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Informal One-Sided Target Zone Model and the Swiss Franc*

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Abstract

This paper develops a new theoretical model with an asymmetric informal one-sided exchange rate target zone, with an application to the Swiss franc following the removal of the minimum exchange rate of CHF 1.20 per euro in January 2015. We extend and generalize the standard target zone model of Krugman (1991) by introducing perceived uncertainty about the lower edge of the band. We find that informal soft edge target zone bands lead to weaker honeymoon effects, wider target zone ranges and higher exchange rate volatility than formal target zone bands. These results suggest that it would be beneficial for exchange rate policy intentions to be stated clearly in order to anchor exchange rate expectations and reduce exchange rate volatility. We also study how exchange rate dynamics can be characterized in models in which financial markets are aware of occasional changes in the policy regime. We show that expected changes in the central bank's exchange rate policy may lead to exchange rate oscillations, providing an additional source of exchange rate volatility, and to capture this it is important to take into account the possibility of regime changes in exchange rate policy.

Keywords: Swiss franc, target zone model, exchange rate interventions
JEL-Classification : F31, E42, C61

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1. Introduction

Since the outbreak of the euro area crisis, Swiss exchange rate policy has been a hotly debated topic. From September 2011 to January 2015 the official exchange rate policy of the Swiss National Bank (SNB) was to maintain a minimum exchange rate of CHF 1.20 per euro. To achieve this objective, the central bank stated that it would be willing to buy foreign currency in unlimited quantities. On 15 January 2015, the SNB took markets by surprise with its decision to discontinue Switzerland's currency floor (SNB, 2015; Jerman, 2016).

Countering an appreciating currency ought to be easier than countering a depreciating currency. A central bank trying to prop up the exchange rate can run out of foreign exchange reserves. A central bank aiming for depreciation can credibly promise to buy as much foreign currency as it takes, since it can print its owncurrency in unlimited amounts. By discontinuing the so-called "minimum exchange rate" in January 2015, the SNB showed that a theoretically unlimited strategy to defend a currency floor may have practical bounds. In particular, there may be an upper limit to how far a central bank balance sheet can grow, including due to concerns about potential future losses on foreign exchange reserves, as suggested for example by Amador, Bianchi, Bocola, and Perri (2016). Amador et al. (2016) provide a theoretical model in which a central bank wants to maintain an exchange rate peg, and responds to increases in demand for domestic currency by expanding its balance sheet. They model so-called 'reverse speculative attacks' triggered by the concern of future balance sheet losses of the central bank. They find that the interaction between the desire to maintain an exchange rate peg and the concern about future balance sheet losses can lead the central bank to first accumulate a large amount of reserves, and then to abandon the peg, and conclude that this was just as had been observed in the Swiss case. The fact that a Swiss referendum was held on 30 November 2014 over the proposition that the SNB should hold at least 20% of its reserves in gold (The Economist, 2014), suggests that there was some political pressure to limit losses on the central bank's balance sheet, even though the referendum was defeated. Thus there may be a limit to conducting central bank policy by steering the exchange rate. As a consequence, the SNB resorted, like many other central banks, to cutting interest rates with all the risks of feeding market distortions that such a policy may entail (see Bank for International Settlements, 2010).

The model presented in this paper applies to the situation where there is no formal one-sided target zone for the currency, but where there are market perceptions of an informal one-sided target zone. This may have been the case following the discontinuation of the SNB's currency floor in January 2015, since proxy measures for the SNB's foreign exchange interventions presented below suggest that the SNB likely continued to intervene in the foreign exchange market.

In light of the fact that exchange rate regimes have been at the centre of academic debate and have been a major concern for policymakers in recent years, this paper develops a new theoretical model with an asymmetric informal (unofficial, not publicly announced) one-sided target zone. Such a model incorporates the notion that the target zone can be seen as a partially credible commitment device. It can be regarded as a generalisation of Krugman's (1991) simple target zone model of exchange rates. In the standard model, the peg and the hard edge boundaries are publicly announced and credible, and market arbitrage mechanisms and interventions take place in whatever amounts are necessary to prevent the target zone from being violated. Our paper is not a normative analysis of the best exchange rate policy or exchange rate target, especially given uncertainty about fundamental drivers of exchange rates.

We find that informal soft edge target zone bands lead to weaker honeymoon effects, wider target zone ranges and higher exchange rate volatility than formal target zone bands. The honeymoon effect stabilises the exchange rate relative to its fundamentals. It refers to the phenomenon that, if the Swiss franc is close to the informal floor, the probability increases that the Swiss franc will hit the floor, which leads to perceived interventions by the central bank. These results suggest that it would be beneficial for exchange rate policy intentionsto be stated clearly in order to anchor exchange rate expectations and reduce exchange rate volatility. We also study how exchange rate dynamics can be characterized in models in which financial markets are aware of occasional changes in the policy regime. We show that expected changes in the central bank's exchange rate policy may in addition be a source of exchange rate oscillations, providing an additional source of exchange rate volatility, and to capture this it is important to take into account the possibility of regime changes in exchange rate policy.

