ISSN 0265-8003

STOCHASTIC PROCESS SWITCHING AND INTERVENTION IN EXCHANGE RATE TARGET ZONES: EMPIRICAL EVIDENCE FROM THE EMS

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Discussion Paper No. 554
July 1991

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CEPR Discussion Paper No. 554

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ABSTRACT

Stochastic Process Switching and Intervention in Exchange Rate Target Zones: Empirical Evidence from the EMS*

Exchange rate target zone models postulate that 'in the absence of intervention' exchange rates are driven by their fundamentals, which in this case are assumed to follow an unregulated Brownian motion process – the continuous time equivalent of a random walk (with drift). Such random walk behaviour of freely floating exchange rates is a well-documented stylized fact. The possibility of policy intervention in foreign exchange markets, however, may lead to stochastic process switching: in a perfectly credible target zone the commitment of policy-makers to intervene at the boundaries of a band for the fundamentals gives rise to speculative bubbles, which stabilize the exchange rate within a narrower band. Inframarginal intervention may add to these stabilizing effects. On the other hand, in target zones which are imperfectly credible, policy intervention may also take the form of a realignment, a permanent jump in the central parity. The present paper employs a Bayesian approach to estimate the relative probabilities of these forms of stochastic process switching by using daily data on the Deutschmark exchange rate for the EMS currencies. The analysis reveals that for these EMS target zones intervention and realignment probabilities have recently declined drastically, and that the ERM is now close to being a fully credible peg.

JEL classification: 431, 432
Keywords: intervention, realignment, EMS, exchange rate target zones

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*This paper is produced as part of a CEPR research programme on Financial and Monetary Integration in Europe (supported by a grant from the Commission of the European Communities under its SPES Programme (no. E89300105/RES)); and under a grant from the Commission of the European Communities under its SPES programme (No. 0016-NL(a)).

Submitted 26 March 1991

NON-TECHNICAL SUMMARY

Target zone models of the exchange rate postulate that, in the absence of intervention, exchange rates are driven by their fundamentals. The obligation of policy-makers, however, to intervene in foreign exchange markets as exchange rates approach the margins of a band, gives rise to speculation which stabilizes exchange rates within this band. This is the typical 'target zone' effect, which has been shown to have a number of testable empirical implications. To date little empirical support for such target zone effects has been provided. Conversely, many of the empirical regularities of exchange rates observed in managed exchange rate arrangements, such as the exchange rate mechanism of the European Monetary System (EMS), are found to be largely inconsistent with the predictions of the simple target zone model.

The present paper explores a new approach to the empirical evaluation of target zone models. It is based on the hypothesis that observable exchange rates in target zones, whether perfectly or imperfectly credible, must frequently exhibit stochastic process switching, caused either by stabilizing intervention, stabilizing speculation or by realignments. In this paper we use a Bayesian approach to estimate the probability of such stochastic process switching.

The evidence may be summarized by stating that stochastic process switching was an important feature of the EMS in its early period, as predicted by exchange rate target zone models. Recently, such frequent stochastic process switching has vanished. This suggests that the EMS has converged to a system of credible target zones, in which exchange rates fluctuate in accordance with an unregulated random walk but do not permanently drift outside the bands. This finding may be explained by the convergence of inflation and interest rates to the low German levels, which has resulted in more stable exchange rate fundamentals. This provides the necessary prerequisite for the proposed tightening of exchange rate target zones during Stage 2 of the Delors plan for a transition to economic and monetary union (EMU). Furthermore, the absence of stochastic process switching also suggests that the present 2.25% bands appear to be too wide to induce stabilizing speculation. Driftless random walk exchange rates with low noise components may require much narrower bands to create 'target zone' effects. Moving ahead with Stage 2 of the transition to EMU may revive these potential merits of exchange rate bands.

A second important result of the paper is that the estimates of intervention probabilities derived from actual DM exchange rate behaviour closely resemble the time paths of EMS interventions by the Bundesbank. Except for the Irish pound, a non-zero probability of random (as opposed to random walk) exchange rate movement coincides with periods in which there was in fact a stabilizing Bundesbank intervention. Furthermore, stabilizing intervention generally takes the form of obligatory intervention at the boundaries of the band. Both results together leave little scope for attributing stochastic process switching in DM exchange rates of EMS currencies to stabilizing speculation of the type postulated in target zone models.

Stochastic Process Switching and Intervention in Exchange Rate Target Zones: Empirical Evidence from the EMS

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1. Introduction

During most of the post-war period many countries have adhered to target zone exchange rate regimes in which the exchange rate is allowed to float more or less freely within a pre-specified band, but foreign exchange market interventions prevent the exchange rate from moving outside the band. In Germany the conduct of monetary policy has been subject to such an exchange rate constraint under the Bretton Woods system, the European currency snake and the European Monetary System (EMS). Each of these three real world target zone arrangements was based on symmetric bands around fixed bilateral central parities, which typically were adjustable by mutual agreement. Within the EMS the Bundesbank currently has the obligation to defend such exchange rate target zones vis-a-vis the French franc (FF), Italian Lira (Lit), Dutch guilder (Hfl), Belgian franc (Bf), Danish krona (Dkr), Irish pound (Ir£), Spanish peseta (Pta) and the British pound (£) by intervention of unlimited amounts at the margin. This is the standard *official bilateral* target zone with binding commitments toward a band, which will be analyzed in this paper. Other forms of non-binding German mark exchange rate target zones, to be analysed in a subsequent paper, have also existed and are partly still in place. One example is the *official unilateral* DM target zone adopted by the Swiss National Bank during the speculative attacks on the Swiss franc in 1979.

*I should like to thank George Alogoskoufis, David Currie, John Driffill, Jürgen Ehlgen, Mervyn King, Martin Klein, Hans-Edi Loef, Jacques Mélitz, Marcus Miller, Mark Salmon and Michael Wickens for useful comments and discussions, and Roel Beetsma for the daily exchange rate data. The usual disclaimer applies.

Furthermore, many countries have adopted *inofficial*, if not to say secret target zones for the DM exchange rate. Such 'shadow targeting' has played an important role in the conduct of monetary policy in Austria throughout the 1980's. An inofficial DM/£ target was also adopted by the Bank of England for some time during 1987. Finally, international policy coordination at the level of the Group-of-Five (G-5) or Group-of Seven (G7)[1] established *semi-official* US dollar exchange rate target zones for the Bundesbank in the Plaza Agreement and the Louvre Accord.

In spite of the existence of many such real world target zone arrangements, their implications for the dynamics of exchange rate determination in rational expectations models have only recently been studied rigorously. In Krugman's (1990) seminal paper a non-linear model of a fully credible target zone is proposed and it is shown that such target zones imply an inherent stabilization of the exchange rate, the so-called 'honeymoon effect'. This is due to the fact that the exchange rate is modelled as the sum of a fundamental and its own expected rate of change: a weak currency position near the edges of a fully credible band implies an increased probability of future intervention and hence the expectation of a future appreciation, which in turn leads to a current strengthening of the currency. Stated differently, the credible precommitment of central banks to restrict the fundamental determinants of exchange rates within certain bands and to intervene in a pre-specified manner as fundamentals hit the edges of these band will stabilize the exchange rate within a narrower range and, depending on certain behavioural parameters, may push it towards the centre of the target zone.

Is this prediction of target zone models consistent with real world experience? Despite the vast growth in theoretical models using the target zone framework, only a few empirical papers are available to date. Unfortunately, the evidence

[1]The G-5 countries are France, Germany, Japan, the United Kingdom and the United States, the G-7 group includes in addition Canada and Italy.

presented in the papers of Svensson (1989, 1991a,b,c), Smith and Spenser (1990), Bertola and Caballero (1990) and Flood, Rose and Mathieson (1990) in general provides only limited empirical support for this class of models. Conversely, many of the empirical regularities of exchange rate behaviour in real world target zone arrangements, in particular in the EMS, are found to be largely inconsistent with the predictions of the simple target zone model.

The present paper explores a new approach to evaluating empirically the relevance of target zone models. The key aspect of the analysis hereby is that observable exchange rates in target zones, whether perfectly credible as in Krugman (1990) and Svensson (1989), or imperfectly credible as in Bertola and Caballero (1990, 1991) or Svensson (1991a,b,c), must frequently exhibit stochastic process switching, caused either by stabilizing intervention, stabilizing speculation or realignments. Employing Bayesian inference, the probability of such stochastic process switching is estimated by using daily data on bilateral German mark EMS spot exchange rates.

The remainder of paper is organized as follows: section 2 reviews the theoretical concepts and empirical implications of standard and extended target zone models. Special emphasis is thereby placed on the time series properties of exchange rates, in particular during period of foreign exchange market regulations, such as stabilizing intervention or realignments. It is shown that such regulations indeed result in stochastic process switching, as discussed in Froot and Obstfeld (1989). The empirical approach to estimating the probability of such stochastic process switching is outlined in section 3. Section 4 presents some simulations which highlight the tracking ability of the algorithm used in detecting stochastic process switching in experimental data. Section 5 presents the results obtained from applying this method to data from the EMS, whist section 6 compares the intervention probability estimates with reported interventions. Section 7 concludes the paper with a summary of the main results and suggestions for further research.

2. Target Zone Models

2.1. Theoretical Concepts of Target Zone Models

The basic components of target zone models, which originated in the work of Krugman (1990), may be characterized as follows:

(a) the exchange rate e_t is driven by a stochastic forcing process f_t, frequently referred to as the exchange rate fundamentals.[2] Actual exchange rates may, however, deviate from the fundamentals due to speculative bubbles $E_t(de_t/dt)$:

$$e_t = f_t + \frac{\alpha}{dt} E_t(de_t) \; ; \tag{1}$$

(b) the fundamentals f_t typically include both variables with autonomous dynamics and variables under the direct control of the monetary authority, which generally aims at maintaining a target zone for the fundamentals by foreign exchange intervention at pre-specified upper ($\bar{f}$) and lower ($\underline{f}$) bounds, thus implying well-specified bounds ($\bar{e}$, $\underline{e}$) for the exchange rate, as will be demonstrated below.

(c) in the absence of intervention the fundamentals f_t follow a continuous Brownian motion (or Wiener, or Wiener–Levy) process:

$$df_t = \eta dt + \sigma dz_t \, , \tag{2}$$

with instantaneous mean drift η and variance σ, where dz_t is the standard Wiener process ($dz_t/dt \equiv w_t$);

(d) the observable process e_t is postulated to be a non-linear twice continuously differentiable function $x(\cdot)$ of the state f_t, which rules out irrational bubbles:

$$e_t = x(f_t) \, . \tag{3}$$

Using equation (1) to (3), Ito's lemma may be applied to obtain an expression for the expectations in (1):

$$\frac{1}{dt} E_t(de_t) = \eta \, x'(f_t) + \frac{\sigma^2}{2} x''(f_t) \, . \tag{4}$$

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[2]Froot and Obstfeld (1989) show (in footnote 2) how equation (1) may be derived from a monetary model of exchange rates such as Mussa (1976). Miller and Weller (1988, 1989a,b) present an interpretation of this equation in terms of Dornbusch's (1976) overshooting model.

