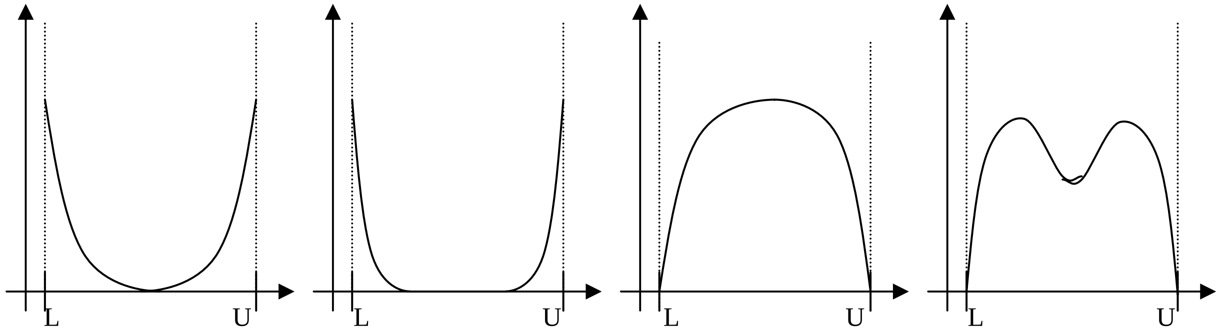
took place, for instance, within the ERM[8] and also in transition countries such as Poland and Hungary[9]. Given such discontinuities, a number of attempts have been made to relax the assumption of perfect credibility and allow for jumps in the central parity. Table 1 summarises the main features of the different extensions and Figure 2 gives the distribution of the exchange rate within the officially announced fluctuation bands.

Table 1. Overview of different models and their implications

	Prices	Credibility	Intervention	HM	SP	Distribution
Krugman (1991)	Flexible	Perfect	Marginal	K	K	U-shaped
Bertola and Caballero (1992)	Flexible	Exogenous realingment risk	Marginal			
Tristani (1994) Werner (1995)	Flexible	Endogenous Realingment risk	Marginal	<FF	<FF	U-shaped
Delgado and Dumas (1992)	Flexible	Perfect	Continuous intramarginal	<K	<K	Hump-shaped
Beetsma and Ploeg (1994)	Sticky	Perfect	Continuous Intramarginal	<K	<K	Hump-shaped
Bessec (2003)	Flexible	Perfect	Two regimes			Twin peak

Notes: HM= honeymoon effect, K denotes the honeymoon effect and smooth-pasting under the Krugman solution. <K (<FF) signals the respective effects being smaller than in the Krugman model (free float).

Figure 2. The distribution of the exchange rate within a target zone.



Krugman model

Endogenous realignment risk

Continuous intramarginal interventions

Two-regime interventions

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[8] Note that no realignment took place for Greece and Denmark in the ERM-2.

[9] In Hungary, the central parity was devalued 23 times between 1990 and 1995 (prior to the introduction of the crawling peg system). Within the framework of the crawling band regime in Poland, the central parity was devalued three times between 1991 and 1993 and was re-valued in 1996 (independently from the ongoing daily devaluations).

2.2.1. Imperfect credibility with exogenous realignment risk

Bertola and Caballero (1992) allow for exogenous realignment risk. The central parity (c), set to zero in the Krugman model is now considered to become part of the aggregate fundamental variable: $f = v - \Gamma + c$ where v is a stochastic term and Γ is the fundamental. The monetary authorities will defend the currency with probability (1-p) when it reaches the edges of the band and will proceed with realignment of the central parity with probability p. Realignment is assumed to be reflected in a shift of the band. The general solution of the model is now as follows:

$$e = f + A \cdot exp(\mu \cdot (f - c)) + B \cdot exp(-\mu \cdot (f - c)) \qquad (3)$$

The model with exogenous realignment risk implies that under certain circumstances (p>=0.5), both the honeymoon effect and smooth pasting disappear.

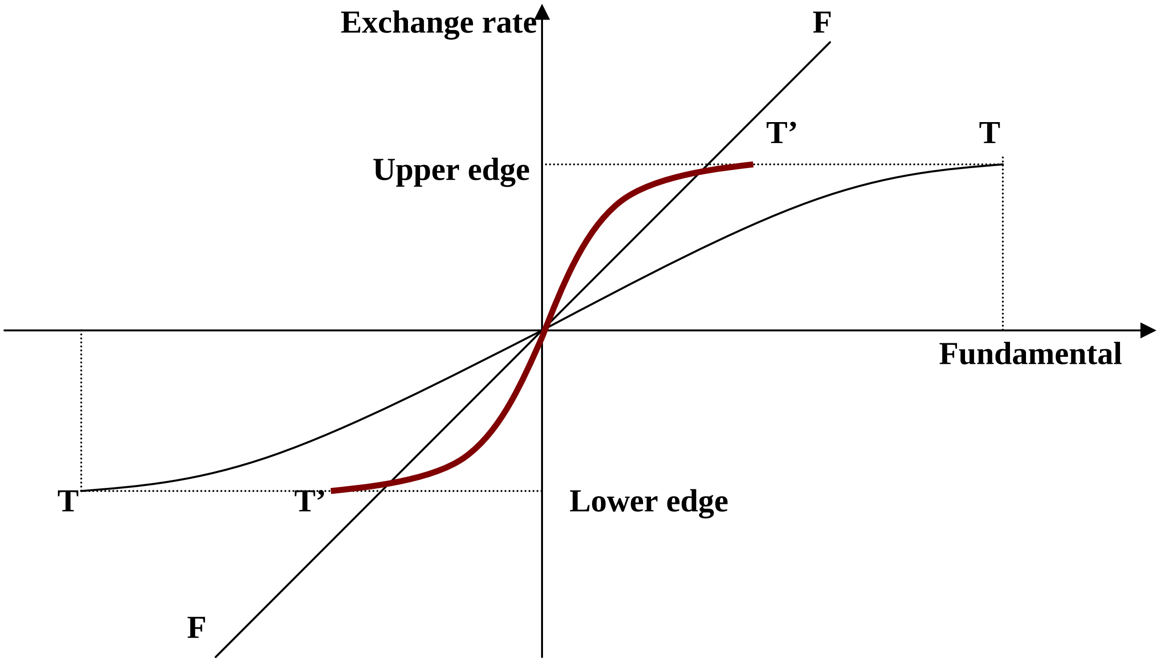
2.2.2. Imperfect credibility with endogenous realignment risk

Clearly, the fact that realignment risk is modelled as exogenous and that realignment only takes place when the exchange rate is at the edges of the band may be too restrictive and need not apply in reality. Tristani (1994) and Werner (1995) set out to model realignment risk as endogenous by assuming that the probability of realignment is a positive function of how far the exchange rate is located from the central parity - the larger the distance, the higher the probability of realignment. The general solution of their model is given by:

$$e - c = (f - c) \cdot (1 + \frac{\lambda \eta p}{w}) + A \cdot exp(\mu \cdot (f - c)) + B \cdot exp(-\mu \cdot (f - c)) \qquad (4)$$

where η, p and w stand for the size of realignment, the probability of a realignment (which is a function of the deviation from the central parity) and the width of the target zone, respectively. Figure 3 shows that a result of the model is that the S curve becomes steeper (line T’T’) when compared to the S curve obtained from the Krugman model (Figure 1.). This in turn implies an even stronger U-shaped distribution of the exchange rate within the band.

Figure 3. Endogenous Misalignment Risk



2.2.3. Perfect credibility with intramarginal interventions

The second main assumption of the Krugman model could fail because the monetary authorities may wish to intervene within the band (i.e intra marginal intervention) and not just in case the exchange rate hits the upper or lower edges of the band (marginal intervention). Mastropasqua et al. (1988) and Delgado and Dumas (1992) argue that about 85% to 90% of total interventions took the form of intramarginal intervention in the ERM before the crises in 1992 and 1993. Regarding the post-crisis period, the exchange rate never hit the upper or lower bound of any of the participating countries, which implies that all interventions were necessarily intramarginal.[10] As a result, it comes as no surprise that the distribution of the exchange rate is usually found to be hump-shaped for currencies participating in ERM and ERM-2, suggesting that the exchange rate spends most of the time in the middle of the band rather than close to the boundaries of the target zone.