The paper proceeds as follows. Section 2 presents the evolution of the Swiss franc-euro exchange rate, and Section 3 presents proxy measures for the SNB's foreign exchange interventions as a function of the EUR/CHF exchange rate, at both a weekly and monthly frequency. Section 4 presents the model and its solution using Switzerland as a motivating example. Analytically, the modelling approach lies at the crossroads of the literature on exchange rate target zones originated by Krugman (1991) and the literature on intervention in the foreign exchange market. With the aim of parsimony in mind, but also wanting to ensure a fair degree of reality, we extend and generalize the standard target zone model by introducing perceived uncertainty about the lower edge, as following the policy change in January 2015. Section 5 concludes, draws some policy implications and hints at future research.

2. Swiss franc-euro exchange rate and currency floor

Within minutes of the announcement to discontinue the minimum exchange rate on 15 January 2015, the Swiss franc rose by 40 percent against the euro (see Figure 1). Following the announcement, the Swiss franc even reached parity against the euro.[1] Following this initial overshooting, the Swiss franc subsequently depreciated from this low level. The model of this paper for an informal one-sided target zone for the Swiss franc presented in Section 4 applies to this latter period, after the initial overshooting. That is, our model applies to a situation where there was no longer a formal one-sided target zone, but when there may have been market perceptions of an informal, not publicly announced, one-sided target zone, since the SNB likely continued to intervene in the foreign exchange market, as suggested by the proxy measures for the SNB's foreign exchange interventions presented in Section 3.[2]

The currency floor had been introduced in 2011 to halt the appreciation of the Swiss franc, and it protected the country's many exporters.[3] It had been effective in preventing an even larger erosion of the competitive position of Swiss exporters. According to the SNB's assessment on 15 January 2015, "The minimum exchange rate was introduced during a period of exceptional overvaluation of the Swiss franc and an extremely high level of uncertainty on the financial markets. This exceptional and temporary measure protected the Swiss economy from serious harm. While the Swiss franc is still high, the overvaluation has decreased as a whole since the introduction of the minimum exchange rate. The economy was able to take advantage of this phase to adjust to the new situation" (SNB, 2015). Streit (2016) finds evidence for Swiss non-financial firms of significant reductions in total stock return volatility as well as market risk following the introduction of the currency floor. In order to counter the appreciation of the Swiss franc, the SNB also announced on 18 December 2014 that it would introduce a negative interest rate of –0.25% on sight deposit account balances at the SNB starting on 22 January 2015, which was reduced further to –0.75% on 15 January 2015, in order to "ensure that the discontinuation of the minimum exchange rate does not lead to an inappropriate tightening of monetary conditions" (SNB, 2015).

[Figure 1 about here]

3. SNB Foreign Exchange Interventions

The model presented in Section 4 applies to the situation where there is no formal one-sided target zone for the Swiss franc, but where there are market perceptions of an informal, not publicly announced, one-sided target zone. This may have been the case following the discontinuation of the SNB's currency floor in January 2015, since proxy measures for the SNB's foreign exchange interventions presented in this Section suggest that the SNB likely continued to intervene in the foreign exchange market.

Between the dates of the introduction of the CHF 1.20 per euro floor and its discontinuation, the SNB's foreign currency reserves increased significantly. At the end of December 2014 they reached CHF 495 billion or almost 80 percent of Swiss GDP – up from CHF 254 billion or almost 45 percent of Swiss GDP at the end of 2011. And with the ECB´s quantitative easing programme, the required amounts of foreign exchange intervention to maintain the floor were about to become far higher, increasing the risk of larger losses on foreign exchange reserves in future. For example, SNB governing board member Zurbrügg mentioned that maintaining the minimum exchange rate would have required increasingly higher foreign exchange interventions: "According to SNB Governing Board member Fritz Zurbrügg, the [Swiss] National Bank would have had to intervene with increasingly large amounts in the foreign exchange market in order to maintain the minimum exchange rate. […] "Extrapolated to one month, we would have had to intervene with around 100 billion francs in January alone", Zurbrügg said in an interview last week […].” Following the discontinuation of the CHF 1.20 per euro floor in January 2015, the SNB’s foreign exchange reserves continued to increase.

In the announcement to discontinue the minimum exchange rate on 15 January 2015, the SNB mentioned that it will “continue to take account of the exchange rate situation in formulating its monetary policy in future. If necessary, it will therefore remain active in the foreign exchange market to influence monetary conditions” (SNB, 2015). Since then the SNB has remained vague about exchange rate interventions ex-post, and generally does not confirm speculations about interventions, with a few exceptions. The SNB also reduced the negative interest rate to –0.75% on 15 January 2015, in the words of former vice-chair Danthine, to “reinstate an interest rate differential with respect to the eurozone, in particular, to limit the appreciation of the CHF that was viewed as the inevitable result of abandoning the floor” (Danthine, 2016).

The most recent SNB interventions have mostly not been publicly announced by the SNB.[4] Ahead of the Brexit referendum, for instance, the SNB did not announce that it would intervene, but referred more generally to taking measures if necessary: “As a small open economy Switzerland is strongly exposed to developments abroad. When the United Kingdom votes next week on whether to remain in the European Union, it can lead to increased uncertainty and turbulences. In this context we will monitor the situation closely and will take measures if needed.” (Jordan, 2016).