This results in a functional equation for the exchange rate:

$$x(f_t) = f_t + \eta x'(f_t) + \frac{\sigma^2}{2} x''(f_t)\,. \tag{5}$$

This second order differential equation has, as shown in Froot and Obstfeld (1989), the general stationary solution:

$$e_t = f_t + \alpha\eta + A_1 e^{\lambda_1 f_t} + A_2 e^{\lambda_2 f_t}\,, \tag{6a}$$

with

$$\lambda_1 = \frac{-\eta + \sqrt{\eta^2 + 2\sigma^2/\alpha}}{\sigma^2} > 0\,,\quad \lambda_2 = \frac{-\eta - \sqrt{\eta^2 + 2\sigma^2/\alpha}}{\sigma^2} < 0\,, \tag{6b}$$

where A_1 and A_2 are constants, determined by the boundary conditions $x(\bar{f})$ $[x(\underline{f})]$ satisfied by the exchange rate e_t at the time of intervention:

$$A_1 = \frac{e^{\lambda_2 \underline{f}} - e^{\lambda_2 \bar{f}}}{\lambda_1 e^{\lambda_1 \bar{f} + \lambda_2 \underline{f}} - \lambda_1 e^{\lambda_1 \underline{f} + \lambda_2 \bar{f}}},\quad A_2 = \frac{e^{\lambda_1 \bar{f}} - e^{\lambda_1 \underline{f}}}{\lambda_1 e^{\lambda_1 \bar{f} + \lambda_2 \underline{f}} - \lambda_1 e^{\lambda_1 \underline{f} + \lambda_2 \bar{f}}}. \tag{6c}$$

These 'smooth pasting' conditions, derived from equation (6a) for $x'(\underline{f}) = x'(\bar{f}) = 0$, ensure that $x(f_t)$ is flat at the boundary of the fundamentals band and tangent to the boundaries of the implied exchange rate band in Krugman's model of infinitesimal marginal intervention. In economic terms, 'smooth pasting' ensures that the exchange rate is never expected to jump in response to intervention.[3] [4] Three types of settings of A_1 and A_2 are relevant in the context of fully or imperfectly credible target zone models:

(a) completely ruling out speculative bubbles and ignoring the existence of a target zone ($A_1 = A_2 = 0$)[5] results in a linear relationship between the exchange rate and its fundamentals. This basically is the *free float* solution under which exchange rates are always driven by a random walk.

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[3]If such jumps were allowed for, risk neutral investors would face an arbitrage opportunity as fundamentals approach the point of intervention.

[4]Flood and Garber (1989) show that this no–jump requirement also provides boundary conditions for more general intervention policies, such as finite intervention strictly in the interior of the band.

[5]Formally this may be derived from the coefficient restriction (6c) by assuming infinitely wide fundamental bands and hence letting the lower bound go to minus infinity and the upper bound to infinity.

(b) in *perfectly credible* target zones 'smooth pasting' ensures $A_1<0$ and $A_2>0$, and the relationship between the exchange rate and its fundamentals has the well-known S-shape, which reflects Krugman's 'honey moon' effect: the existence of perfectly credible fundamentals band gives rise to speculative bubbles which stabilize the behaviour of the exchange rates within the edges of a narrower band. This result holds for all credible target zones, whether with or without inframarginal intervention.

(c) in *imperfectly credible* target zones policymakers have the option to either fight the parity or to initiate a realignment. Bertola and Caballero (1990) show that in this case the constants A_1 and A_2 depend, amongst other things, on the relative probabilities of these mutually exclusive events. In particular, they demonstrate that 'smooth pasting' ($A_1<0$, $A_2>0$) only occurs if at the boundary of the fundamentals band the realignment probability (π^1_t) is small ($\pi^1_t<1/2$), whilst $\pi^1_t=1/2$ leads to the free float solution ($A_1=A_2=0$). Finally, in a non-credible target zone ($\pi^1_t>1/2$) speculation is de-stabilizing ($A_1>0$, $A_2<0$) and the relationship between the exchange rate and its fundamentals has an inverted S-shape.

2.2. Empirical Implications of Target Zone Models

The above target zone models have a number of important empirical implications, not all of which have yet been tested empirically.

At a purely descriptive level, one may argue with Avesina (1990) that existing target zones models poorly mirror EMS reality since they predict that there will be a realignment each time the process driving the fundamentals (and hence the exchange rate) hits the boundaries of the band. Real world EMS exchange rates of certain currencies have, however, remained on the boundaries for some time and even slightly crossed it without requiring a realignment.[6] Furthermore, EMS exchange rates have occasionally exhibited large jumps in response to intervention at the boundaries, in particular prior to realignments.[7] Both stylized facts from EMS exchange rate behaviour are inconsistent with the assumptions of the fully credible target zone model, but can be accounted for in models of imperfectly credible target zone, such as Bertola and Caballero (1990).

At a more formal level, the predictions of target zone models have been tested in two distinctive ways. In the first approach a quantified measure of exchange rate fundamentals is required in order to draw inference, whilst the second approach focuses on the distributional and time series properties of observable exchange rates in target zones.

Empirical tests using an *observable* proxy of exchange rate fundamentals typically focus on the non-linearities of target zone models and deal with the issue of whether the relationship between this fundamental proxy and the exchange rate

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[6]This puzzling fact is accounted for below by allowing exchange rate fundamentals to be subject to by both transitory and permanent shocks: the central bank's confusion over the relative importance of both types of shocks now justifies intervention as an alternative to a realignments if fundamentals are beliefed to move only transitorily at the boundaries of the band. One may think of this as the real world equivalent to *reflecting barriers*, where intervention ceases as soon as fundamentals move back inside the band.

[7]See for example the behaviour of the FF/DM and Bf/DM exchange rates in figures 5 and 8 prior to the March 1983 realignment.

is S–shaped, as postulated by Krugman (1990), or linear or inversely S–shaped, both of which may be the case in Bertola and Caballero's (1990) model of an imperfectly credible target zone. A review and extensive new empirical evidence for the EMS along this line of research, which most commonly uses interest rate differentials as a proxy of fundamentals, is provided in the paper by Flood, Rose and Mathieson (1990). The authors conclude that they have not found compelling evidence of non–linearities, at least not of the sort implied by target zone models.

Target zone models also have a number of implications which can be tested without quantifying a measure of exchange rate fundamentals. These are examined in Bertola and Caballero (1990), Floot, Rose and Mathieson (1990), Svensson (1989, 1991a,b,c) and Smith and Spenser (1990).

The paper by Smith and Spencer (1990) outlines a testing strategy for target zone models based on the method of simulated moments. Their approach is to map simulated moments (mean, variance, skewness and kurtosis) of exchange rate levels and changes from calibrated standard target zone models with the corresponding moments from real world data by minimizing a moment–matching loss function. Systematic empirical evidence for the EMS based on this approach is not yet available.[8]

A number of papers, in particular Bertola and Caballero (1990) and Flood, Rose and Mathieson (1990), provide non–statistical tests of the empirical implications of models with perfectly credible target zones, such as Krugman (1990). These models predict that:

(a) most of the exchange rate variability should be observable in the middle of the band, and

(b) exchange rate distributions inside the band should be bi–modal, with a higher density at the edges of the band;

[8]This statement is based on results of expected exchange rates for 1 year ahead.

However, models of imperfectly credible target zones with a high realignment probability, as in Bertola and Caballero (1990), imply just the opposite. Thus, unless it is possible to separate the credibility issue from the stylized facts about exchange rate behaviour in target zones, any such evidence is meaningless and must not be interpreted as rejecting (or supporting) this class of models.

The issue of target zone credibility is explicitly addressed in Svensson (1991a). Svensson's simple tests for the credibility of a target zone involves plotting the expected future exchange rates extracted from the terms structure of interest rate differentials against the implied maturity bands. Similar evidence presented in Flood, Rose and Mathieson (1990) for the German mark exchange rates of ERM countries suggests that the EMS possessed short–term[9] credibility, but – with the exception of the Dutch exchange rate – lacked long–term[10] credibility, even for more recent data.

Finally, Svensson (1991a,b,c) explores the implications of a target zone for exchange rate fundamentals with respect to interest rate differentials. Note that here the interest rate differential is not assumed to be a proxy of the exogenous fundamental forcing process f_t, but is endogenously determined via discrepancies between the expected maturity exchange rate and the instantaneous exchange rate, which are both non–linear functions of the exogenous fundamentals. Consequently the interest rate differential is also a non–linear function of the fundamentals. Thus, a target zone for the fundamentals implies a target zone for both exchange rates and interest rate differentials, whereby the latter is narrower the longer the maturities are. Svensson (1991b) also shows that the relationship between the exchange rate and the interest rate differential is non–linear, but becomes flatter and less non–linear for longer maturities. As reported above, tests of the former hypothesis for the EMS are provided in Flood, Rose and Mathieson (1990), albeit

[9]Results for expected exchange rates for 2 days and 30 days ahead are presented.
[10]This statement is based on results of expected exchange rates for 1 year ahead.

independant of Svensson's theoretical framework. On the latter hypothesis evidence from the EMS is not yet available. However, by using data for the unilateral Swedish exchange rate target zone, Svensson (1991b) estimates a *linearized* version of his model and regresses interest rate differentials of various maturity on the exchange rate. The estimated slope coefficients do indeed exhibit the expected pattern of being smaller for longer maturities.

The present paper explores a new approach to evaluating the relevance of target zone models in explaining stylized facts of exchange rate behaviour in the EMS. It thereby follows the second strand of literature in not specifying a measure of exchange rate fundamentals. Consequently, the non–linearity assumption of target zone models can not be evaluated and is thus irrelevant in the present context. Instead, the paper's focus is exclusively on the time series properties of observable exchange rates in target zones, which will be specified more precisely in the next section. The empirical approach taken below is to evaluate the credibility of an exchange rate target zone in terms of the likelihood of stochastic process switching, which either takes the form of stabilizing speculation, stabilizing intervention or of a realignment. It is thereby important to note that in the absence of actual intervention data, which typically are disclosed by central banks, the first two forms of process switching are impossible to distinguish empirically.