Considerable effort has been made to build target zone models that are able to account for intramarginal interventions. For example, Delgado and Dumas (1992) modify the Krugman model so as to account for intramarginal interventions, which are assumed to take place

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[10] Brandner and Grech (2002) provide some summary statistics on the intervention activity of the participating countries' central banks after 1993.

continuously inside the target zone if the exchange rate deviates from the central parity. The solution provided by Delgado and Dumas (1992) is:

$$e = \frac{f + \alpha p f_0}{1 + \alpha p} + AM(\frac{1}{2\alpha p}, \frac{1}{2}, \frac{p(f_0 - f)^2}{\sigma_v^2}) + BM(\frac{1 + \alpha p}{2\alpha p}, \frac{3}{2}, \frac{p(f_0 - f)^2}{\sigma_v^2}) \frac{\sqrt{p}(f_0 - f)}{\sigma_v} \quad (5)$$

where M is the hypergeometric function and f_0 being the fundamental's value when the exchange rate is equal to the central parity. Figure 4 shows the main result of the model: although the honeymoon effect diminishes considerably (line T'T') when compared to the honeymoon effect under perfect credibility and marginal intervention, the exchange rate is nonetheless still less volatile than under free-float.[11] Similarly, smooth pasting is also substantially reduced in this set up because market agents know that monetary authorities have already intervened. If A and B are set to zero, the Delgado and Dumas solution collapses to $e = \frac{f + \alpha p f_0}{1 + \alpha p}$, which happens to be the case of managed floating without fixed boundaries. In such a setting, all interventions would qualify as intramarginal. The solution shows that the exchange rate is stabilised compared to the free-float position and interventions induce a mean reversion of the exchange rate towards the central parity (line F'F'). Put differently, even in the absence of a formal target zone-type of exchange rate arrangement, central bank interventions can stabilise the exchange rate relative to the case of a free-float.

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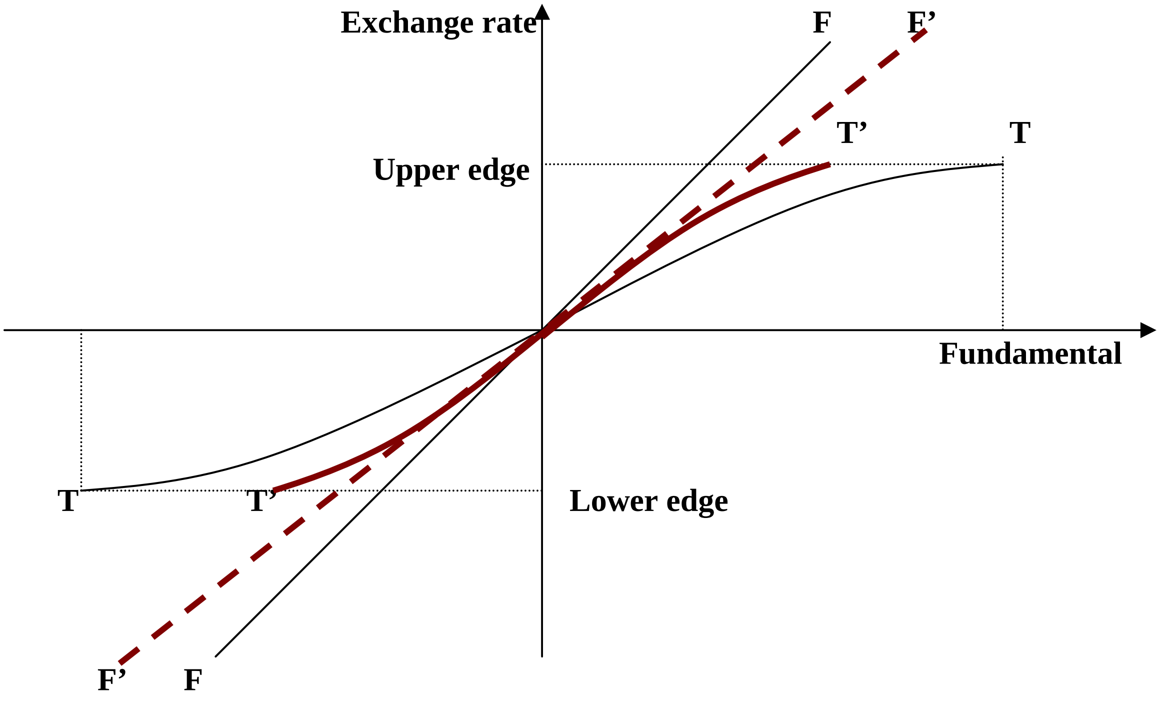
[11] Note that this is not necessarily the case in a multilateral target zone with intramarginal interventions. For example, Serrat (2000) shows that in such a setting , exchange rate volatility can be larger than under a free float.

Figure 4. Intramarginal Interventions



2.2.4. Sticky prices with intramarginal interventions

A major drawback of the models presented above is that they are based, without exception, on the flexible-price monetary model, which assumes that purchasing power parity (PPP) holds continuously. However, it is a well-established fact that PPP does not hold continuously[12], and therefore some kind of rigidities should be introduced into the modelling framework. Following the example of the Dornbusch overshooting model, Miller and Weller (1991) introduce sticky prices into the Krugman model. In addition to sticky prices, Beetsma and Ploeg (1994) complete the model with intramarginal interventions and show that sticky prices coupled with intramarginal interventions leads to a hump-shaped distribution of the exchange rate within the target zone.

2.2.5. Unofficial bands within the target zone

Bessec (2003) proposes that it is unlikely that monetary authorities would be willing to intervene continuously, independently of the distance of the exchange rate from the central parity. Instead, she argues that it is more likely that monetary authorities do not intervene in the

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[12] See e.g. Rogoff (1996) and MacDonald (1995,2004).

immediate neighbourhood of the central parity and allow the exchange rate to fluctuate in a given corridor around the central parity. Only if the exchange rate exits this corridor do the monetary authorities step in to intervene. This kind of regime can be described by the combination of the Krugman model and the Delgado and Dumas model. For example, consider e_U and e_L, which denote, respectively, the upper and lower bounds within the band beyond which the monetary authorities intervene in order to bring back the exchange rate to the central parity. The solution is thus a combination of the free-float Krugman solution, if $e_L \leq e \leq e_U$, and the Delgado and Dumas solution in case the exchange rate is below the lower bound ($e < e_L$) or above the upper bound ($e > e_U$)[13]:

$$e = \begin{cases} DELGADO-DUMAS\_solution & if \quad e > e_U \\ KRUGMAN\_free-float\_solution & if \quad e_L \leq e \leq e_U \\ DELGADO-DUMAS\_solution & if \quad e < e_L \end{cases} \tag{6}$$

Notice that the upper and lower regimes need not have equal parameters because the monetary authorities may have asymmetric preferences. Table 1 hereafter summarises the main features of the different models and the corresponding exchange rate distributions are plotted in Figure 2.

Although the theoretical model suggests that it is only intramarginal interventions by the monetary authorities that create a band of inaction, it is worth noting that, in practice, a large number of other factors may also be responsible. Such factors are the ability of the monetary authority to stabilise the national currency by other policy actions. Second, moral persuasion and appropriate communication towards the markets are also likely to influence the exchange rate. More particularly, market expectations and the credibility of the monetary authorities are likely to play a big role. If the monetary authorities are credible, it may suffice to intervene in very small amounts in the market to persuade agents that the exchange rate will remain stable. Or, even better, the possibility of market intervention and a well established track record of the monetary authorities may bring about relative exchange rate stability. Finally, expectations may

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[13] Bartolini and Prati (1999) develop a different model that may be able to capture such behaviour. In particular, they argue that there is a narrow, unofficial band within the officially announced band. The narrow band is soft in that its boundaries are not only not publicly announced but also they change given that a moving average rule based on past values of the exchange rate is assumed. This set up is indeed very close to reality given that the European Monetary Institute and the ECB evaluated the criterion on exchange rate stability on the basis of a 10-day moving average.

also be stabilised because of fundamentals becoming increasingly stable, or because of expected future developments of the fundamentals. This kind of effect may have played a special role in the run-up to the euro in the late 1990s, when the markets expected a high degree of macroeconomic convergence to occur across countries. Therefore, the band of inaction could be viewed as a band where the exchange rate dynamics resemble a random walk process whereas outside the band, the above factors can result in the exchange rate mean reverting. In the remainder of the paper, when using the expression 'band of inaction', we have this broader interpretation in mind.