Following Brexit, the SNB publicly announced that it had intervened: “"Following the UnitedKingdom’s vote to leave the European Union, the Swiss franc came under upward pressure," the central bank said via e-mail. "The Swiss National Bank has intervened in the foreign exchange market to stabilize the situation and will remain active in that market"” (Bloomberg, 2016). SNB president Jordan confirmed the intervention over the weekend following Brexit: “"We have always said that we are active in the foreign exchange market if necessary," SNB Chairman Thomas Jordan said at a finance event in Bern, Switzerland. "A situation like we experienced over the weekend is a situation which warranted this need and we went in to stabilize the market."” (Reuters, 2016). Another exception was at the height of the euro area sovereign debt crisis (Bloomberg, 2015, as cited below).

Some evidence suggests that foreign exchange intervention is often geared to limiting what policymakers may see as unwarranted, and possibly harmful, deviations from equilibrium levels (Daude & Yeyati 2014; Bank for International Settlements 2005, 2013).[5] Daude, Yeyati, and Nagengast (2014) present evidence for the prevalence of such exchange rate intervention in emerging economies, and show that it mitigates real exchange rate volatility. An overvalued exchange rate may be generated in the presence of safe haven effects arising in situations of pronounced uncertainty and/or if the exchange rate overreacts to news. In this case, exchange rate intervention against the direction that the exchange rate is moving may be a useful instrument to reduce the distortion.

The theoretical literature on optimal exchange rate interventions is enormous. For a seminal paper, see Boyer (1978). Reeves (1997) constructed a game-theoretic framework with partial credibility and non-rational expectations to examine the mode of action of the signalling channel. In this set-up exchange rate interventions represent signals of future monetary policy and hence affect exchange rate expectations. Note that it is not at all clear that exchange rate interventions will always be beneficial. In particular, the central bank may not know the true economic fundamentals but face uncertainty and misperceptions about them. Moreover, the central bank may not be capable of correctly identifying the equilibrium exchange rate implied by the fundamentals or, even if it would be able to do so, the costs of the exchange rate interventions may be too high relative to the benefits. Furthermore, persistent changes in investor preferences can have persistent effects on exchange rates.

Another argument supportive of a case for exchange rate interventions is that the authorities’ information set may be superior to the information set of market participants. On this argument the central bank could make the intervention data set publicly available, since this would eliminate the informational asymmetry.[6]

Archer (2005) argues thattransparent foreign exchange intervention is preferable to secret intervention because it increases the power of the signalling and coordination channels, which increases the effectiveness of intervention. A number of explanations have been put forward to explain why foreign exchange interventions may not be made public. In a situation of high uncertainty and volatility of foreign exchange markets, it may be risky for a central bank to announce publicly the intention of intervening, especially if the effectiveness may not be believed by market participants (see Cukierman & Meltzer, 1986).

Transparency about foreign exchange intervention and exchange rate policy may have adverse effects, which need to be weighed against the potential benefits of transparency about exchange rate policy and intervention implied by the signalling channel. Possible adverse effects include increased pressure on the exchange rate from possible speculative attacks, for which communication about foreign exchange intervention or exchange rate policy could function as a coordination device, and increases in the size of speculative flows and in the costs of carrying reserves (Chutasripanich & Yetman, 2015). Ambiguity about past and planned amounts of foreign exchange intervention and desired exchange rates may help a central bank counter or prevent coordinated speculative attacks. This is in contrast to communication about the monetary policy framework in the form of an inflation target, and in contrast to communication about the policy rate (for surveys see Blinder, Ehrmann, Fratzscher, de Haan, & Jansen, 2008, and Moessner, Jansen, & de Haan, 2017), where no such adverse effects from speculative attacks are present.

For example, in Mexico a transparent rule-based foreign exchange intervention mechanism introduced in December 2014 was discontinued in February 2016 because of pressures on the exchange rate, including due to apparent speculation by foreign exchange traders against the rule-based mechanism, while the possibility of future discretionary intervention was kept open (Domanski, Kohlscheen, & Moreno, 2016).[7] Due to an increase of electronic trading volumes (accounting for around two thirds of foreign cash market turnover in 2015, an increase from less than 50% before the global financial crisis), the effects of foreign exchange intervention on the exchange rate may depend more and more on the central bank's ability to surprise markets (Domanski et al, 2016). Some papers find that central banks use secret foreign exchange intervention to maximise the impact on the exchange rate (Dominguez & Frankel, 1993; Neely, 2001; Sarno & Taylor, 2001).

Weekly FX intervention proxy

Sight deposits are currently the most important means of financing for SNB currency purchases. Thus changes in total sight deposits in Swiss francs at the SNB are a proxy for the SNB's FX interventions (Auer, 2015).[8] But sight deposits can also change for reasons other than interventions, for example due to flight-to-safety by banks, and they are therefore only an imperfect proxy measure for foreign exchange interventions.