2.3. Time Series Properties of Exchange Rates in Target Zones

2.3.1. Exchange Rates and Fundamentals

To illustrate the empirical approach taken in this paper, let us adopt the discrete time equivalent of the above target zone model. Let us define an *unobservable* scalar state $\mathfrak{f}_t$, which is related in the non–linear fashion suggested by equation (6) to some *observable* fundamental f_t under the control of the monetary authority.[11] Further assume that the authority's control over the exchange rate is imperfect and subject to random control errors $\mathfrak{v}_t$, which may also be related in a non–linear fashion to the uncontrollable component v_t of the fundamentals.[12] This allows us to express the *observable* exchange rate as a linear *measurement equation* in the *unobservable state* $\mathfrak{f}_t$:

$$e_t = \mathfrak{f}_t + \mathfrak{v}_t , \qquad E(\mathfrak{v}_t)=0,\ E(\mathfrak{v}_t\mathfrak{v}_t')=\sigma^2 h_1,\ E(\mathfrak{v}_t\mathfrak{v}_{t-j}')=0\ \forall\ j\neq 0 , \tag{7}$$

or equivalently, as a non–linear functional relation $x(\cdot)$ between the *observable* exchange rate e_t and the *observable fundamental* f_t:

$$e_t = x(f_t) + x(v_t), \qquad E(v_t)=0,\ E(v_tv_t')=\sigma^2 h\ ,\ E(v_tv_{t-j}')=0\ \forall\ j\neq 0 , \tag{7'}$$

Since the present paper will not use observable fundamentals to make inference about the likelihood of stochastic process switching, the analysis below will focus on the linear measurement equation (7).

As in standard target zone models the unobservable state $\mathfrak{f}_t$ is assumed to follow a Brownian motion process. The discrete time analogous of the Brownian motion process is a random walk with deterministic drift η. In the present paper a slightly more general process structure, a random walk with a stochastic drift η_t,

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[11] In Froot and Obstfeld (1989a) these controllable components of the fundamentals are the relative money supplies, which are altered via unsterilized foreign exchange market interventions.

[12] In Froot and Obstfeld's (1989a) interpretation of the target zone model in terms of a monetary model of the exchange rate it is shown that the non–controllable component of their non–scalar fundamentals f_t is a linear function of relative velocity shocks. Consequently, the non–controllable component of the exchange rate in the target zone model is, as suggested by the right hand side of equation (6), a non–linear function of the underlying velocity shocks to the fundamentals.

which itself follows a random walk, is allowed for. The dynamics of the state f_t are described by the *state transition equations*:

$$f_t = f_{t-1} + \eta + w_t, \qquad E(w_t)=0,\ E(w_t w_t')=\sigma^2 q_1,\ E(w_t w_{t-j}')=0\ \forall\ j\neq 0. \qquad (8a)$$

$$\eta_t = \eta_{t-1} + r_t, \qquad E(r_t)=0,\ E(r_t r_t')=\sigma^2 q_2,\ E(r_t r_{t-j}')=0\ \forall\ j\neq 0 \qquad (8b)$$

For simplicity, v_t, w_t and r_t are assumed to be independently distributed, with w_t and r_t being also independent of the initial states f_0 and r_0.

The above dynamic linear model reduces to the bubble free (α=0) clean float version (A_1=A_2=0) of the standard target zone model (6) for h_1=q_2=0, which of course implies f_t=f_t:

$$e_t = f_t, \qquad (9a)$$

$$f_t = f_{t-1} + \eta_t + u_t, \qquad E(w_t)=0,\ E(w_t w_t')=\sigma^2 q_1,\ E(w_t w_{t-j}')=0\ \forall\ j\neq 0, \qquad (9b)$$

$$\eta_t = \eta_{t-1}, \qquad (9c)$$

which describes the behaviour of the exchange rate in the absence of any form of intervention. This reference model is used below as a benchmark against which the likelihood of stochastic process switching is judged.

2.3.2. Intervention Policies

Assume now that the exchange rate approaches its fluctuation bounds. In this case stochastic process switching must occur and may take two forms.

2.3.2.1. Stabilizing Foreign Exchange Market Interventions

Policymakers may intervene in foreign exchange markets to defend the target zone. The regulated state (f_t^o) is thereby frozen at its past level (f_t^o=f_{t-1}), which requires that the exchange rate effects of intervention must offset the potentially de-stabilizing effects from of the state's immanent dynamics. In this case the exchange rate e_t fluctuates randomly around the intervention margin f_t^o,

$$e_t = f_t + \mathfrak{v}_t, \qquad E(\mathfrak{v}_t)=0,\ E(\mathfrak{v}_t \mathfrak{v}_t')=\sigma^2 h_1,\ E(\mathfrak{v}_t \mathfrak{v}_{t-j}')=0\ \forall\ j\neq 0, \qquad (10a)$$

$$f_t = f_{t-1} = f_t^o \qquad (10b)$$

where f_t^o is a function of the width of the band (σ_b) and the standard deviation of the measurement error ($\sigma_v = \sigma^2 h_1$).

2.3.2.2. Realignments

Alternatively policy–makers may initiate a realignment. Think of this as a policy induced large permanent jump of the state f_t. In standard target zone models this leaves the long–run drift characteristics of the state unaltered. In view of the model's applicability to the EMS experience, however, it may be desirable to make the long–run drift characteristics of the state dependant on the history of realignments: many ERM countries initially used the system as a crawling peg, but later moved to more level pegging policies as disinflation and realignments, that is adjustments for cumulative past inflation differentials, led to more stable exchange rate fundamentals. To capture such effects of realignments the deterministic drift η has been replaced by a stochastic drift η_t, which is assumed to be subject to permanent but relatively infrequent shocks r_t:

$$e_t = f_t \,, \tag{11a}$$

$$f_t = f_{t-1} + \eta_t \,, \tag{11b}$$

$$\eta_t = \eta_{t-1} + r_t \,, \qquad E(r_t)=0,\ E(r_t r_t')=\sigma^2 q_2,\ E(r_t r_{t-j}')=0\ \forall\ j\neq 0. \tag{11c}$$

A run of negative r's thereby has the effect that it reduces the trend rate of devaluation (η_0) and hence renders to be exchange rate target zones more stable.

2.3.2.3. Realignment Probabilities

Assume that the unobservable state f_t driving the exchange rate follows an unregulated stochastic process with probability α_t and is regulated by policy intervention with probability $(1-\alpha_t)$. At each point in time the public is uncertain about the action of the policymaker, who may either fight the parity or initiate a realignment. Assume that the public assigns subjective probabilities β_t and $(1-\beta_t)$ to these mutually exclusive events. Then the realignment probability (π_t^3) in an imperfectly credible target zone is given by $\pi_t^3=(1-\alpha_t)(1-\beta_t)$, whilst the probability of stabilizing intervention is $\pi_t^2=(1-\alpha_t)\beta_t$. Of course, the probability that the state will continue to follow an unregulated stochastic process is given by $\pi_t^1=1-\pi_t^2-\pi_t^3$. It is thereby assumed that probabilities are explicitly time–varying and that they are driven by Markov processes.

In Bertola and Caballero (1990) the realignment probability in an imperfectly credible target zone is modelled as a constant. The authors derive an important result: they show that the existence of stabilizing speculation in a relatively credible target zone ($\pi_t^3<1/2$) still makes it possible for the authorities to defend the parity with only modest intervention. However, in a non–credible target zone ($\pi_t^3>1/2$) de–stabilizing speculation forces the authorities to take drastic action if they decide to defend the parity. This result derives from the fact that in this case the relationship between the exchange rates and its fundamentals has an inverted S–shape, which makes exchange rates more variable at the edges of the band than they would be under a free float, that is, the random walk. Hence, the model of Bertola and Caballero (1990) predicts that prior to a realignment stochastic process switching from random walk behaviour to higher order variability at the edges of the band occurs, just as modelled in the realignment model above.

3. Estimating the Probability of Stochastic Process Switching

To obtain an estimate of the probability of stochastic process switching ($\pi_t=\pi_t^2+\pi_t^3$) a learning algorithm, the so-called Bayesian multi-process Kalman filter of Harrison and Stevens (1971, 1976), is employed. For a more formal description of this method and for references to other applications in economics the discussion in Weber (1988a,b) should be consulted.

The working of the algorithm may best be explained by transforming the above model into its general state-space representation:

$$e_t = z_t' a_t + S v_t\,, \qquad E(v_t)=0,\ E(v_t v_t')=\sigma^2 H,\ E(v_t v_{t-j}')=0\ \forall\ j\neq 0 \tag{12a}$$

$$a_t = T a_{t-1} + R u_t\,, \qquad E(u_t)=0,\ E(u_t u_t')=\sigma^2 Q,\ E(u_t u_{t-j}')=0\ \forall\ j\neq 0 \tag{12b}$$

whereby the following specifications apply:

$$S=1,\ H=h_1,\ a_t=[f_t\ \eta_t],\ u_t=[w_t\ r_t],\ z_t'=[1\ 0],\ T=\begin{bmatrix}1&1\\0&1\end{bmatrix},\ R=\begin{bmatrix}1&1\\0&1\end{bmatrix},\ Q=\begin{bmatrix}q_1&0\\0&q_2\end{bmatrix}. \tag{13}$$

The multi-process framework now requires the alternative process models to be specified as sub-models of the above general model. In the present context this is done by simply introducing certain zero restrictions for the variance-covariance matrices of the residuals. For example, our reference model (M_t^1) assumes that in the absence of policy intervention exchange rates follow a random walk with deterministic drift η, and results from (12a,b) and (13) by setting $h_1=q_2=0$. The stabilizing intervention model (M_t^2) views exchange rates as a stationary stochastic process which fluctuates randomly around regulated constant fundamentals and is obtained for $q_1=q_2=0$.[13] Finally, the realignment model (M_t^3) follows for $h_1=q_1=0$.

Given these three alternative specifications of the variance-covariance matrices Q^i and H^i (i=1,2,3) estimates of the unobservable state vectors a_t^i and their variance-covariance matrices $\sigma^2 P_t^i$ may now be extracted from the observable process e_t by using the Kalman filter. At this point stochastic process switching is explicitly taken into account.

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[13]Clearly, to freeze fundamentals at any level f_t the stabilizing intervention must always just offset their constant drift η.

Assume that the observable exchange rate process switches from model M^i_{t-1} (i=1,2,3) in period t–1 to model M^j_t (j≠i) in period t. Let us denote this process switching model by $M^{ij}_{t;t-1}$. The Kalman filter's prediction and update equations:

$$\alpha^{ij}_{t;t-1} = T\alpha^{i}_{t-1,t-1} \tag{14a}$$

$$P^{ij}_{t;t-1} = TP^{i}_{t-1,t-1}T' + RQ^{j}R' \tag{14b}$$

$$\alpha^{ij}_{t;t} = \alpha^{ij}_{t;t-1} + K^{ij}_t\epsilon^{ij}_t \tag{14c}$$

$$P^{ij}_{t;t} = (I-K^{ij}_t z'_t)\, P^{ij}_{t;t-1}\, (I-K^{ij}_t z'_t)' + K^{ij}_t H^j K^{ij}_t \tag{14d}$$

$$\epsilon^{ij}_t = y_t - z'_t\alpha^{ij}_{t;t-1} \tag{14e}$$

$$K^{ij}_t = P^{ij}_{t;t-1}z_t(F^{ij}_t)^{-1} \tag{14f}$$

$$F^{ij}_t = z'_tP^{ij}_{t;t-1}z_t + S'H^jS \tag{14g}$$

may then may be used to forecast exchange rate movements under three types of pure stochastic processes and six types of stochastic process switching, given a suitable initialization of the state vector (a_{t_0}) and its variance–covariance matrix ($\sigma^2P_{t_0}$). The empirical relevance of stochastic process switching may now be evaluated in probabilistic terms.