3. Econometric Issues: The SETAR-GARCH model

In this section, we propose a simple non-linear time series model with local non-stationary behaviour but overall ergodic characteristics, which is a discrete-time representation of the mixed-solution model proposed by Bessec (2003). The model aims to detect the non-stationary behaviour of the exchange rate within an official band (ψ_2, ψ_1), when it stays within the band of inaction[14] around the officially announced central parity, while allowing for global mean reversion towards the band of inaction contemplated by the monetary authorities. The specification we propose is a simple three-regime self-exciting threshold autoregressive (SETAR) model with a central band in which the variable behaves like a unit root process.[15] The errors in the specification have a simple GARCH (1,1) structure in order to account for the time-varying variance and volatility clustering observed in the data.

The specification of the model is the following,

$$\Delta y_t = \begin{cases} \chi_0 + \lambda_1 y_{t-1} + \sum_{k=1}^{K} \chi_k \Delta y_{t-k} + \varepsilon_t & \text{if } y_{t-1} \geq \phi_1 \\ \delta_0 + \sum_{k=1}^{K} \delta_k \Delta y_{t-k} + \varepsilon_t & \text{if } \phi_1 \geq y_{t-1} \geq \phi_2 \\ \pi_0 + \lambda_2 y_{t-1} + \sum_{k=1}^{K} \pi_k \Delta y_{t-k} + \varepsilon_t & \text{if } \phi_2 \geq y_{t-1} \end{cases} \qquad (7)$$

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[14] In practice, there are a number of factors that may lead to the emergence of a band of inaction, as explained in section 2.

[15] The SETAR-GARCH model proposed presents a more parsimonious specification than the STAR parametrization in Lundbergh and Teräsvirta (2003), and appears as a special case of the latter if the thresholds correspond to the official target zone bands. In our modelling strategy, however, we allow for an intramarginal band of inaction whose limits need not correspond to the officially stated ones, and that is actually estimated.

where the error term, ε_t, is assumed to follow a GARCH (1,1) process,

$$\varepsilon_t \Big| I_t \quad N(0,\sigma_t)\,,$$

$$\sigma_t^2 = \gamma + \alpha \cdot \varepsilon_{t-1}^2 + \beta \cdot \sigma_{t-1}^2\,, \tag{8}$$

where I_t refers to the information set available in period t. Notice that if $\lambda_i \in (-1,0)$, $i=1,2$, for suitable values of χ_0 and π_0, y_t will present overall mean reverting features to the band (ϕ_1 , ϕ_2), which is assumed to be contained in the official band (ψ_2, ψ_1). Inside the band, however, the variable behaves as a unit root process with GARCH errors. A homoskedastic version of this model is used in Bessec (2003) to assess the dynamics of the exchange rate of selected countries within ERM.

We intend estimating the model given by (7) - (8) in the following way. For a given series y_t , the model is estimated setting the values of ϕ_1 and ϕ_2 to actual realizations of y_t in the sample (say starting with the tenth and ninetieth percentile of the empirical distribution of y_t). The process is repeated for all combinations of ϕ_1 and ϕ_2 corresponding to realized values (after ensuring that a minimal percentage of the observations falls in the central band) and the pair (y_1 , y_2) corresponding to the model with a minimal sum of squared residuals is chosen as the estimator of (ϕ_1,ϕ_2). Given the estimates of the threshold values, which are constant over time, and which delimit the band, the estimation of the full model is straightforward using maximum likelihood methods.[16]

In our analysis, we obtain the estimates for the thresholds that define the band using a grid search over the realized values of y_t after trimming 10% in the extremes of the empirical distribution of y_t. The grid search was carried out at 5% steps, ensuring that at least 20% of the observations fall in the nonstationary regime defined by the band.[17]

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[16] The optimal lag length for the autoregressive component is determined using the Schwarz information criterion.

[17] This means that for both the lower and the upper bound threshold, the search is performed from the 10th percentile to the 90th percentile of the distribution. This is much more general than what is done, for instance, in Bessec (2003) who searches from the 5th to the 35th percentile of the distribution for the lower bound threshold and from the 70th to the 95th percentile for the upper bound threshold.

An important issue that needs to be taken into account explicitly is how to test the significance of the the simple unit root against non-linear model.[18] Due to the fact that the threshold parameters ϕ_1 and ϕ_2 are not identified under the null hypothesis of a linear unit root process with GARCH errors, the usual likelihood ratio test statistic for testing this hypothesis against the alternative of a SETAR model such as (7)-(8) does not have a standard limiting distribution (for literature on this problem, see Andrews and Ploberger, 1994, Hansen, 1996, 2000; Caner and Hansen, 2001, consider the problem when the underlying stochastic process has a unit root). We therefore intend carrying out the test using a bootstrap procedure in the spirit of Hansen (2000) and Caner and Hansen (2001). Let T be the sample size. First, we compute the standard likelihood ratio (LR) test statistic,

$$LR = 2(\log L_{TAR} - \log L_{UR}),$$

where L_{TAR} is the likelihood of the model given by (7)-(8) and L_{UR} is the likelihood of the linear unit root model given by

$$\Delta y_t = \theta_0 + \sum_{k=1}^{K} \theta_k \Delta y_{t-k} + \varepsilon_t, \tag{9}$$

where the error term is assumed to follow a GARCH (1,1) process such as the one given in (8). With the estimated parameters of model (9) (including the estimated GARCH parameters), we simulate T observations of y_t under the null of linearity. A linear unit root model and a SETAR model are estimated using these simulated data, and the likelihood ratio test statistic, LR_n^S, is computed.[19] This procedure is repeated N times and the bootstrap p-value for the null of a unit root process against the alternative of a SETAR model such as (7)-(8) is given by

$$p_{LR} = \sum_{n=1}^{N} I(LR > LR_n^S) / N,$$

where $I(\cdot)$ is the indicator function that takes the value of 1 if the argument is true and zero otherwise. That is, the p-value corresponds to the proportion of simulated likelihood ratio test

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[18] To a certain extent, the choice of the unit root model as the null hypothesis could be considered arbitrary, but it appears as a natural model to which the SETAR-GARCH model should be compared if we consider the time series properties of the exchange rate series.

[19] Given that it is not ensured that the replicated data will actually cross the estimated thresholds, the SETAR models for the simulated data are estimated setting the thresholds at the quantiles of the replicated series corresponding to the estimated thresholds obtained with the actual data.

statistics that exceed the value of the test statistic computed with the actual data.[20] The bootstrap test was carried out using *N*=500 replications.

4. Data Issues

4.1. Data Description

The dataset contains average daily deviations of nominal exchange rates vis-à-vis the prevailing central parity[21]. The currencies considered are of countries which participated in the system: Austria, Belgium, Denmark, Finland, France, Germany, Ireland, Italy, the Netherlands, Portugal and Spain. Although the ECU was the official currency of the ERM, it is widely acknowledged that ERM was centred around the German mark. Therefore, we use exchange rate series vis-à-vis the German mark and these data were obtained from the Bundesbank.[22] In its convergence report of 1998, in the run-up to the euro, the European Commission used the median currency[23] as the benchmark currency for the assessment of the criterion on exchange rate stability. To our knowledge, the median currency has not been used in any previous study aimed at testing target zone models. Thus, we also look at the deviations vis-à-vis the median currency.[24] For the German mark, the time period is the post-1993 crisis period: it begins in September, 1 1993 and ends in February, 28 1998. Although Austria officially entered the ERM after its entry to the EU in 1995, the period from 1993 is investigated for this country because it

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[20] Notice that the bootstrap test used is a simple example of the non-pivotal bootstrap testing procedures described in Pesaran and Weeks (2001) for non-nested model testing.

[21] Notice that the central parity of the Spanish and the Portuguese currencies were devalued vis-à-vis the German mark on March 6, 1995 by 7% and 3.5%, respectively. That is, the deviations from the central parity are obtained using the central parity prevailing prior to March 6, 1995 and then the devalued central parity from March 6, 1995 onwards. The Irish pound was revalued by 6% on March 16, 1998. This realignment is, however, outside the period investigated in this paper.

[22] See appendix for Datastream codes.