This proxy measure of changes in total sight deposits in Swiss francs at the SNB is available at weekly frequency from the SNB, which is at higher frequency than the monthly foreign exchange reserves data, and therefore gives a more time-exact picture of the associated exchange rate levels.[9] Changes in total sight deposits in Swiss francs at the SNB, from the week starting 19 January 2015, i.e. after removal of minimum exchange rate, to mid-July 2016, against weekly averages of the EUR/CHF exchange rate, are shown in Figure 2.

[Figure 2 about here]

We can see strong evidence of intervention around parity of the euro against the CHF – total sight deposits in Swiss franc at the SNB increased by CHF 26.2 billion in the week starting 19 January 2015. We can also see some evidence of intervention at levels of the EUR/CHF exchange rate between around 1.03 and 1.11, with a possible concentration at a level of around 1.08. This is close to the level of 1.07, which economists expected to be defended by the SNB, as mentioned above (Neue Züricher Zeitung, 19 June 2016). The measure post-Brexit only, i.e. from the week starting 20 June 2016, is marked as filled triangles in Figure 2.

Monthly FX intervention proxies

Another proxy measure for the SNB's FX intervention is changes in foreign currency reserves. We use data on total foreign currency reserves in convertible foreign currencies. A further proxy measure is changes in foreign currency reserves adjusted for valuation changes.[10] These two proxy measures are shown in Figure 3 against monthly averages of the EUR/CHF exchange rate, and suggest that the SNB may have intervened at levels of the EUR/CHF exchange rate of around 1.04 to 1.10. But foreign currency reserve changes may occur for reasons unrelated to central bank intervention.[11] Moreover, the valuation adjustment is imperfect. These two proxy measures are therefore only imperfect measures. Furthermore, since these are monthly measures, we cannot relate them to the exact exchange rate levels, but only to monthly averages.

Despite the drawbacks of the three proxy measures, all provide some indication of possible foreign exchange intervention by the SNB for levels of the EUR/CHF exchange rate between around 1.04 and 1.10, which we use to motivate the calibration of our informal edge target zone model presented in the next section. However, the evidence from these three proxy measures is also consistent with the SNB having tried to prevent a CHF appreciation to varying degrees at all exchange rate levels observed since 2015, rather than having a clear intervention threshold to enforce a particular lower bound.

[Figure 3 about here]

4. An Informal Single-Edged Target Zone Model

The model presented in this Section applies to a situation where there is a formal one-sided target zonewhich is only partially credible. It also applies to a situation where there are market perceptions of an informal, not publicly announced, one-sided target zone, as may have been the case following the discontinuation of the SNB's currency floor in January 2015, as discussed in Section 3.

Our model can be regarded as a generalisation of Krugman´s (1991) simple target zone model of exchange rates. In the standard model, the peg and the hard edge boundaries are publicly announced and credible, and market arbitrage mechanisms and interventions take place in whatever amounts are necessary to prevent the band from being violated. A number of papers have modified and relaxed the assumption of perfectly known bands. Klein (1992) and Chen, Funke, and Glanemann (2013) have presented models in which the width of the band is unknown to the public. Thus, the dynamics of the exchange rate is not only driven by fundamentals but also by expectations with respect to the width of the band. In this context, interventions reveal the true edge of the band. This mechanism stresses the information role of interventions.

In contrast, our model develops the notion that the exchange rate band can be seen as a partially credible commitment device, within a new theoretical framework with an asymmetric informal one-sided target zone. Moreover, in the absence of an announced target zone, a central bank's policies, including foreign exchange interventions, may generate perceptions in the market that there is an informal one-sided target zone. The contribution of the paper comprises theoretical exchange rate modelling. We do not claim to have developed a way to model the day-to-day movements of the EUR/CHF exchange rate since 15 January 2015.

Standard Krugman model

It is natural to consider the basic Krugman (1991) framework with a perfectly known and credible strong band as a benchmark. The model is based on the flexible-price monetary model and thus purchasing power parity is assumed to hold continuously. We do this, despite the fact that predictions derived from the standard Krugman model have not stood up well in empirical tests (see, for example, Svensson, 1992). We feel that this choice is justified, because our main focus in this paper is on theoretical modelling issues. Moreover, Lera and Sornette (2016) find that during the period when the SNB enforced the minimum exchange rate of 1.20 Swiss francs per euro, the EUR/CHF exchange rate was well explained by Krugman's target zone model, but seemingly only under strong pressure pushing the exchange rate close to the boundary of the target zone.

In the standard target zone framework, the dynamics of the exchange rate results from the intervention obligations. This gives rise to areflected or regulated Brownian motion and the exchange rate exhibits mean reversion towards the band.[12] After 15 January 2015, market participants are likely to have formed expectations of the informal band based on the actual exchange rate and suspected interventions. Thus, the log of the exchange rate S can be written as the sum of the log of the fundamentals F and its expected change:

(1) $$s_t = f_t + \lambda \frac{E[ds_t]}{dt},$$

where $E[\cdot]$ denotes the expectations operator for exchange rate changes with $\lambda > 0$, $\ln S = s$ and $\ln F = f$. Following the usual assumption of the target zone framework, we assume that the log of the fundamentals follows a simple Brownian motion without a drift,