The probability distribution of the alternative process models is calculated and recursively updated in the Bayesian part of the multi–process Kalman filter by using Bayes' law. To illustrate this process, assume that each model M^i_t at each point in time has a prior probability $E_{t-1}\pi^i_t$ as well as a posterior probability π^i_t, and that the probability of process switching $M^{ij}_{t;t-1}$ is denoted by π^{ij}_t. According to Bayes' theorem the conditional posterior probability π^{ij}_t of each model may then be calculated as:

$$\begin{aligned}\pi^{ij}_t \;=\; & \text{PROB}\{\, e_t \mid M^j_t, M^i_{t-1}, (e_{t-1},e_{t-2},e_{t-3},\ldots)\} \\ * \; & \text{PROB}\{\, M^j_t \mid M^i_{t-1}, (e_{t-1},e_{t-2},e_{t-3},\ldots)\} \\ * \; & \text{PROB}\{\, M^i_{t-1} \mid (e_{t-1},e_{t-2},e_{t-3},\ldots)\} \\ / \; & \text{PROB}\{\, e_t \mid (e_{t-1},e_{t-2},e_{t-3},\ldots)\}\,,\end{aligned} \tag{15}$$

and can be formalized in terms of the Kalman filter from above as:

$$\pi_t^{ij} = k_t\, L_t^{ij}\, E_{t-1}\pi_t^{j}\, \pi_{t-1}^{i}\,, \tag{16}$$

with

$$L_t^{ij} = \left[2\Pi\, \sigma^2\, F_t^{ij}\right]^{-(1/2)} \exp\left[-(\epsilon_t^{ij})^2 \,/\, 2\sigma^2\, F_t^{ij}\right], \tag{17}$$

$$E_{t-1}\pi_t^{j} = \frac{\theta E_{t-2}\pi_{t-1}^{j} + \psi_{t-1}^{j}}{\sum_j \left(\theta E_{t-2}\pi_{t-1}^{j} + \psi_{t-1}^{j}\right)}\ \text{, with } \theta=1, \tag{18}$$

$$\pi_{t-1}^{i} = \sum_j \pi_{t-1}^{ji}\,, \tag{19}$$

$$\psi_{t-1}^{j} = \sum_i \pi_{t-1}^{ji}\,, \tag{20}$$

The transformation of old prior ($E_{t-2}\pi_{t-1}^{j}$) and posterior (ψ_{t-1}^{j}) probabilities into new prior probabilities ($E_{t-1}\pi_t^{j}$) for the subsequent period in equation (18) represents the Bayesian learning mechanism. This probability learning is largely determined by the relative forecasting performance of the individual models over the recent periods, as measured by the likelihood function (17) of each model.

Given the individual state estimates M_t^{ji} from the Kalman filter and their respective probabilities π_t^{ji} from the Bayesian part of the algorithm, it is now possible to condense the estimates for the mean and variance of the state as:

$$\alpha_t^{j} = \sum_i \pi_t^{ij}\alpha_t^{ij} \,/\, \pi_t^{j}\ , \tag{21a}$$

$$P_t^{j} = \sum_i \pi_t^{ij}\{P_t^{ij} + [(\alpha_t^{ij}-\alpha_t^{j})(\alpha_t^{ij}-\alpha_t^{j})]\} \,/\, \pi_t^{j}\ , \tag{21b}$$

where $\pi_t^{j}=\sum_i \pi_t^{ij}$ holds. The inclusion of the term $[(\alpha_t^{ij}-\alpha_t^{j})(\alpha_t^{ij}-\alpha_t^{j})]$ in addition to the individual estimates P_t^{ij} in equation (21b) is justified by the fact that a large dispersion of the point estimates around their average should reduce the confidence in the precision of the average point estimate.

Having briefly described the model and the estimation procedure to be used in the present paper, the adequacy and power of the present approach to estimating stochastic process switching probabilities in exchange rate target zones may best be demonstrated in a simulation exercise before applying the methods to real world exchange rate data.

4. Simulations of Stochastic Process Switching in Target Zone Models

In order to demonstrate the usefulness of the above estimating procedure for imperfectly credible target zone models it is instructive to start from Krugman's famous 'honey moon' effect in a perfectly credible target zone. To reproduce this effect, the non-linear measurement equation (7'), with $\mathfrak{f}=x(f_t)$ given by the right-hand side of equation (6), was combined with the state transition equations (8a,b). By assuming a deterministic zero fundamental drift ($\eta_t=\eta_{t-j}=0\ \forall\ j$) and a symmetric band for the exchange rate (with $\lambda_1=-\lambda_2=0.2$, $A_1=-A_2=-1$), Figure 1 is obtained.[14] Figure 1a displays the well-known S-shaped relationship between the exchange rate and its fundamental, both normalized around the initial parity. Note that the S-shaped curve here is contaminated by measurement noise as a result of the assumption of incompletely controllable fundamentals. The implied time series behaviour of exchange rates and fundamentals is depicted in Figure 1b and clearly shows the effects of 'smooth-pasting' as the fundamentals drift further away from the parity.

Figure 2 displays the results of a simulation based on the linearized version (with $A_1=A_2=0$) of the measurement equation (7) with $\mathfrak{f}_t=f_t$ and the state transition equations (8a,b), again for a deterministic zero fundamental drift ($\eta_t=\eta_{t-j}=0\ \forall\ j$) and a symmetric band (of ±5) for the exchange rate. Instead by stabilizing speculation the exchange rate is now kept within the band by stabilizing intervention, which also leads to stochastic process switching from random walk behaviour to stationary fluctuations. Whilst the relationship between exchange rates and fundamentals in Figures 1a and 2a differ somewhat due to the linear approximation, the time series properties of observable exchange rates in Figures 1b and 2b closely resemble one another and are observationally equivalent.

[14]The noise components v_t and w_t were both generated as standard normal random numbers. All simulations and estimates were carried out in GAUSS, version 2.0.

To model the behavior of exchange rates in imperfectly credible target zones a second type of stochastic process switching, the realignment, has to be allowed for. For simplicity, it is assumed that realignments are initiated whenever it has been repeatedly required that a given parity be defended (say 200 times).[15] Again simulating the linearized version of the target zone model (7, 8a,b) with $f_t = f_t$ for a deterministic zero fundamental drift ($\eta_t = \eta_{t-j} = 0 \ \forall \ j$) and a symmetric band (of ±4) yields the time series processes for exchange rates and fundamentals in Figure 3a, which depicts two types of stochastic process switching: first, observable exchange rates switch from random walk behaviour to stationary stochastic fluctuation at the edges of the bands as the fundamentals drift outside the exchange rate target zone. Second, as intervention becomes unsustainable, the realignment shifts both the exchange rate and the central parity upwards to whatever is the current level of the fundamentals. This stylized behaviour of exchange rates in a target zone with repeated realignments now allows the Bayesian multi–process Kalman filter's ability to detect stochastic process switching to be tested. Note that the occurrence of stochastic process switching, say from unregulated random walk behaviour to regulated stationary stochastic fluctuations (and vice versa after a realignment), is thereby evaluated in terms of the relative probabilities assigned to the alternative process models at each point in time. Figure 3b clearly indicates that the filter tracks stochastic process switches quite well. As fundamentals move outside the exchange rate band (indicated by a dotted vertical line) and intervention forces exchange rates to fluctuate randomly at the upper margin, the Bayesian probability learning process revises upwards the probability π_t^2 of the stabilizing intervention model until it is close to one. As the realignment occurs (indicated by

[15]In the real world the ability to defend the parity and hence the frequency of realignments typically depends on the size of the required intervention given a limited stock of foreign exchange reserves. Extensions of the present time series framework to more structural models of exchange rate target zones with observable fundamentals, as in Miller and Weller (1988, 1989a,b), should formalize this link explicitly.

the dashed vertical line) and exchange rates are again driven by the unregulated random walk of the fundamentals, this probability immediately falls sharply and then converges to zero until the process is repeated. One distinctive feature of the filter deserves special emphasis: there is some delay in the learning about process switching which results from the present choice of a long memory specification (θ=1) of the Bayesian probability learning process in equation (18). Discounting past information (say θ=0.5) would speed up this learning (forgetting) process but would also result in more erratic probability estimates.

Having discussed the type of results to be obtained by the proposed estimation procedure, the empirical estimates of the process switching probabilities inherent in daily EMS exchange rate data may now be described.

5. Empirical Estimates of Stochastic Process Switching Probabilities in the EMS

Before discussing the details of the estimates of process switching probabilities in the EMS it is useful to first give a brief account of the history of EMS realignments and to highlight some stylized facts about EMS exchange rate behaviour.

Table 1 reports that during the sample period (79/03/13 to 90/08/28) twelve EMS realignments took place. During this first decade of the EMS the frequency of EMS realignments has declined, and so has their size. The first impression therefore is that the EMS has recently become a system of more credible exchange rate target zones.

This interpretation is confirmed by the estimates in Figures 4a and 4b, which report the regime averages of the estimated stochastic process switching probabilities for the German mark exchange rates in the EMS. These probability estimates suggest that the EMS has recently converged to a system of credible target zones in which exchange rates fluctuate in an unregulated random walk manner and without tendency to stochastic process switching. This finding may be explained by the fact that the convergence of inflation and interest rates to the low German levels during the late–1982 to mid–1986 deflation period has led to exchange rate fundamentals which no longer possess the tendency to permanently drift outside the band.

A closer look at the results reveals that throughout the first EMS decade the average realignment probabilities were never above 20 percent, with the highest estimate being obtained for the French franc (DM/FF) exchange rate in the first post–1983 regime (83/03/21–85/07/22). Furthermore, except for the French franc and Irish pound (DM/Ir£) exchange rates, the average estimates of realignment probabilities in Figure 4b are negligibly small for the period after the general realignment of 21 March 1983 (regime R7). The impression that the EMS has recently converged to a system of credibly fixed bands is also supported by

Figure 4a. Stationary stochastic fluctuations of exchange rates at the intervention margins appear to have played a major role in the EMS during the period prior to March 1983. Thereafter the probability of stabilizing intervention/speculation is virtually zero for all bilateral DM rates. Furthermore, the results indicate that throughout the pre–1983 period stabilizing intervention/speculation appears to have played a dominant role only for the Irish Pound.

The above regime averages of stochastic process switching probabilities give only a rough picture of the EMS experience. A more detailed account of relevance of stochastic process switching for the DM exchange rate target zones of EMS currencies is revealed by the time–paths of the estimates of stochastic process switching probabilities in Figures 5 to 10, which also display the actual bilateral exchange rates and the EMS target zones implied by the parity grid.