[23] "(…) median currency is (the currency) which has an equal number of currencies above and below it within the grid at the official ecu fixing on any given day " (European Commission, 1998, p. 123). In more practical terms, for each participating country, the deviation of the bilateral exchange rate against the ECU from its official ECU central parity is determined. Subsequently, the countries are ranked and the 6th out of the 11 participating currencies is chosen in the ranking. It should be noted that the median currency is chosen on a daily basis, implying that the currency chosen as the median currency could have changed day-by-day.

[24] In addition to the ecu, the German mark and the median currency, three other benchmarks could be, in theory used: (a) the strongest currency of the system, (b) bilateral exchange rates with no benchmark currency and (c) the synthetic euro.

maintained a tight peg with respect to the German mark for this period[25]. Using the extended data for Austria allows us to investigate whether or not the ERM entry provoked a change in exchange rate behaviour. The series are shorter for Finland and Italy, which joined/re-entered ERM, respectively, on October 15 and November 25, 1996. For the median currency,[26] the series runs from March 1, 1996 to February 28, 1998.

For ERM-2, only Denmark is considered and deviations vis-à-vis the central parity against the euro are taken for the period January 4, 1999 to April 28, 2004.[27]. The source of the data are the ECB.[28]

Finally, we also analyse the exchange rate behaviour of four CEECs. The exchange rate against the euro is studied for the Czech Republic, Hungary, Poland and Slovakia. For the Czech Republic and Slovakia, the period starts in January 1, 1999 when the euro was introduced. For these two currencies, the deviation against the period average is used because they have been having managed floating. The period begins on March 1, 2000 (close to the outset of free floating, April 12, 2000) for Poland and on May 4, 2001 (the widening of the bands to +/-15%) for Hungary. On June 4, 2003, the central parity was devalued by some 2.26%. As in the case of Portugal and Spain, the deviations vis-à-vis the pre- and the post-devaluation parities are determined. For all four countries, the sample runs to April 28, 2004. Data are drawn from the ECB for the Czech Republic and Poland, from the National Bank of Hungary for Hungary and from Datastream for Slovakia.

4.2. A Preliminary Analysis of the Data

The distribution of the exchange rate within the target zone are estimated using the Epanechnikov kernel density function for 1993 to 1998 (and 1996 to 1998 for Finland and Ireland) vis-à-vis the German mark, for 1996 to 1998 for the median currency and for 1999 to 2004 for the euro. Figures reported in Appendix 2 reveal two important features of the data.

First, a considerable part of the distributions exhibit a double-hump shape. This is especially the case for the Austrian Schilling, the Danish koruna, the Dutch Gulder, the French frank, the Irish

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[25] As a matter of fact, Austria had a pegged exchange rate regime vis-à-vis the German mark since the late 1970s. Austria entered the ERM at the fixed peg exchange rate regime it unilaterally maintained beforehand.

[26] We are grateful to André Verbanck from the European Commission (DG ECFIN) for providing us with these data series.

[27] Greece is excluded because of its ephemeral stay in ERM and ERM-2.

pound and the Portuguese escudo vis-à-vis the deutschemark. With the exception of the Spanish peseta and the Dutch gulder, all currencies have a hump shaped distribution vis-à-vis the median currency.

Brandner and Grech (2002)[29] report kernel density estimations for DM purchases and sales for 6 countries, namely Belgium, Denmark, Spain, France, Ireland and Portugal. Although the period investigated includes some of the turmoil in August 1993,[30] their graphs match remarkably well with our kernel estimates reported in the Appendix for the period from 1993 to 1998. For Belgium, they show increase DM sales at the central parity whereas DM purchases occurred at about 0.2% -0.3% in the stronger side of the fluctuation band. For Denmark, the monetary authorities proceeded with increased DM purchases at 2% from the central parity in the weaker side and sold DM at the central parity. For France, DM purchases and sales are reported to take place respectively at about 5% and 1% away from the parity on the weaker side. Regarding Ireland, the monetary authorities reportedly sold DM at 5% from the parity on the weaker side and bought DM at 10% from the parity on the stronger side. For Portugal, the interventions at about 4% from the central parity on the weaker side and at 2% from the parity on the stronger side are also broadly in line with exchange rate developments. As for Spain, DM sales are found to occur mostly at 10% from the central parity on the weaker side. A reason for this finding is that Brander and Grech (2002) start the period in August 1993 during the crisis during.

For the series against the euro, a marked twin peaked distribution is to be observed for the Czech koruna, and to a lesser extent for the Danish and Slovak currencies. This provides us with some preliminary evidence on the presence of non-linearity of the type described by the SETAR model.

The second characteristic of the data is the asymmetric distribution. For the ERM, a large part of the distribution of the Austrian, Danish, French and Portuguese currencies is located on the weaker side of the band. By contrast, the exchange rate was most often on the stronger side of the band for Denmark, Finland and the Netherlands. This holds true, in particular, for the end

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[28] See appendix for Datastream code.
[29] Brandner and Grech (2002), p. 23.
[30] Their sample covers August 2, 1993 to April 30, 1998 while our period spans from September 1, 1993 to February 28, 1998.

of the period under study. Regarding the euro series, both countries with formal target zone arrangements, namely Denmark and Hungary, had their currencies predominantly on the stronger side of the band.

5. Empirical results

The SETAR – GARCH(1,1) model described earlier was applied first to the exchange rate series vis-à-vis the German mark, for countries participating in ERM. We first took the whole post-1993 (after the ERM crisis) until the announcement of the final conversion rates in early 1998. Then, the estimations were repeated by decreasing the period by one year in each step until the beginning of the reference period taken for the convergence report of the European Commission and the European Monetary Institute is reached.[31] Subsequently, the period was shortened by yearly steps, while maintaining the starting date fixed.[32] Finally, the two subperiods determined by the devaluation of the central parity are analysed for Portugal and Spain.[33]

From the results reported in Table 2a and Table 2b, a number of interesting points emerge. First, the analysis of the estimated upper and lower bounds of the band of inaction shows that there are two groups of countries. The first group consists of countries which have very narrow bands for the entire period. For instance, for the whole period, the absolute bandwidth is 0.05% for Austria, 0.35% for Belgium and 0.15% for the Netherlands.[34] The scale of these ranges remains largely unchanged for the subperiods. This is not surprising given the fact that these countries shadowed very narrowly the monetary policy of the Bundesbank and sought to stabilise their currencies relative to the German mark accordingly. The results for Austria deserve special attention. Notwithstanding the fact that Austria formally joined the ERM only in 1995, the estimated upper and lower bounds are very stable over time lending, supporting the proposition that exchange rate behaviour was not affected by Austria's entry into the ERM.

The second group, comprising the rest of the countries has considerably larger bands. The absolute width of the estimated band was 3.66% for Portugal, 1.28% for France, 3.46% for Denmark, about 4% for Spain and roughly 10% for Ireland for the period from 1993 to 1998.

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[31] The following three periods were considered: September 1, 1994 to February 28, 1998; September 1, 1995 to February 28, 1998; March 1, 1996 to February 28, 1998.

[32] The following three periods were considered: September 1, 1993 to September 1, 1997; September 1, 1993 to September 1, 1996; September 1, 1993 to September 1, 1995.

[33] September 1, 1993 to March 5, 1995 and March 6, 1995 to February 28, 1998.

With the exception of Ireland, the estimated bandwidth decreases towards the end of the period: below 1% for Denmark, France and Spain, and close to 2% for Portugal. For Ireland, the estimated bandwidth rises from about 4% from 1993 to 1995 to nearly 8% from 1993 to 1997 and then drops to 2% at the end of the period (1996 to 1998). Note that Italy and Finland, which entered ERM only in 1996, had bandwidths comparable to that in Belgium and the Netherlands.[35]

The second observation regards the position of the estimated band of inaction relative to the officially announced central parity. Regarding the narrow-band countries, the estimated effective fluctuation band is mostly located symmetrically from the central parity for Austria, and mainly on the stronger side for Belgium. In the Netherlands, the whole band is always located on the stronger side. Note also that the Italian and Finnish currencies are also found to be situated on the stronger side. For the second group of countries, we note that the boundaries of the estimated exchange rate bands are mostly located on the weaker side of the official target zone for Denmark and France. For both countries, the narrowing down of the band manifested itself with the estimated weaker threshold moving closer to the central parity. Although the Portuguese escudo was located on the weaker side at the beginning of the period, the estimated band shifted entirely to the stronger side by the last period. For Ireland, Portugal and Spain, the estimated band was on the weaker side from the official parity and moved to the stronger side of the official fluctuation band by the end of the period.[36]

Third, the estimated autoregressive terms (λ_{upper}; λ_{lower}), indicating mean reversion to the upper and lower edges (ϕ_{upper}; ϕ_{lower}), have in the majority of cases the expected negative sign, but they are not statistically significant in a number of cases. Generally, they are more significant for the entire period and then become less so towards the end of the period. However, a more

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[34] Notice that the estimation method ensures that at least 20% of the observations fall in the band of inaction.