(2) $$df_t = \sigma dW_t,$$

where σ represents the constant risk parameter of the log of the fundamentals and W_t denotes the standard Wiener process.[13] Applying Itô's lemma to the expectations term yields

(3) $$s = f + \frac{\lambda}{2}\sigma^2 \frac{d^2 s}{df^2},$$

it is obvious for a one-sided target zone with a credible lower band that the analytical solutions for the steady-state observations for financial market participants are as follows,

(4) $$s = f + Ae^{-\sqrt{\frac{2}{\lambda\sigma^2}}f} = f + Ae^{-rf},$$

where $A > 0$ is a positive parameter and $r = +\sqrt{\frac{2}{\lambda\sigma^2}}$. The meaning of equation (4) is straightforward. Without central bank interventions, financial market participants would anticipate a one-to-one relationship between the exchange rate and the fundamentals. In other words, $s = f$ shows the unregulated exchange rate dynamics. The exponential term Ae^{-rf} causes the bending of the exchange rate function and thus generates the target zone nonlinearity. We need to determine the parameter A. The parameter A depends upon the lower band s^l and the associated fundamentals f^l. Employing the value-matching condition enables the determination ofthe constant A as

(5) $$s^l = f^l + Ae^{-rf^l}.$$

The term smooth pasting denotes the phenomenon that the path of the exchange rate smoothes out on its way to s^l and that its slope becomes zero when it actually hits s^l.[14] The smooth-pasting condition implies

(6) $$0 = 1 - Ae^{-rf^l},$$

which gives us the constant A as

(7) $$A(f^l) = \frac{e^{rf^l}}{r}.$$

The associated relationship for the fundamental value f^l and lower band s^l thus is

(8) $$s^l = f^l + \frac{1}{r}$$

Equations (5) and (6) imply that the intervention-value parameter A is a function of f^l and hence a function of s^l: $A(s^l) = \frac{e^{rs^l-1}}{r}$. Rearranging and solving for s finally gives us the reduced form relationship between the exchange rate and the fundamentals f driven by the lower band s^l:

(9) $$s(f|s^l) = f + \frac{e^{rs^l-1}}{r} e^{-rf}$$

The linear part, f, represents the solution for a free float. The nonlinear part, $\frac{e^{rs^l-1}}{r} e^{-rf}$, is known as the honeymoon effect and refers to the phenomenon that if the Swiss franc is close to the informal floor, the probability increases that the Swiss franc will hit the floor, which leads to perceived interventions by the central bank. As a consequence, the probability that the Swiss franc will depreciate is higher than the probability that it will appreciate further. From this it follows that the Swiss franc will appreciate less than given by the fundamentals f alone. In other words, the honeymoon effect stabilises the exchange rate relative to its fundamentals.[15] Intuitively, equation (9) is characterized by the following features:

i. For very small values of s^l, such as the limiting case $s^l \to -\infty$, the interventions go to zero as $e^{rs^l-1} \to 0$. Thus, the exchange rate becomes almost free floating.

ii. For a very small adjustment parameter or very small risk parameter in equations (2) and (3), i.e. $\lambda \to 0$ and/or $\sigma \to 0$, we have $r \to \infty$. This means that interventions are ineffective for $\lambda \to 0$ and unnecessary for $\sigma \to 0$.

iii. For $f \to \infty$ the intervention term disappears and the exchange rate is free floating as only a lower bound s^l exists.

Normal distribution for s^l

In the original Krugman (1991) model, the reduced form relationship between exchange rates and fundamentals is driven by the perfectly known and credible floor. Conversely, what happens when the relationship is driven not by the floor itself but by expectations regarding the band? How can we model perceived uncertainty of market participants as to s^l and the central bank's determination to defend the informal floor?

To keep the model tractable, and consistent with the empirical evidence in Section 3, we assume that the interventions have a normal distribution for s^l, and equation (8), which shows a linear relationship between s^l and f^l, also implies a normal distribution for f^l. In other words, we have $s^l \sim N(s^{le}, \sigma_s^2)$ and $f^l \sim N(f^{le}, \sigma_s^2)$. A complicating issue is that foreign exchange market intervention can happen not only at the boundary of the target zone (marginal intervention), but also within the band (intramarginal intervention), which could reflect a policy of timely "leaning against the wind". With intramarginal interventions, the honeymoon effect will be smaller than in the standard target zone model. This is due to the fact that the probability of the exchange rate hitting the boundaries is smaller if intramarginal interventions are successful. Klein and Lewis (1993) have extended the model to the case of stochastic intra-marginal interventions. Inthe current setup, the possibility of intramarginal interventions might be reflected in a smaller value of the uncertainty parameter σ_s.