For the French franc (FF) exchange rate high intervention probability estimates are obtained for the period following the first EMS realignment in November 1979 and for the period between the French presidential elections of May 1981 and the second FF devaluation of October 1981 (see Figure 5). The election of President Mitterand and the October 1981 realignment also result in sharp transitory jumps in the realignment probability. Furthermore, the estimates reflect the 'weekend syndrome' of a FF weakness (especially late in the week) due to persistent realignment rumours during March to June 1982 and prior to the realignment in March 1983.[16] The estimated realignment probability thereby remains relatively high even after the adoption of the austerity programme in France. Thus, whilst the substantial tightening of foreign exchange controls after March 1983 may have succeeded in insulating domestic interest rates from speculative attacks, it did not immediately achieve a U–turn in expectations about further devaluations.

[16]See Ungerer *et al.* (1986), Appendix 1, Table 5. on 'EMS: Periods of Strain'.

For the Italian lira rate (DM/Lit) the wide fluctuation band of ±6% is responsible for the consistently low realignment probability estimate, which only increases temporarily during the October 1981 realignment. Furthermore, Figure 6 indicates that high intervention probability estimates are only obtained for the period following the DM weakness in the EMS during October 1980 and for the period of divergent Lira behaviour surrounding the March 1981 realignment.

For the Dutch guilder rate (DM/Hfl) the realignment and intervention probability estimates in Figure 7 are small prior to the March 1983 realignment and zero thereafter. This indicates a perfectly credible target zone in which fundamentals follow an unregulated driftless random walk with a – relative to the level – low error–variance. In fact, Figure 6a indicates that an even narrower target zone than the current ±2.25% would have been fully credible for the post–1983 DM/Hfl exchange rate.

For the Belgian franc rate (DM/BF) high intervention probability estimates are displayed in Figure 8 for the periods of December 1979 to March 1980, March 1981 to September 1981 and around the March 1983 realignment. Note that for all three periods Ungerer *et al.* (1986) report heavy intervention to support the weak BF in the EMS. A high realignment probability is only found for December 1981, as pressure on the BF (divergence indicator below –75) emerged following the breakdown of negotiations to form a government. Finally, the post–1985 DM/BF target zone is found to be fully credible, despite the fact that the BF was weak, that is, in the lower half of the target zone almost throughout this period.

In Figure 9 the Danish krona rate (DM/Dkr) has high realignment probabilities only in the period between September 1979 and March 1980, during which the Dkr was the weakest EMS currency and devalued twice against all other currencies. Apart from some wavering during 1981 a high intervention probability estimate for the Dkr is only obtained for the period of December 1982 to March 1983, during which a comprehensive stabilization programme (temporary wage freeze and progressive dismantling of capital controls) was initiated. Again, the post–1985 DM/Dkr target zones are fully credible, whereby the Dkr had periods of both strength and weakness relative to the DM in the EMS.

For the Irish pound rate (DM/Ir£) non–zero realignment probability estimates are displayed in Figure 10 for the period surrounding the October 1981 and August 1986 realignments. However, high intervention probability estimates are obtained throughout the pre–1984 period, in particular prior to EMS realignments when the exchange rates fluctuated for prolonged periods around the intervention thresholds. In fact, the time path of the pre–1983 DM/Ir£ exchange rate resembles many characteristics of the simulations for imperfectly credible target zones from Figure 4. However, for the post–1987 period the DM/Ir£ exchange rate behaviour is fundamentally different and the bilateral target zones become fully credible. This is consistent with the results of Weber (1991), which show that recently the Irish pound has become one of the hard EMS currency which is credibly pegged to the German mark.

Finally, the results for the Spanish peseta rate (DM/Pta), which has been subject to a wide fluctuation band of ±6% since June 1989, differ drastically from those for the above older EMS currencies. In particular, non–zero realignment and intervention probability estimates are to be found for the post–1987 period prior to the Spanish ERM entry, and again towards the end of the sample. This suggests that in spite of the relative strength of the peseta to the mark, the Spanish DM target zone is not yet fully credible.

Summarizing the above evidence it may be stated that stochastic process switching was an important feature of the EMS in its early period, as predicted by exchange rate target zone models. Recently, such frequent stochastic process switching has vanished. Two important conclusions derive from this: first, EMS target zones have recently become more credible. This provides the necessary pre–request for the intended tightening of exchange rate target zones during 'stage 2' of the Delors' plan for a transition to economic and monetary union (EMU). Second, stochastic process switching due to stabilizing intervention and/or stabilizing speculation (Krugman's 'honey moon' effect) also appear to be absent recently as random walk exchange rate fundamentals appear to no longer possess the tendency to drift outside the given bands. In a target zone framework one may argue that the given bands of ±2.25% are nowadays too wide to induce stabilizing speculation. Driftless random walk exchange rates with low noise components may require much narrower bands to create 'honeymoon effects'. Moving ahead with 'stage 2' of the transition to EMU and tightening the fluctuation margins may therefore revive these potential merits of exchange rate bands.

6. EMS Intervention and Stochastic Process Switching Probabilities

In addition to evaluating the relevance of target zone models, the above evidence may be used to obtain important insights into the intervention schemes adopted by EMS central banks. Such foreign exchange market interventions are typically subject to central bank secrecy and mystique, and intervention data are generally not available to the public. However, in order to check whether the above intervention probability estimates and their time paths consistently track down actual DM interventions of EMS central banks, the knowledge of the quantitative intervention data is not necessary. Instead, a qualitative intervention dummy or (–1,0,1)–variable, which indicates daily net sales (–1), net purchases (1) or absence of foreign exchange market interventions, would suffice.

Such qualitative (–1,0,1) information about EMS interventions of the Bundesbank, which in principle can be constructed from the central bank's monthly publications,[17] is displayed in the bottom panel of Figure 12. The

[17]The "Statistische Beihefte zu den Monatsberichten der Deutschen Bundesbank, Reihe 5", indicate periods of changes (net sales and purchases) in the Bundesbank's net foreign exchange reserve position due to EMS interventions. A dummy variable constructed from this source does not substantially differ from the corresponding coding of actual EMS intervention data, which were used in the present study.

similarity to the time paths of the intervention probability estimates displayed in Figure 4a is striking, in particular with respect to the differences between the pre–1983 and the post–1983 system.

An obvious related question, which is of interest in the context of target zone models, is whether the Bundesbank's EMS interventions have been predominantly obligatory marginal interventions or intramarginal interventions. To answer this question, the remaining panels of Figure 12 display bilateral DM target zone dummies, which are equal to zero if the exchange rate is strictly within the band, equal to one if it is at (or slightly above) the upper boundary, and equal to minus one at (or slightly below) the lower boundary. The most remarkable result of Figure 12 is that the intervention dummy can be almost completely constructed by aggregating all bilateral DM target zone dummies. Thus, there is clear evidence that most EMS interventions of the Bundesbank must be attributed to compulsory marginal intervention. This strongly supports the results reported in Camen (1986), Giavazzi and Giovannini (1987), Claassen (1988) and Mastropasqua *et al* (1988), who all reach similar conclusions.

With a view to the relevance of target zone models for the EMS two key findings from above deserve emphasis: first, except for the Irish pound, a non–zero probability of stationary exchange rate movements typically coincides with stabilizing intervention. Second, stabilizing intervention generally takes the form of obligatory intervention at the boundaries of the band. Both results together leave little room for attributing stochastic process switching in DM exchange rates of EMS currencies to stabilizing speculation of the type postulated in target zone models.

7. Conclusions and Suggestions for Further Research

The above empirical evidence suggests that stochastic process switching of EMS exchange rates has played a vital role in the early stages of the system, especially in the period prior to the March 1983 realignment. Recently, in particular after the realignment of January 1987, such stochastic process switching of exchange rates has vanished completely and EMS exchange rate target zones have become highly credible. This new found stability of the nominal EMS exchange rate target zones has to be viewed as the outcome of an increased stability of EMS exchange rate fundamentals, caused by the convergence of inflation and interest rates during the 1982–86 deflation period. The latter hypothesis is, however, not formally tested in the present paper. Extension of the present analysis to empirical work on stochastic process switching probabilities in target zone models with observable fundamentals are clearly the next step of investigation. Several directions of promising further research exist.

First, exchange rate fundamentals may be approximated by observable economic variables, say by interest rate differentials, as in Svensson (1989, 1991b), Bertola and Caballero (1990) or Flood, Rose and Mathieson (1990). In this case the target zone for the exchange rate translates into a target zone for interest rate differentials, which consequently will also exhibit stochastic process switching as speculative attacks or stabilizing interventions occur. Applying the same methods as above will extract estimates of these process switching probabilities from the data. The advantage of using interest rate data in addition to exchange rates thereby is that interest rates, in particular off–shore rates, have a large speculative component and typically reflect expectations about realignments before these actually take place. A similar argument applies to forward exchange rates or foreign exchange risk premia, which are analysed in a target zone context in Svensson (1991a, 1991c), Flood, Rose and Mathieson (1990) and Bartolini and Bodnar (1990). The point is that both interest rate differentials and forward exchange rates allow evidence to be obtained on increased realignment probabilities under speculative attacks in addition to inferring stochastic process switching to stabilizing intervention from spot exchange rate data prior to a realignment.

A second alternative to the present time series approach is to interpret the state space model (12a,b) as a structural target zone model with observable fundamentals ($z_t^{'}$), given say by a vector including a constant (c) and the interest rate differential ($i_t - i_t^*$). Using the Bayesian multi-process approach in a regression model with time-varying coefficients (a_t) provides a framework for testing (in a probabilistic context) during which periods exchange rates are driven by the observable fundamentals ($i_t - i_t^*$) and when stochastic process switching to stationary fluctuations around some constant (c) occurs.

A third option is to use the linearized approximation of the measurement equation (7) together with its non-linear form (6) in the Bayesian multi-process regression model based on the extended Kalman filter and to evaluate directly the relevance of this non-linearity assumption of target zone models in terms of the relative probability assigned to both models by real world data.

Finally, non-linear models of continuous state space trajectories driven by regulated Brownian motion and controlled via discrete high frequency measurement (radar tracking) exist in the technical literature on satellite orbit determination. Optimal filtering and smoothing algorithms for such non-linear discrete-continuous state-space models based on the extended Kalman filter are available and may be fruitfully applied to target zone models.