[35] Our results can be directly compared with those reported in Bessec (2003), who uses monthly data for the Belgian, Danish, French, Irish and Dutch currencies against the German mark. Bessec (2003) estimated a time-varying threshold model for the period from 1979 to 1998 with the threshold changing in 1993 when the fluctuation band widened. The comparison of the threshold obtained for the post-1993 shows that our method for searching the thresholds, coupled with the use of daily data, gives more precise threshold values. Although the thresholds are very similar for Belgium, our thresholds differ greatly from the ones reported in Bessec(2003), Table 5, for the other countries.

[36] Our results are at odds with the findings of Bessec (2003) - Table 5, since she finds that both the upper and lower mean reversion coefficients are always significant for all countries and because her estimated coefficients are much larger in absolute terms than ours.

detailed examination of the results indicates considerable heterogeneity across countries. For Austria, the mean reversion to the band detected for the whole period seems to be unstable because the estimated coefficients are systematically insignificant for the sub-periods. Similarly, no significant band mean reversion could be found for Italy.

For the Netherlands and Spain, both coefficients are negative and significant for most of the sub-periods. With regard to Spain, two different regimes are hidden behind the band mean reversion behaviour detected for the whole period if the time of the devaluation of the central parity is considered as the dividing line for the two sub-periods. The estimated band is situated from 4.04% to 8.34% away from the official central parity on the weaker side before the devaluation and is located from 0.99% on the stronger side from the official parity to 1.74% on the weaker side from the official parity.

For some countries, the mean reversion to the band seems to be one sided. For instance, there is mean reversion only towards the estimated upper (stronger) bound in Belgium, Denmark and Finland, and only towards the lower edge of the estimated band for France and Portugal. This could be an indication of the presence of different pressures for different countries. In Belgium, and Finland, the estimated upper and lower bounds are mostly on the stronger side. Thus, the market situation may have been one to avoid excessive appreciation. By contrast, in France, the estimated lower boundary to which the mean reversion occurs happens to be on the weaker side. The analysis of the sub-periods shows, however, that there is two-sided mean reversion from 1993 to 1997, and one-sidedness is the feature of the period from 1996 to 1998. Hence, to counteract depreciation pressures and to bring the lower bound closer to the central parity may have been typical for these countries. The fact that the coefficients become insignificant for the period from 1996 to 1998 could suggest that by that time, non-linearity diminished and the exchange rate started behaving like a linear process in the face an increased credibility during the run-up to the euro. The decrease in non-linearity is also confirmed by the p-values, which show that in some cases the three-regime SETAR model is no better than the linear unit root specification.

Fourth, the ARCH and GARCH terms (α and β) of the conditional variance equation are correctly signed ($\alpha > 0; \beta > 0$) and statistically significant at the 1% level for almost all cases. At the same time, the sum of these two parameters is very close to, or larger, than unity, implying that the error terms are integrated GARCH processes for most of the series. Interestingly, the α coefficient is found to be insignificant for the Austrian schilling against the German mark for 1996 to 1998 and for the Spanish peseta vis-à-vis the median currency. Given that β is very close to unity, especially for Spain, it may lend support to the hypothesis of constant conditional variance (for insignificant estimates of γ) or linearly changing variance (if γ is significant) in a deterministic fashion.

The results obtained on the basis of the median currency for the period from 1996 to 1998 are reported in Table 3. They appear similar to those noted for the German mark. The estimated upper and lower bounds, the width and the location of the band for the median currency are comparable to those obtained using the German mark. However, it is possible to detect more non-linearity than when using the German mark. This is especially the case for Austria and Belgium. Also, the median currency approach allows us to look at Germany, for which the SETAR model performs remarkably well.

Table 2a. Model estimates using the German mark

	$period$	k	ϕ_{upper}	ϕ_{lower}	λ_{upper}	λ_{lower}	α	β	$p-value$
ATS_DEM	1993-1998	1	0.02%	-0.03%	-0.0703***	-0.0785**	0.0383***	0.9527***	0.002
ATS_DEM	1994-1998	2	0.02%	-0.03%	-0.1307***	-0.0826**	0.0399***	0.9383***	0.000
ATS_DEM	1995-1998	1	0.02%	-0.03%	-0.1235**	-0.1075	0.0505***	0.9131***	0.000
ATS_DEM	1996-1998	1	0.00%	-0.03%	0.0308	-0.1056	0.0341	0.8711***	0.000
ATS_DEM	1993-1995	1	0.04%	0.02%	-0.0036	-0.0118	0.0465*	0.9073***	0.002
ATS_DEM	19931996	1	0.04%	0.00%	-0.0276	-0.0544**	0.0582***	0.9074***	0.000
ATS_DEM	1993-1997	1	-0.02%	-0.04%	-0.0101	0.0021	0.0408***	0.9474***	0.000
BEF_DEM	1993-1998	7	0.30%	-0.05%	-0.126***	-0.011	0.0931***	0.903***	0.038
BEF_DEM	1994-1998	1	0.26%	-0.06%	-0.0924***	-0.0016	0.0771***	0.9161***	0.002
BEF_DEM	1995-1998	1	0.29%	-0.07%	-0.0847**	0.0808	0.0172***	0.9711***	0.066
BEF_DEM	1996-1998	1	0.17%	-0.07%	0.0167	0.039	0.0144*	0.9728***	0.078
BEF_DEM	1993-1995	7	0.13%	-1.12%	-0.0667*	0.0423	0.446***	0.5866***	0.004
BEF_DEM	19931996	8	0.27%	0.04%	-0.0834**	-0.0001	0.1259***	0.8795***	0.014
BEF_DEM	1993-1997	7	0.27%	-0.04%	-0.1021***	-0.0152	0.1082***	0.8949***	0.058
DKK_DEM	1993-1998	1	0.09%	-3.55%	-0.0856*	0.0193**	0.1323***	0.8794***	0.002
DKK_DEM	1994-1998	1	0.01%	-2.46%	-0.0905**	-0.0736***	0.135***	0.8767***	0.000
DKK_DEM	1995-1998	1	-0.06%	-1.21%	-0.0703**	-0.0347	0.0649***	0.924***	0.000
DKK_DEM	1996-1998	1	-0.33%	-1.19%	-0.0723***	-0.0677	0.053***	0.9448***	0.000
DKK_DEM	1993-1995	1	-2.61%	-3.27%	0.0149	0.0011	0.1669***	0.846***	0.018
DKK_DEM	19931996	1	-2.06%	-3.55%	-0.0309**	0.0207**	0.1579***	0.8605***	0.004
DKK_DEM	1993-1997	1	-0.03%	-3.27%	-0.1429**	-0.0024	0.136***	0.8767***	0.004
NGL_DEM	1993-1998	3	0.52%	0.37%	-0.0745***	-0.0029	0.073***	0.9307***	0.002
NGL_DEM	1994-1998	1	0.54%	0.31%	-0.0824***	-0.0191**	0.0986***	0.9066***	0.000
NGL_DEM	1995-1998	1	0.57%	0.01%	-0.0675**	-0.1395**	0.1178***	0.8917***	0.008
NGL_DEM	1996-1998	1	0.45%	0.24%	0.0432**	-0.0289***	0.1274***	0.8828***	0.002
NGL_DEM	1993-1995	3	0.60%	0.37%	-0.0988*	-0.1278**	-0.0056	0.9981***	0.006
NGL_DEM	19931996	1	0.65%	0.60%	0.0233	-0.0119	0.0577***	0.9302***	0.000
NGL_DEM	1993-1997	1	0.52%	0.25%	-0.0693***	-0.0341	0.0647***	0.9159***	0.002
FRF_DEM	1993-1998	1	-0.69%	-2.01%	0.0016	-0.0219***	0.1014***	0.9066***	0.032
FRF_DEM	1994-1998	1	-0.74%	-1.88%	-0.0002	-0.0122	0.1048***	0.9058***	0.006
FRF_DEM	1995-1998	1	-0.76%	-2.71%	-0.0009	-0.0599	0.0759***	0.9244***	0.028
FRF_DEM	1996-1998	1	-0.73%	-1.61%	0.0008	-0.1815**	0.07***	0.9304***	0.004
FRF_DEM	1993-1995	1	-2.22%	-4.33%	-0.003	-0.0831	0.1032***	0.9024***	0.010
FRF_DEM	19931996	1	-2.20%	-4.74%	0.0017	-0.1561**	0.0974***	0.9011***	0.010
FRF_DEM	1993-1997	1	-0.90%	-3.86%	-0.0796***	-0.0777***	0.1012***	0.8989***	0.014