Market participants can only observe the interventions with a mean value s^{le} for exchange rates and observations have a normal distribution around s^l. It is obvious that $E[s^l] = s^{le}$ and $E[f^l] = f^{le}$. With the above distribution for s^l, we can analyse the response from financial market participants by taking expectations of value-matching condition equation (5) conditional upon the observed normal distributions to determine how the uncertainty about the SNB's preferences and thus the informal band feeds back into the dynamics of the exchange rate. The exponential term e^{-rf^l} of equation (5) has the properties of $E\left[e^{-rf^l}\right] = e^{\frac{1}{2}r^2\sigma_s^2}e^{-rf^{le}}$. Therefore, equation (5) now becomes

(10) $$s^{le} = f^{le} + Ae^{\frac{1}{2}r^2\sigma_s^2}e^{-rf^{le}}.$$

The corresponding smooth-pasting condition around the observed f^{le} is denoted by

(11) $$0 = 1 - Ae^{\frac{1}{2}r^2\sigma_s^2}e^{-rf^{le}}.$$

This yields

(12) $$s^{le} = f^{le} + \frac{1}{r}.$$

Hence, the variable A is determined as

(13) $$A = \frac{1}{r}e^{-\frac{1}{2}r^2\sigma_s^2}e^{rs^{le}-1}.$$

Substituting equation (13) back into equation (4) we finally get the law of motion of the exchange rate in the informal band system

(14) $$s = f + \frac{1}{r}e^{-\frac{1}{2}r^2\sigma_s^2}e^{rs^{le}-1}e^{-rf}.$$

Compared with equation (9), the impact of interventions is reduced by the factor $e^{-\frac{1}{2}r^2\sigma_s^2}$, which implies that higher uncertainty about the intervention range leads to a smaller smile and thus a lower *J*-curve.

Next we study the properties of this informal band model. The baseline parameters are , $\lambda = 0.9$, $s^{ls} = \ln 1.07$, and $\sigma_s = 0.04$.[16] Under the assumptions sketched out above, Figure 4 portrays the dynamics of the logged exchange rate versus the logged fundamentals. The blue line always gives the exchange rate dynamics according to equation (9). The pink lines are 45 percent degree lines representing the free-float solution. The horizontal dashed lines represent $s^{ls} = \ln 1.07$. In order to cast light on perceived SNB policy uncertainty, various combinations of $\sigma_s = 0.04$ are assumed in each of the four graphs. The details are as follows: upper left panel $\sigma_s = 0.02$; upper right panel: $\sigma_s = 0.06$; lower left panel: $\sigma_s = 0.06$; lower right panel: $\sigma_s = 0.08$.

[Figure 4 abouthere]

Several properties of the solution are apparent from Figure 4. First, as expected, the resulting dynamics of the exchange rate is *J*-shaped even in the absence of a formal lower floor. Second, an important difference between the solution for a fully credible formal lower floor and a perceived informal lower floor is that a unique exchange rate is defined as a function of the fundamentals for the traditional (credible) one-sided target zone, while a family of such curves is defined for the perceived informal one-sided target zone. Third, for perceived uncertainty about the informal lower floor ($\sigma_s > 0$), the resulting *J*-shaped curve is a monotonically increasing function of the level of . Put the other way round, the moderating effect is the stronger, the greater the credibility of the policymaker and the lower the uncertainty about the lower band. Fourth, while all curves are almost identical near $s = \ln(1.07)$, the informal band curves become steeper than the hard band curve as the exchange rate approaches the edges. Hence, informal soft edge bands lead to weaker honeymoon effects, wider target zone ranges and higher exchange rate volatility.

Since the honeymoon effects become weaker as uncertainty about the informal lower band increases, as shown in Figure 4, a policy conclusion from the numerical simulations is that central bank communication about exchange rate policy would help to anchor exchange rate expectations and reduce exchange rate volatility. A central bank's exchange rate policy intentions regarding a lower band could be stated clearly to reduce misinterpretation. Furthermore, misreading of a policy could be corrected in a timely manner. In line with this conclusion, Archer (2005) argues that transparent FX intervention is preferable to secret intervention (see Section 3).

However, transparency about foreign exchange intervention and exchange rate policy may also have adverse effects, which would need to be weighed against the potential benefits of transparency about exchange rate policy and intervention implied by our model, including due to the effects of possible speculative attacks, which are not modelled here (see the discussion in Section 3). Moreover, uncertainty and misperceptions about fundamentals, which are not modelled here, could affect the desirability of transparency.

Markov switching framework

Next, we allow for exchange rate dynamics with discrete regime shifts. The pivotal requirement for the honeymoon effect to function properly is that the public believes that the informal target zone will persist. So far a point estimate for s augmented with a normal distribution has been assumed. Given that Markov-switching models have become a popular tool to allow for parameter instability and parameter uncertainty, we go beyond the previous exercises and pursue the analysis further by augmenting the framework with a bivariate Markov-switching model.[17] In other words, we characterize financial market's uncertainty about the informal floor via the possibility of regime changes. The main advantages of regime-switching models are that they (i) provide a high goodness of fit in face of policy switches; (ii) can accommodate a wide variety of macroeconomic shocks and nonlinearities; (iii) can visualize the impact of unobservable variables such as credibility of announcements or anticipation of forthcoming events; and (iv) can take the prospect of policy shifts and exchange rate dynamics alternating between regimes changes into account.