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Tab. 1: EMS Realignments, ECU Weight Revisions and Major Council Decisions

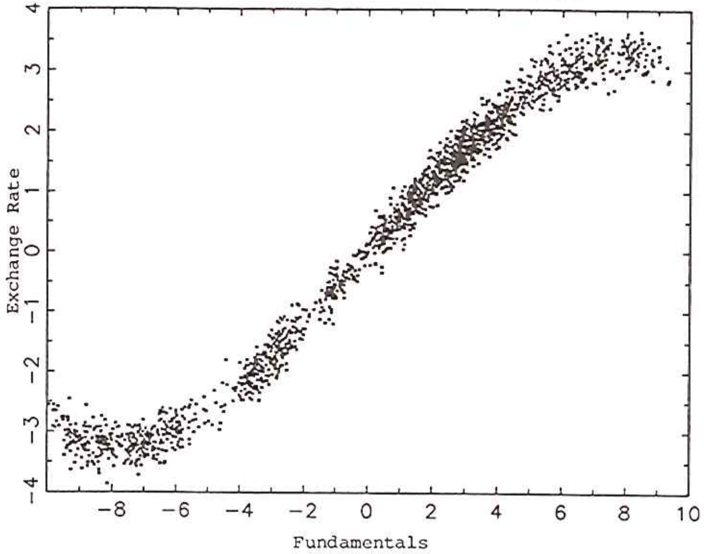
1979	Mar. 13	exchange rate mechanism (ERM) starts to operate; initial currency weights in ECU currency basket: DM 32.0%, FF 19.0%, UKL 15.0%, Lit 10.2%, Hfl 10.1%, BF 8.5%, Dkr 2.7%, Dra 1.3%, IrL 1.2%	
	Sep. 24	1. realignment	(DM +2%, Dkr -2.9%)
	Nov. 30	2. realignment	(Dkr -4.8%)
1981	Mar. 22	3. realignment	(Lit -6%)
	Oct. 5	4. realignment	(DM +5.5%, FF -3%, Lit -3%, Hfl +3.5%)
1982	Feb. 22	5. realignment	(BF -8.5%, Dkr -3%)
	June 14	6. realignment	(DM +4.25%, FF -5.75%, Lit -2.75%, Hfl +4.25%)
1983	Mar. 21	7. realignment	(DM +5.5%, FF -2.5%, Lit -2-5%, Hfl +3.5%, BF +1.5%, Dkr +2.5%, IrL -2.5%)
1984	Sep. 17	revision of currency weights in ECU currency basket (DM 32.0%, FF 19.0%, UKL 15.0%, Lit 10.2%, Hfl 10.1%, BF 8.5%, Dkr 2.7%, Dra 1.3%, IrL 1.2%)	
1985	July 22	8. realignment	(DM +2%, FF +2%, LIT -6%, Hfl +2%, BL +2%, Dkr +2%, IRL +2%)
1986	Apr. 7	9. realignment	(DM +3%, FF -3%, Hfl +3%, Bf +1%, Dkr +1%)
	Aug. 4	10. realignment	(IRL -8%)
1987	Jan.12	11. realignment	(DM +3%, Hfl +3%, Bf +2%, Dkr +2%)
	Sep. 12	Basle–Nyborg Agreement of the Committee of Central Bank Governors to strengthen the ERM; measures include a wider use of fluctuation bands	
1989	June 19	Spain enteres the exchange rate mechanism of the EMS with a wide fluctuation margin of ±6%	
	Sep. 21	revision of currency weights in ECU currency basket (DM 30.1%, FF 19.0%, UKL 13.0%, LIT 10.15%, Hfl 9.4%, Bf 7.9%, PES 5.3%, Dkr 2.45%, IRL 1.1%, DRA 0.8%, ESC 0.8%)	
1990	Jan. 8	12. realignment	(LIT - 3.7%), narrowing of band to ±2.25%
	Oct. 8	United Kindom enters the exchange rate mechanism of the EMS with a wide fluctuation margin of ±6%	

Sources: OECD *Economic Surveys*: *Germany*, *France*, *Italy*, *Netherlands*, *Belgium and Luxembourg*, *Denmark*, *Ireland*, various issues, Commission of the European Communities *The EMS*: *Ten Years of Progress in European Monetary Co-operation*, and Ungerer *et al.* (1986).

Notes: At realignments + (-) indicates a revaluation (devaluation) in % against those currencies whose bilteral parities remained unchanged, except for the two general realignments (March 1983, July 1985), for which the percentages from the official communiqué are shown.

Fig. 1: Exchange Rates and Fundamentals in a Credible Target Zone

(a) Relationship between Exchange Rates and Fundamentals



(b) Time Series Behaviour of Exchange Rates and Fundamentals

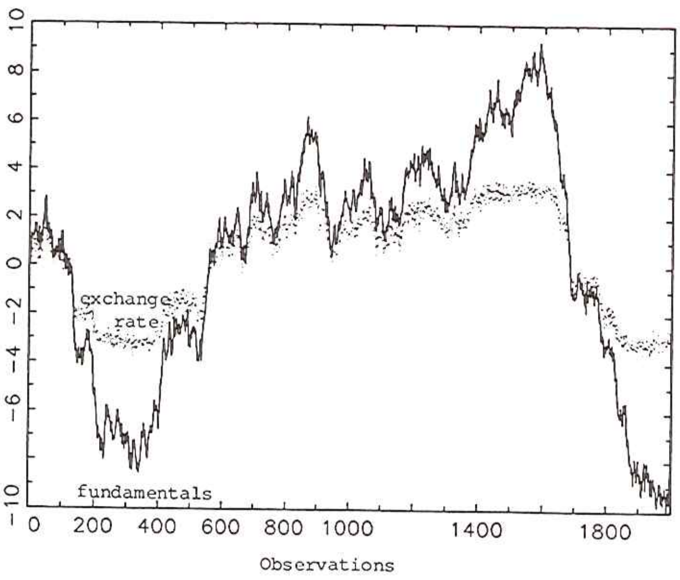
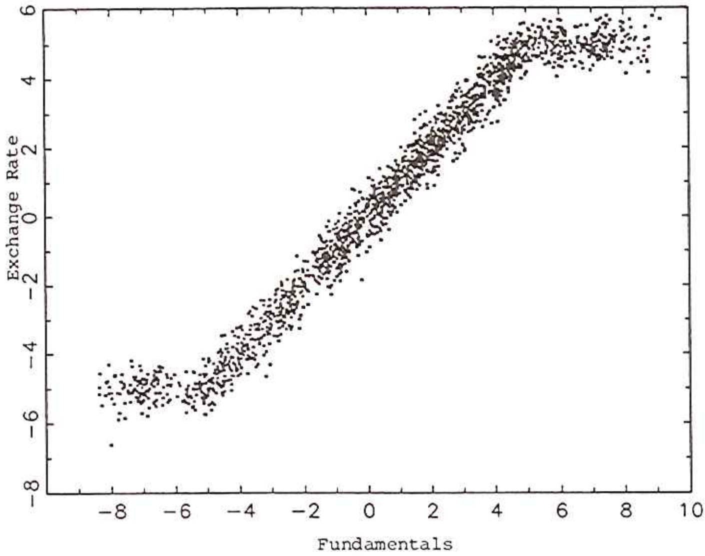


Fig. 2: Exchange Rates and Fundamentals under Stochastic Process Switching

(a) Relationship between Exchange Rates and Fundamentals



(b) Time Series Behaviour of Exchange Rates and Fundamentals

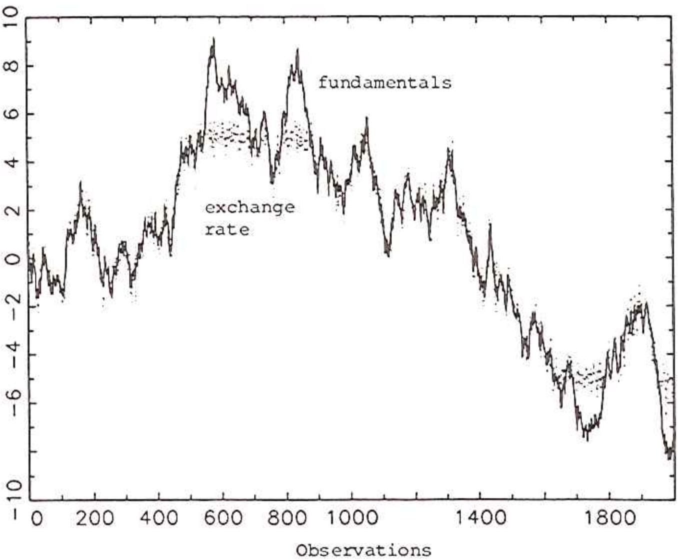
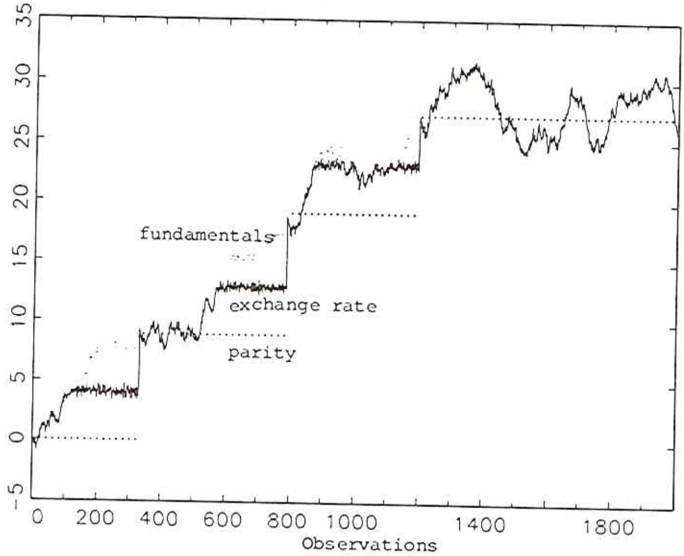


Fig. 3: Exchange Rates and Fundamentals under Stochastic Process Switching and Realignments

(a) Time Series Behaviour of Exchange Rates and Fundamentals



(b) Multi-Process Kalman Filter Estimates of Stochastic Process Switching Probabilities

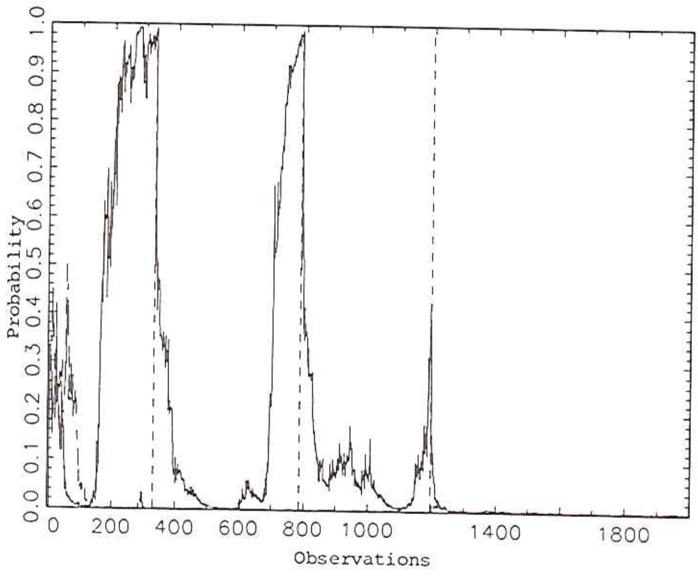
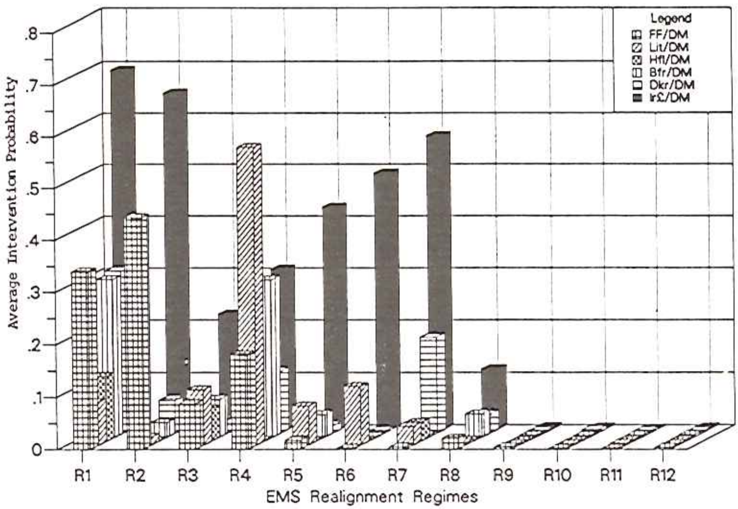