Notes: k is the lag length used in the AR process, ϕ_{upper} and ϕ_{lower} represent the upper (stronger) and lower (weaker) limits of the band of inaction, towards which the exchange rate exhibits mean reversion and positive (negative) figures refer to a position on the stronger (weaker) side of the officially announced band; λ_{upper} and λ_{lower} stand for the autoregressive coefficients, which capture mean reversion; α and β are the ARCH and GARCH coefficients from the conditional variance equation. *, ** and *** indicate significance at the 10%, 5% and 1% levels, respectively. The p-value is for the null of an AR against an alternative of a SETAR.

Table 2b. Model estimates using the German mark

	$period$	k	ϕ_{upper}	ϕ_{lower}	λ_{upper}	λ_{lower}	α	β	$p-value$
IEP_DEM	1993-1998	1	4.75%	-5.35%	-0.0655***	-0.0346	0.1018***	0.8012***	0.000
IEP_DEM	1994-1998	1	5.99%	-4.49%	-0.0756***	-0.0612*	0.132***	0.7986***	0.004
IEP_DEM	1995-1998	1	9.03%	6.60%	0.1883***	0.0059	0.1923***	0.7628***	0.000
IEP_DEM	1996-1998	4	8.90%	6.55%	0.0595	0.0052	0.2956***	0.6569***	1.000
IEP_DEM	1993-1995	1	-0.39%	-4.47%	-0.0055	-0.0828*	0.0545***	0.9239***	0.006
IEP_DEM	19931996	1	-0.37%	-3.04%	-0.0114	-0.0336*	0.0541***	0.9321***	0.004
IEP_DEM	1993-1997	1	3.89%	-4.06%	-0.059***	-0.0488*	0.0288***	0.9566***	0.006
ESP_DEM	1993-1998	1	-0.99%	-3.72%	-0.0473***	-0.0805***	0.0942***	0.9186***	0.000
ESP_DEM	1994-1998	1	0.83%	-5.70%	-0.0628***	-0.102***	0.1257***	0.8968***	0.004
ESP_DEM	1995-1998	1	1.04%	0.21%	-0.0223	-0.0103	-0.0017***	0.9986***	0.038
ESP_DEM	1996-1998	1	1.16%	0.84%	-0.024	-0.0125	0.1015***	0.9016***	0.000
ESP_DEM	1993-1995	1	-1.75%	-7.99%	-0.0664	-0.5411***	0.1319***	0.8391***	0.010
ESP_DEM	19931996	1	-1.60%	-6.44%	-0.0237*	-0.1449***	0.2226***	0.7174***	0.018
ESP_DEM	1993-1997	1	0.70%	-4.03%	-0.0665***	-0.078***	0.1081***	0.8963***	0.000
ESP_DEM	Pre real	1	-4.04%	-8.34%	-0.0988***	-0.4876***	0.2962***	0.7747***	0.004
ESP_DEM	Post real	1	0.99%	-1.74%	-0.0461**	-0.0815***	0.0138***	0.9813***	0.000
PTE_DEM	1993-1998	1	-0.08%	-3.74%	-0.0031	-0.2597***	0.104***	0.9069***	0.002
PTE_DEM	1994-1998	1	-0.32%	-3.32%	-0.0023	-0.1757***	0.1092***	0.9024***	0.008
PTE_DEM	1995-1998	1	1.76%	1.14%	-0.0553	-0.0112*	0.0734***	0.927***	0.018
PTE_DEM	1996-1998	1	1.89%	-0.26%	-0.0694*	0.0016	0.0821***	0.9204***	0.016
PTE_DEM	1993-1995	1	-3.69%	-4.52%	-0.0088	-0.7588***	0.1594***	0.8379***	0.000
PTE_DEM	19931996	1	-0.79%	-3.88%	-0.1195	-0.3029***	0.1065***	0.8947***	0.000
PTE_DEM	1993-1997	1	0.09%	-3.88%	-0.0328**	-0.3086***	0.1037***	0.8937***	0.000
PTE_DEM	Pre real	1	-3.28%	-4.62%	-0.0145	-0.0916	0.209***	0.8215***	0.000
PTE_DEM	Post real	1	-0.31%	-1.86%	-0.0019	-0.0977***	0.0649***	0.9354***	0.010
ITL_DEM	1996-1998	1	1.37%	0.99%	-0.0615	-0.0306	0.1771***	0.8302***	0.040
FIM_DEM	1996-1998	1	1.97%	1.60%	-0.2884***	-0.005	0.2269***	0.7971***	0.008

Notes: as for Table 2a.

Table 3. Model estimates using the median currency,
March 1, 1996 to February 28, 1998

	k	ϕ_{upper}	ϕ_{lower}	λ_{upper}	λ_{lower}	α	β	$p-value$
ATS_MED	2	-0.02%	-0.28%	-0.5608***	-0.0903	0.4342***	0.701***	0.002
BEF_MED	2	0.00%	-0.29%	-0.0712***	-1.2519***	0.3596***	0.4464***	0.004
NLG_MED	2	0.39%	0.00%	-0.0055	0.0005	0.4888***	0.4986***	0.004
DKK_MED	8	-0.29%	-1.23%	0.0081	-0.2593	0.208***	0.8211***	0.000
DEM_MED	3	-0.04%	-0.26%	-0.7665***	-0.3688***	1.0702***	0.3854***	0.000
FRF_MED	1	-0.74%	-1.02%	-0.0186**	-0.0137	0.2769***	0.769***	0.002
ESP_MED	1	1.09%	0.59%	-0.0424	-0.0195	-0.0043	1.0006***	0.000
PTE_MED	1	1.73%	0.58%	-0.0633	-0.0694***	0.1447***	0.8717***	0.002
IEP_MED	1	9.18%	6.80%	0.2163***	0.0001	0.197***	0.7524***	0.000
ITL_MED	1	0.94%	0.35%	-0.1091	-0.0812	0.1682***	0.8416***	0.010
FIM_MED	1	1.28%	0.86%	-0.0866***	-0.0659	0.2005***	0.8262***	0.004

Notes: as for Table 2a. The period begins on October 4, 1996 for Finland and on November 15, 1996 for Italy.

Finally, we now turn to the estimation results for the currencies expressed against the euro, for the period 1999 to 2004. During the period when the Danish krone was in ERM-2, the estimated bandwidth decreases further from the 0.8% figure, reported above, in the original ERM period to 0.4%. However, the mean reversion coefficient bears the correct sign and is significant only for the lower bound.

For the CEE countries against the euro we find the following. Hungary is an interesting case because on May 4, 2001, it widened the fluctuation bands around the central parity.[37] From May 2001 to April 2004, the estimated upper and lower thresholds were located, respectively, 11% and 6.76% away from the central parity (both on the stronger side of the official fluctuation band of ±15%). The mean reversion coefficients have a negative sign and are significant. This would seem to give strong support for the fact that exchange rate policy targeted a narrow band, which it judged compatible with the inflation target. However, this is only part of the story. On June 4, 2003, the central parity was devalued by some 2.26%, which triggered considerable depreciation of the currency inside the band. Looking at the period from May 4, 2001 to June 3, 2003 reveals that until the devaluation of the central parity, mean reversion was significant only on the upper (stronger) threshold. So, mean reversion to the lower threshold detected for the whole period may refer to the post-devaluation period.

According to the statement of the Monetary Council of the National Bank of Hungary, dated August 18, 2003, “the Monetary Council puts the equilibrium exchange rate, which foster rapid economic growth without endangering price stability in the range of 250 to 260 forints per euro”. Relative to the then prevailing central parity of 282.36 forint per euro, this means a band of 7.92% to 11.46% on the stronger side of the official fluctuation margins. Thus, the estimated band for the whole period from 2001 to 2004 (upper bound=11%; lower bound=6.76%) is broadly in line with the implicit target of the Hungarian monetary authorities.