How do we introduce such dynamics into the informal target zone model?[18] To fix ideas, we assume that the exchange rate dynamics is subject to discrete regime shifts governed by a two-regime Markov process with constant transition probabilities.[19] Formally, ▯ is the probability of state 1 jumping to state 0, and $1-\phi$ is the probability of state 1 remaining in the same state. Similarly, θ denotes the probability of state 0 jumping to state 1, and $1-\theta$ is for state 0 remaining in the same state.[20] Thus, the probability of shifting from state 0 to state 1 in an interval of time of length dt is θdt, and the probability of switching from state 1 to state 0 is ϕdt. Note that the jump probabilities need not be identical because the central bank may have asymmetric preferences. A perfectly credible lower bound is obtained by setting the switching probabilities to zero. Regime switches might occur in an attack-type crisis when the Swiss franc suddenly comes under pressure or appreciates strongly in ways inconsistent with the present policy regime. Therefore it is reasonable to assume $s_0^l > s_1^l$ in the recurrent two-state process.[21] In other words, we assume that the exchange rate triggering interventions in state 0 is higher than in state 1. This assumption is made largely for convenience.

In the following we analyse some of the channels through which cross-regime effects come about and assess their policy relevance. In the following subsection we assume that market participants know the current state of the exchange rate regime and are able to conjecture the switching probabilities. Under these two assumptions, the two regimes can be characterised as follows:

$$s_0^{le} = \frac{(1+\phi)s_0^l + \theta s_1^l}{1+\phi+\theta}, \tag{15}$$

$$s_1^{le} = \frac{(1+\theta)s_1^l + \phi s_0^l}{1+\phi+\theta}, \tag{16}$$

where s_0^{le} (s_1^{le}) is the expected lower band for state 0 (1). The above equations are obtained by taking the expected value of the lower bands for state 0 and state 1, respectively. The next task is to solve for the Markov-switching interventions. The state-dependent law of motion of the exchange rate in the Markov switching version of the model is given by

$$s_0 = f + \lambda\left[\frac{1}{2}\sigma_0^2\frac{d^2 s_0}{df^2} + \theta(s_1 - s_0)\right], \tag{17}$$

$$s_1 = f + \lambda\left[\frac{1}{2}\sigma_1^2\frac{d^2 s_1}{df^2} + \phi(s_0 - s_1)\right], \tag{18}$$

where σ_0 and σ_1 are the risk parameters for the fundamentals in state 0 and state 1, respectively.

What is the implied momentum of this assumption? The existence of two states introduces a complication, in that the exchange rate will jump to the new edge of the informal band as appropriate by means of an instantaneous discrete intervention. There are two cases to be distinguished. When a policy change from state 0 to state 1 occurs, and the actual exchange rate at this juncture satisfies the condition $s_0 \geq s_1^l$, then no interventions will take place. The reason is that the central bank tolerates a further appreciation of the exchange rate beyond s_0^l up to s_1^l. On the contrary, in the case of a reverse jumpfrom state 1 to state 0, an actual exchange rate in the range $s_0^l \geq s_1 \geq s_1^l$ will trigger an immediate intervention to sustain the new regime 0. This implies that over the range $s_0^l > s_1 > s_1^l$, we need to change equation (18) as follows so as to satisfy the boundary conditions:

$$s_1 = f + \lambda\left[\frac{1}{2}\sigma_1^2\frac{d^2 s_1}{df^2} + \phi\left(s_0^{le} - s_1\right)\right]. \tag{19}$$

In the next step, we modify the standard method for solving for the exchange rate in terms of the fundamentals, to allow for there being two states of the world. There are two cases to be distinguished. In the first case the new regime satisfies the range $s_0^{le} \geq s_1 \geq s_1^{le}$.

In the second case, $s_1 \geq s_0^{le}$ and $s_0 \geq s_0^{le}$ is valid. These two cases cover all the possibilities, and we consider them in turn. As shown in Appendix A, the solution for $s_0^{le} \geq s_1 \geq s_1^{le}$ and $s_0 \geq s_0^{le}$ is as follows:

(20) $$s_0 = \left(\frac{1}{(1+\lambda\theta)} + \frac{\lambda\theta}{(1+\lambda\theta)(1+\lambda\phi)}\right) f + \frac{\lambda\phi\lambda\theta s_0^{le}}{(1+\lambda\theta)(1+\lambda\phi)} + A_{00}e^{-r_0 f} + A_{01}e^{-r_1 f},$$

(21) $$s_1 = \frac{f}{1+\lambda\phi} + \frac{\lambda\phi s_0^{le}}{1+\lambda\phi} + A_1 e^{-r_1 f},$$

(22) $$A_{01} = -\frac{\lambda\theta}{\left(\sigma_0^2 \frac{(1+\lambda\phi)}{\sigma_1^2} - 1 - \lambda\theta\right)} A_1,$$

where $r_0 = \sqrt{\frac{2(1+\lambda\theta)}{\lambda\sigma_0^2}}$, $r_1 = \sqrt{\frac{2(1+\lambda\phi)}{\lambda\sigma_1^2}}$, and A_{00}, A_{01}, A_{10}, and A_1 are constants to be determined by the boundary conditions. The analogous solution for the second case of $s_1 \geq s_0^{le}$ and $s_0 \geq s_0^{le}$ is provided in Appendix B.