Fig. 4: Period Averages of Estimated Stochastic Process Switching Probabilities

(a) Average Intervention Probability



(b) Average Realignment Probability

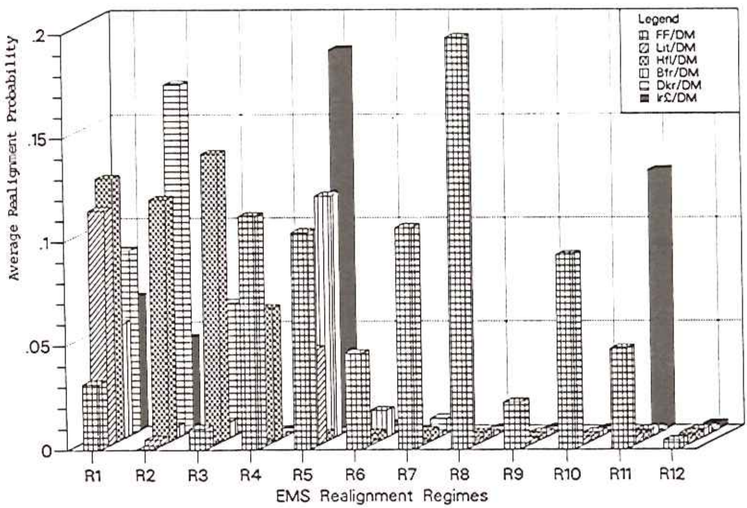
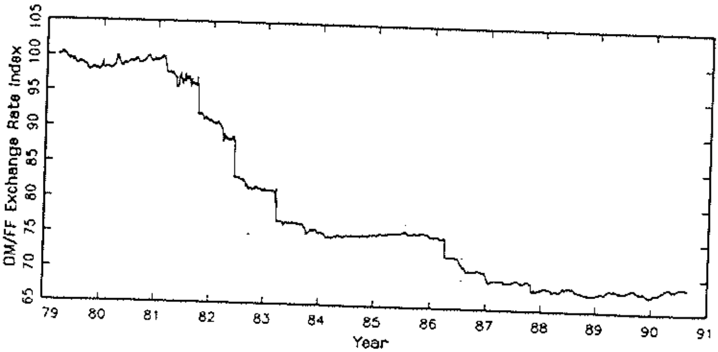
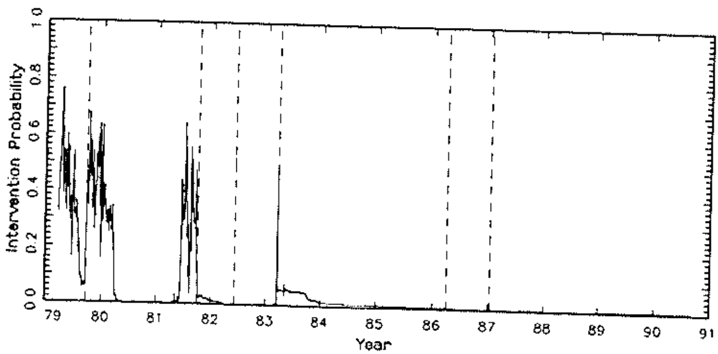


Fig. 5: Bilateral DM/FF Exchange Rate Target Zones in the EMS and Estimates of Stochastic Process Switching Probabilities

(a) DM/FF Exchange Rate and EMS Target Zones



(b) Estimates of Intervention Probability



(c) Estimates of Realignment Probability

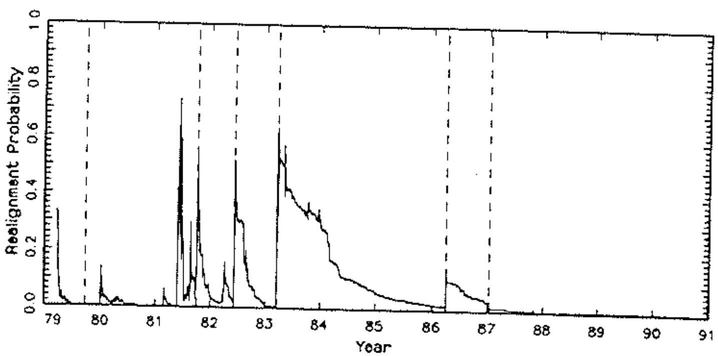
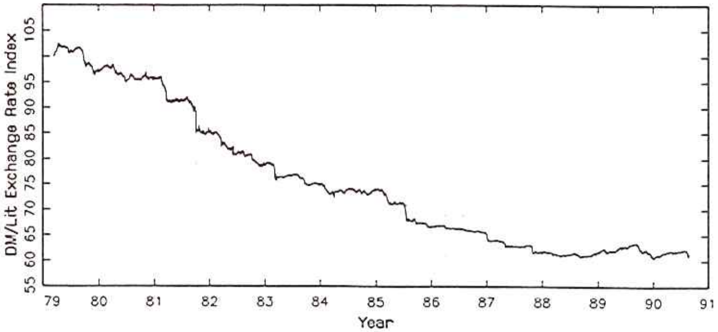
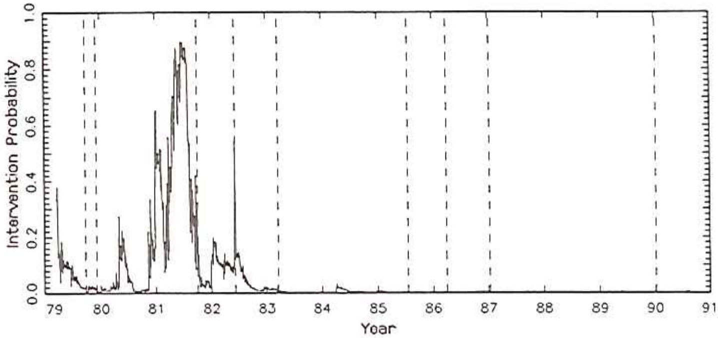


Fig. 6: Bilateral DM/Lit Exchange Rate Target Zones in the EMS and Estimates of Stochastic Process Switching Probabilities

(a) DM/Lit Exchange Rate and EMS Target Zones



(b) Estimates of Intervention Probability



(c) Estimates of Realignment Probability

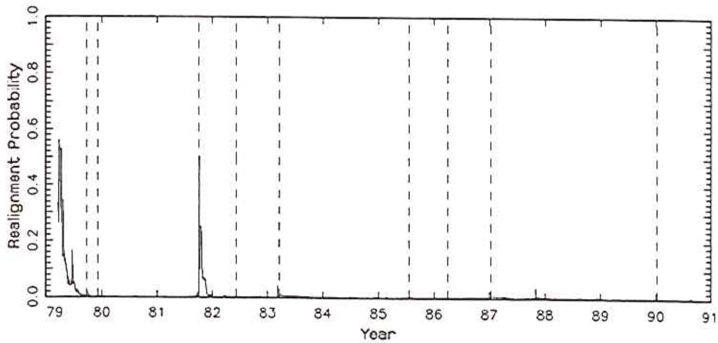
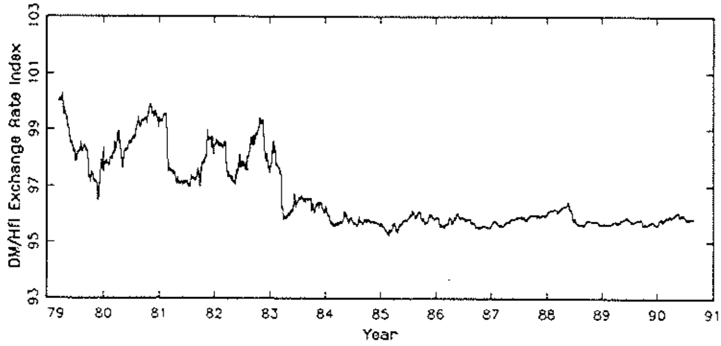
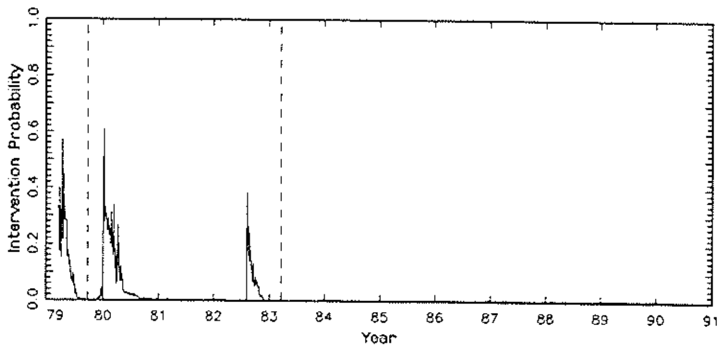


Fig. 7: Bilateral DM/Hfl Exchange Rate Target Zones in the EMS and Estimates of Stochastic Process Switching Probabilities