As shown earlier, a special case of the Delgado-Dumas solution is tantamount to managed floating without officially announced target zones, which could also induce some non-linear behaviour in the exchange rate. In particular, if the monetary authorities are targeting an

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[37] Note that the crawling peg system was abandoned only on October 1, 2001. However, at the time of the widening of the fluctuation band from ±2.25% to ±15%, the rate of crawl was already very low, 0.00654% a day, amounting to a total devaulation of the central paritiy of around 1.12% until October 1, 2001. Therefore, we believe that this did not have an impact on the behaviour of the exchange rate within the band.

implicit target zone, the SETAR model should be particularly useful to detect it because in such a case, interventions would be undertaken only if a depreciation or appreciation of the nominal exchange rate exceeded a given pain threshold of the monetary authorities. This may be the case of the Czech Republic and Slovakia, which have *de jure* and *de facto* managed floating. Notwithstanding the official free floating regime of the Polish zloty vis-à-vis the euro, we may still expect some mean reversion behaviour towards a band of inaction. Results reported in Table 4 confirm our suspicion about the presence of non-linear behaviour. However, the mean reversion appears to be one-sided. There are signs of significant mean reversion only on the strong side for the Czech Republic and Poland, and only on the weak side for Slovakia. The mean reversion of the Czech koruna and the Polish zloty may actually reflect the recent switch from huge nominal appreciation to a large depreciation of the two currencies. The width of the estimated band is close to 7% for the Czech Republic and Slovakia, which is in sharp contrast with the detected wide band of more than 17% for Poland, lending more empirical support for more active exchange rate policies in the two former countries.

Likewise for the period preceding the introduction of the euro, there appears to be strong integrated GARCH effects in the conditional variance for all cases.

Table 4. Model estimates using the euro

	$period$	k	ϕ_{upper}	ϕ_{lower}	λ_{upper}	λ_{lower}	α	β	$p-value$
DKK_EUR	1999-2004	1	0.38%	-0.01%	0.0051	-0.2474***	0.1368***	0.8464***	0.004
CZK_EUR	1999-2004	1	1.70%	-5.73%	-0.0109**	-0.0134	0.0808***	0.8599***	0.038
SKK_EUR	1999-2004	1	2.30%	-4.16%	-0.0025	-0.0779**	0.1678***	0.7223***	0.018
ZTY_EUR	2000-2004	2	10.26%	-7.14%	-0.0445**	-0.0045	0.1259***	0.8204***	0.006
HUF_EUR	2001-2004	1	11.00%	6.76%	-0.1165***	-0.3748**	0.4443***	0.5412***	0.000
HUF_EUR	2001-2003	1	12.35%	11.00%	-0.2249***	0.0125	0.5858***	0.5473***	0.000

Notes: as for Table 2.

7. Conclusions

In this paper, we have applied a three-regime SETAR model with GARCH errors to daily exchange rate data for countries participating in post-1993 ERM and ERM-2, and for selected CEE economies. The underlying idea of the theoretical model is that the monetary authorities do not intervene in the proximity of the central parity where the exchange rate behaves like a random walk. However, the exit of the exchange rate from this band of inaction on either side triggers policy action by the monetary authorities, which forces the exchange rate to return to the band.

We have argued that such a modelling framework is better suited to capturing exchange rate dynamics in a target zone, particularly the ERM variant of a target zone, than the frameworks used in previous research because it captures mean reversion to a band of inaction within the official target zone and gives a more realistic description of the behaviour of ERM currencies. A further novelty of our work is that in addition to using DM-based bilaterals we also use median currency-based bilaterals for the original ERM period. Given the way in which the ERM was supposed to work, the latter bilaterals are the more appropriate in any target zone modelling of this system.

For the ERM experience we are able to place the countries in two groups depending on the size of the bandwidth. For Austria, Belgium and the Netherlands, we found very narrow and very stable thresholds delimiting the band of inaction. This holds true for Italy and Finland for the period they re-entered/joined the ERM in 1996. Also, for these countries, the estimated bands were usually located on the stronger side of the official band. For the second group of countries - Denmark, France, Ireland, Portugal and Spain - the estimated bandwidth is substantially higher for the whole period but it decreases towards the end of the period. Simultaneously, we observe a shift of the bands either toward the central parity or into the stronger part of the official fluctuation bands. Although we find evidence in favour of reversion towards the band, this reversion partly disappears by the end of the period. In the paper, we divided the whole period into sub-periods to account for time-varying threshold values. A future avenue for research would be to estimate time-varying break points to tackle this issue

For Hungary, we detected a narrow band of 7% to 11% on the stronger side of the official band. We have also shown that reversion to the band occurred to the upper threshold before June 4, 2003 when the central parity was devalued, and mean reversion happened to the lower and the upper threshold for the whole period. For the other CEE countries which have not been pursuing a policy of explicit exchange rate bands we find evidence of non-linear exchange rate behaviour and the observed mean reversion is one-sided.

Overall, there appears to be strong evidence in favour of a mean reversion towards a band even, although the extent of this reversion is very heterogeneous across countries. Confronting our results with intramarginal intervention data for six countries participating in the ERM highlights several important points. First, the monetary authorities intervened often within the estimated bands, except for Portugal. Second, interventions were used to smooth out short-term fluctuations instead of targeting an implicit band. Third, in some cases larger intervention (relative to the average of the whole period) turned out to be effective in turning an exchange rate trend. Fourth, in some cases, mean reversion to the band occurred in the absence of official intervention in the foreign exchange markets. These results would seem to imply that official interventions are not a panacea for addressing exchange rate turbulence. In reality, mean reversion to the band could be the outcome of a range of factors, such as direct and indirect central bank interventions, moral persuasion, communication with the markets, stabilisation of market expectations in the face of increased credibility of the monetary authorities or because of an increased stability of the underlying fundamentals. However, large and co-ordinated interventions may be able to impact on the market exchange rate.

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Annex:

I. Datastream codes:

	Source	DEM		Source	EURO
Austria	Deutsche Bundesbank	DMATSSP	Denmark	European Central Bank	DKECBSP
Belgium	Deutsche Bundesbank	DMBECSP	Czech Rep.	European Central Bank	CZECBSP
Denmark	Deutsche Bundesbank	DMDKKSP	Hungary	European Central Bank	HNECBSP
Finland	Deutsche Bundesbank	DMFIMSP	Poland	European Central Bank	POECBSP
France	Deutsche Bundesbank	DMFRFSP	Slovakia	Datastream	SXEURSP
Ireland	Deutsche Bundesbank	DMIEPSP			
Italy	Deutsche Bundesbank	DMITLSP			
Netherlands	Deutsche Bundesbank	DMNLGSP			
Portugal	Deutsche Bundesbank	DMPTESP			
Spain	Deutsche Bundesbank	DMESPSP			