(a) DM/Hfl Exchange Rate and EMS Target Zones



(b) Estimates of Intervention Probability



(c) Estimates of Realignment Probability

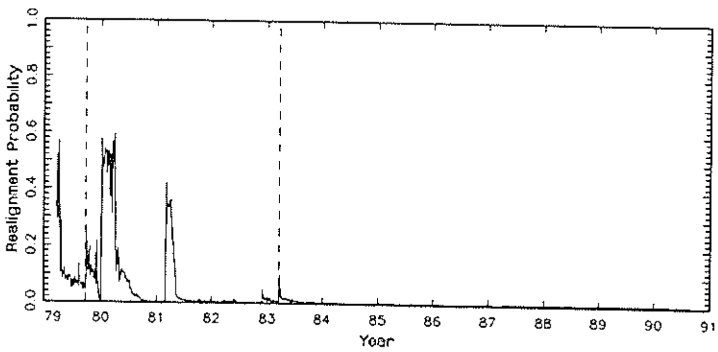
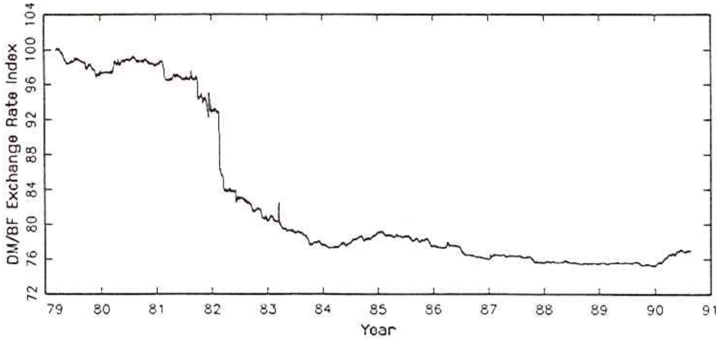
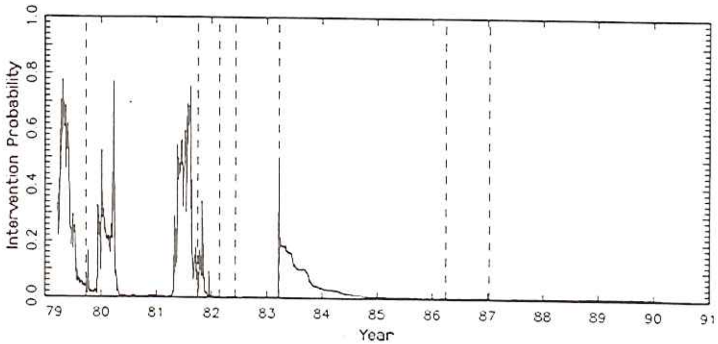


Fig. 8: Bilateral DM/BF Exchange Rate Target Zones in the EMS and Estimates of Stochastic Process Switching Probabilities

(a) DM/BF Exchange Rate and EMS Target Zones



(b) Estimates of Intervention Probability



(c) Estimates of Realignment Probability

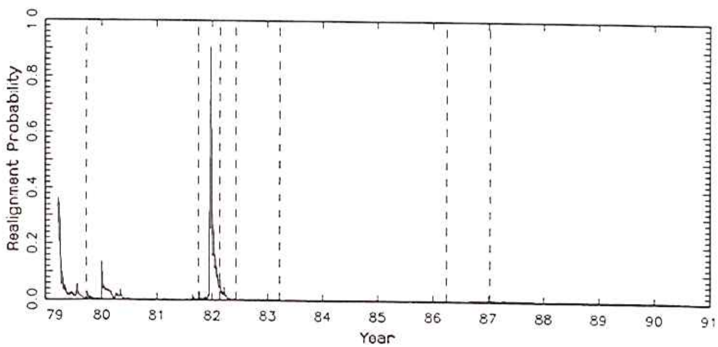
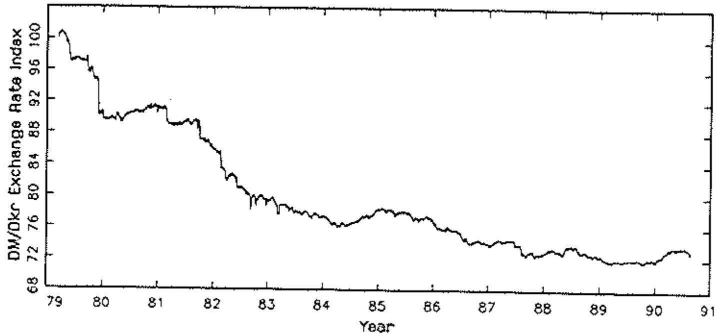
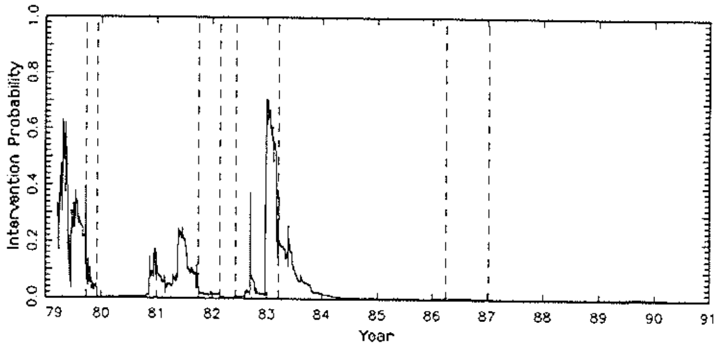


Fig. 9: Bilateral DM/Dkr Exchange Rate Target Zones in the EMS and Estimates of Stochastic Process Switching Probabilities

(a) DM/Dkr Exchange Rate and EMS Target Zones



(b) Estimates of Intervention Probability



(c) Estimates of Realignment Probability

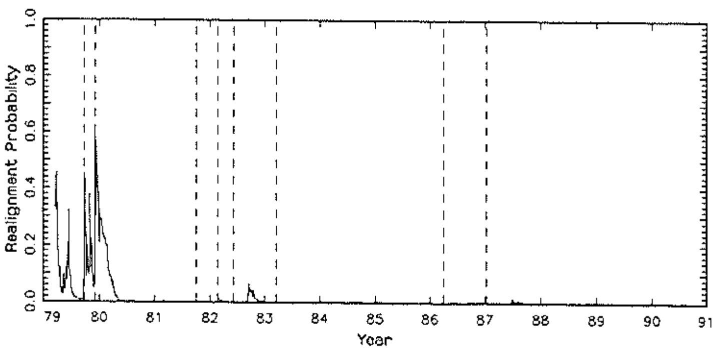
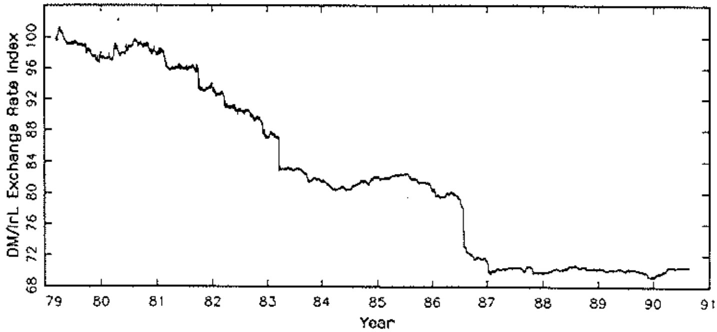
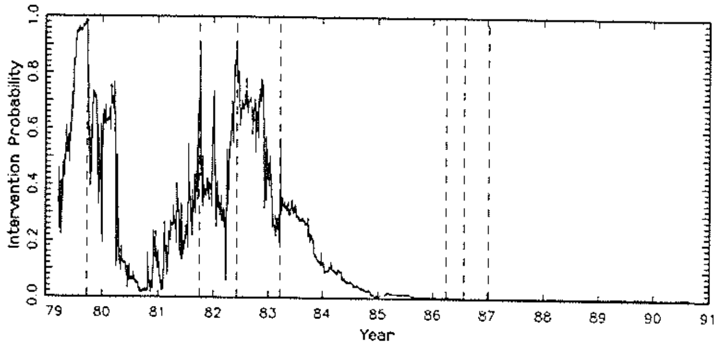


Fig. 10: Bilateral DM/IrL Exchange Rate Target Zones in the EMS and Estimates of Stochastic Process Switching Probabilities

(a) DM/IrL Exchange Rate and EMS Target Zones



(b) Estimates of Intervention Probability



(c) Estimates of Realignment Probability

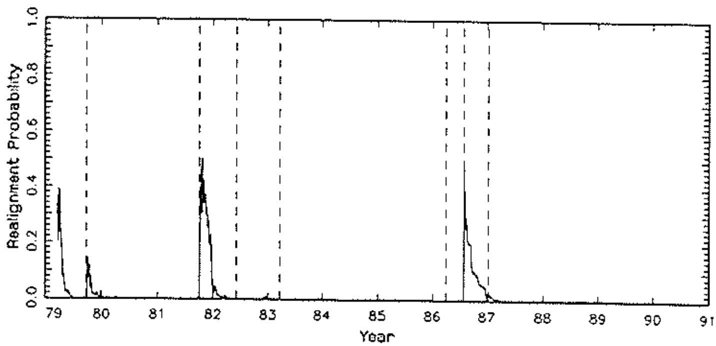
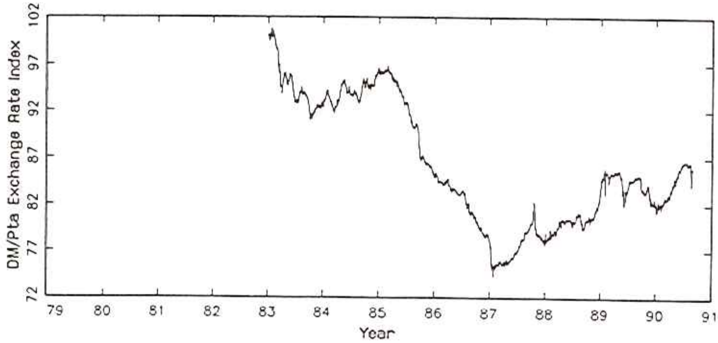
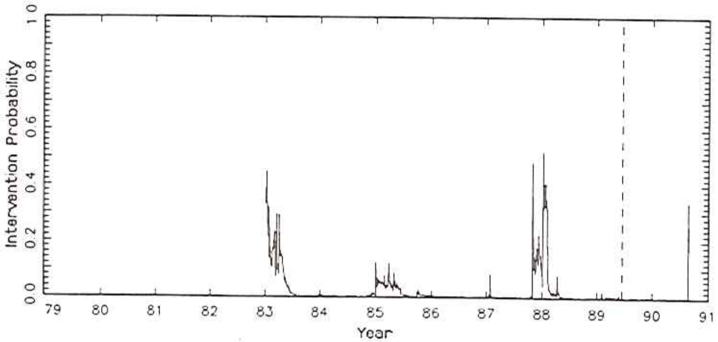


Fig. 11: Bilateral DM/Pta Exchange Rate Target Zones in the EMS and Estimates of Stochastic Process Switching Probabilities

(a) DM/Pta Exchange Rate and EMS Target Zones



(b) Estimates of Intervention Probability



(c) Estimates of Realignment Probability

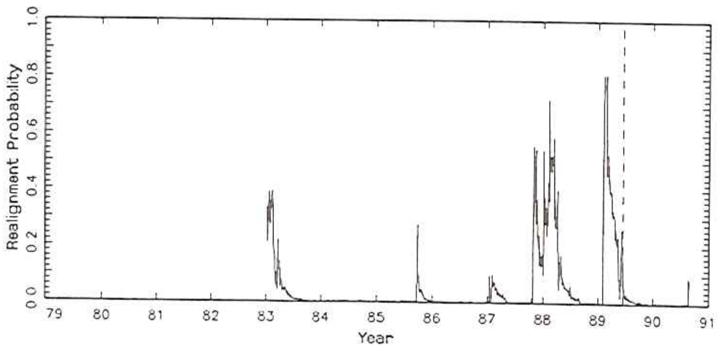


Fig. 12: EMS Target Zone Dummies Indicating a Position at the Boundaries and EMS Intervention Dummy for the German Bundesbank