II. Distribution of exchange rate deviations from central parity

Figure 1. Distribution vis-à-vis the German mark, 1993 to 1998

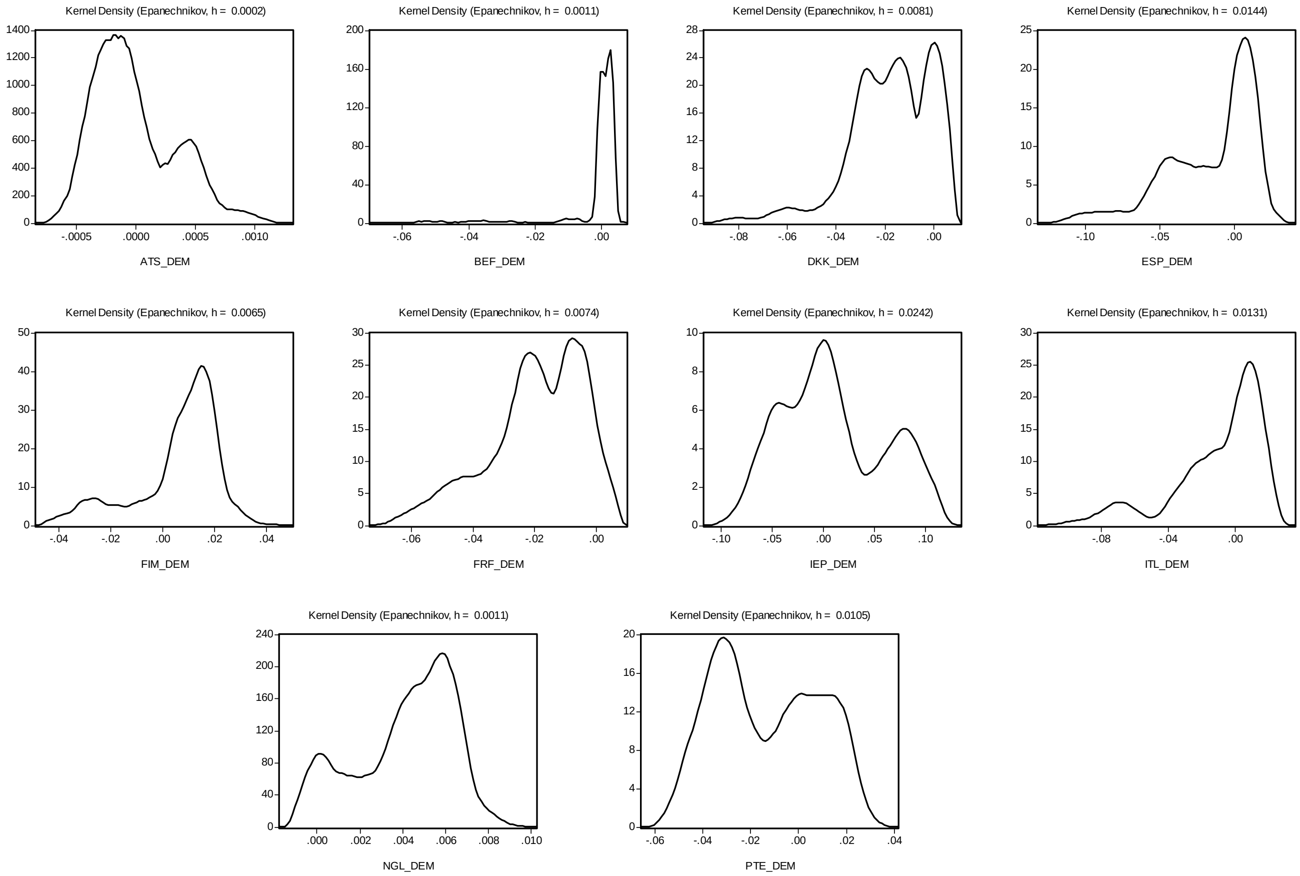


Figure 2. Distribution vis-à-vis the the median currency, 1996 to 1998

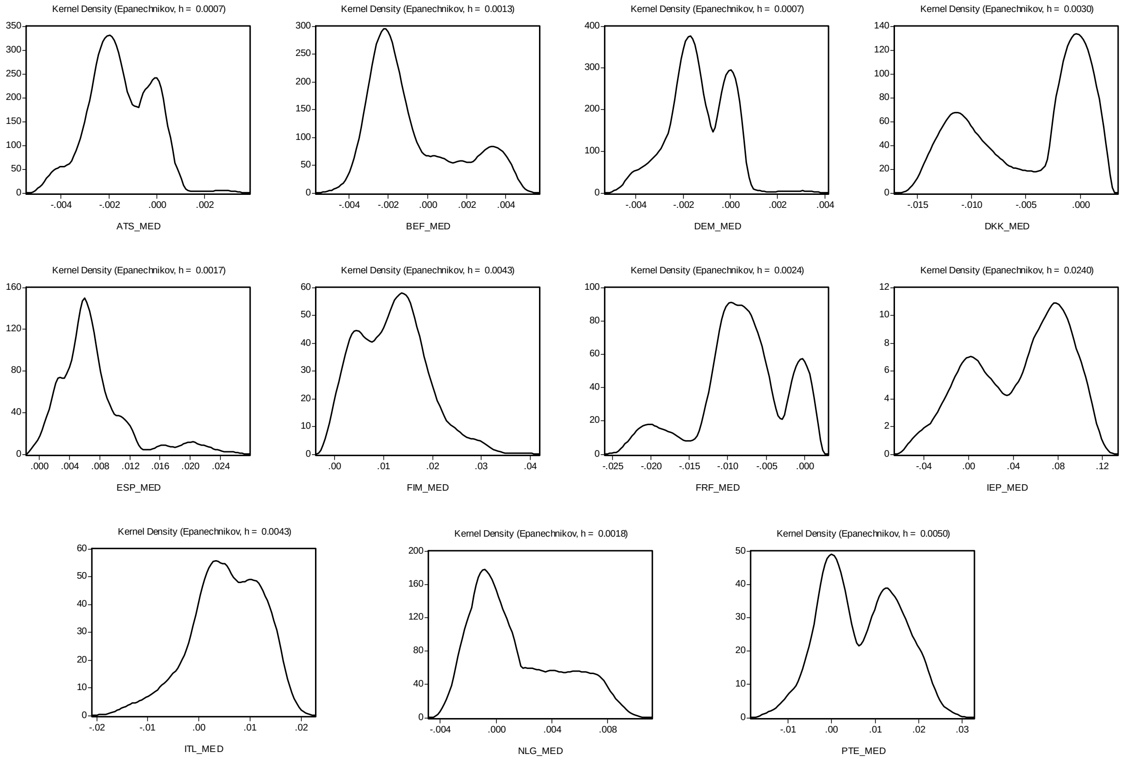
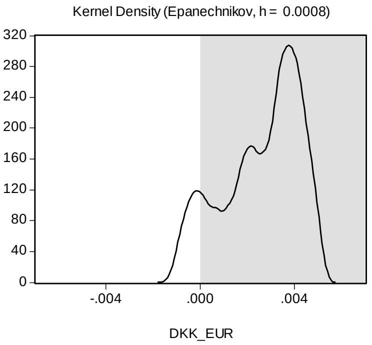


Figure 3. Distribution vis-à-vis the euro, 1999/2001 to 2004


Kernel Density (Epanechnikov, h = 0.0008)
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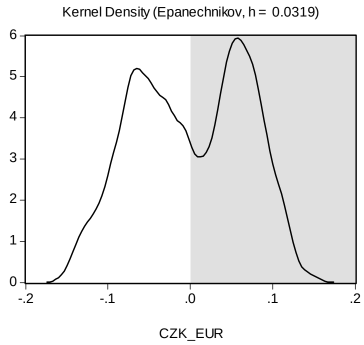
240
200
160
120
80
40
0
-.004
.000
.004
DKK_EUR


Kernel Density (Epanechnikov, h = 0.0319)
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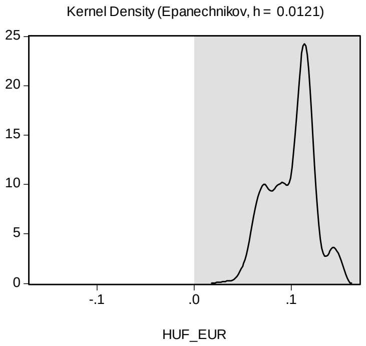
5
4
3
2
1
0
-.2
-.1
.0
.1
.2
CZK_EUR


Kernel Density (Epanechnikov, h = 0.0121)
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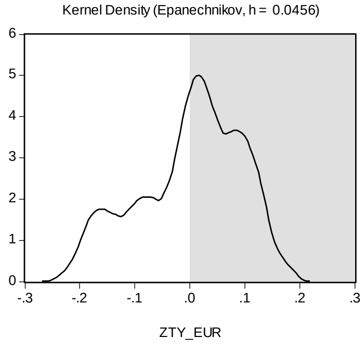
20
15
10
5
0
-.1
.0
.1
HUF_EUR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4
3
2
1
0
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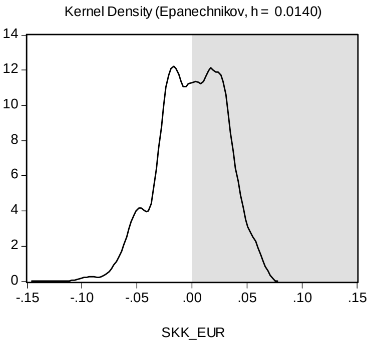
-.2
-.1
.0
.1
.2
.3
ZTY_EUR


Kernel Density (Epanechnikov, h = 0.0140)
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12
10
8
6
4
2
0
-.15
-.10
-.05
.00
.05
.10
.15
SKK_EUR

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