The Markov-switching version of the model is characterised by the fundamentals f_0^{le} and f_1^{le} perceived by market participants and the associated exchange rates s_0^{le} and s_1^{le}. The expected values of the lower bands, s_0^{le} and s_1^{le}, then reflect the corresponding values of f_0^{le} and f_1^{le}. The regime-dependent value-matching and smooth-pasting conditions at the Swiss franc's floor are given by:

(23) $$s_0^{le} = \left(\frac{1}{(1+\lambda\theta)} + \frac{\lambda\theta}{(1+\lambda\theta)(1+\lambda\phi)}\right) f_0^{le} + \frac{\lambda\phi\lambda\theta s_0^{le}}{(1+\lambda\theta)(1+\lambda\phi)} + A_{00}e^{-r_0 f_0^{le}} + A_{01}e^{-r_1 f_0^{le}},$$

(24) $$s_1^{le} = \frac{f_1^{le}}{1+\lambda\phi} + \frac{\lambda\phi s_0^{le}}{1+\lambda\phi} + A_1 e^{-r_1 f_1^{le}},$$

(25) $$0 = \left(\frac{1}{(1+\lambda\theta)} + \frac{\lambda\theta}{(1+\lambda\theta)(1+\lambda\phi)}\right) - r_0 A_{00}e^{-r_0 f_0^{le}} - r_1 A_{01}e^{-r_1 f_0^{le}},$$

(26) $$0 = \frac{1}{1+\lambda\phi} - r_1 A_1 e^{-r_1 f_1^{le}}.$$

Numerical examples

In consideration of equations (23) and (24), we can numerically determine the fundamentals f_0^{le} and f_1^{le} at the perceived regime-dependent intervention bands. After having obtained the values of A_{00}, A_{01}, and A_{11}, we can use numerical simulations to gain further insight into the regime-dependent exchange rate dynamics in the informal target zone model with Markov-switching via equations (20) and (21), respectively. We use this exercise to have a feel for the model and to draw a map of the exchange rate sensitivity to various structural characteristics of the Markov-switching environment. We hope to show that the insights gained from simulations are sufficiently rich to indicate that it provides a useful complement to theory. Adding this first-order Markov chain stochasticity into the model leads to the numerical simulation results for the regime-dependent dynamics of the Swiss franc in Figures 5 and 6.

In Figure 5 we show numerical simulation results of how exchange rate dynamics can be characterized in models in which financial markets are aware of occasional changes in the policy regime. Figure 5 shows representations of the *J-*

shaped dynamics of the exchange rate for different values of s_0^l and s_1^l for given jump probabilities $\phi = \theta = 0.2$ on a case-by-case basis. Thus, the discontinuity is represented by a shift in the perceived mean. In the upper left (right) graph a policy regime change from $s_0^l = \ln 1.07$ to $s_1^l = \ln 1.02$ ($s_1^l = \ln 1.00$) is simulated. In the lower left graph $s_0^l = \ln 1.20$ and $s_1^l = \ln 1.07$ are simulated. In other words, this panel presents the case of a perceived switch back to the regime prior to 15 January 2015. Finally, the lower right panel gives the dynamics of the exchange rate for the two regimes $s_0^l = \ln 1.02$ and $s_1^l = \ln 1.00$.

[Figure 5 about here]

Four interesting results emerge. First, the exchange rate dynamics alternates between regimes (see the two J-curves in each of the panels). Second, there is mutual interdependence of the *J*-curves across regimes. The mere fact that a regime change might happen has effects even when no regime change has taken place. Third, despite this fact it is notable that the lower floor remains a stabilizing instrument even under regime-switching expectations, as evidenced by the *J*-shaped dynamics in each of the panels in Figure 5. Put differently, even in the presence of Markov-switching and boundaries that are not publicly announced, the exchange rate is stabilized relative to the case of a free float. Fourth, the story is more subtle than has been acknowledged so far. Figure 5 indicates that in the Markov-switching version of the model the exchange rate will jump to a new *J*-curve as soon as the perceived lower floor has changed. Put differently, rightly or wrongly expected changes in the central bank's exchange rate policy cause shifts in the *J*-curves and may lead to exchange rate oscillations. This additional source of volatility cannot be detected if uncertainty is computed conditioning on a sole regime. Therefore, it is important to take into account the possibility of regime changes.

[Figure 6 about here]

Next, we also present numerical simulation results which show that the contribution of the different regimes to the overall volatility does not depend only on the size of the policy shocks, but also on the shocks' frequency and persistence. In Figure 6 we relax the assumption of given jump probabilities $\phi = \theta = 0.2$. To repeat, θ denotes the probability of state 0 jumping to state 1 and ϕ is the probability of state 1 jumping to state 0. By contrast, $s_0^l = \ln 1.07$ and $s_1^l = \ln 1.02$ is assumed throughout. Under these assumptions, the four graphs summarize the model simulation results for different jump probabilities ϕ and θ. The comparison indicates how different jump probabilities change the dynamics of the exchange rate.

Again three interesting results emerge. First, the jump probabilities and thus policy shifts play a big role, as can be seen for example by comparing the *J*-curves for the jump probabilities of (0.1,0.1)in the top left panel with those for the higher jump probabilities of (0.5,0.5) in the bottom right panel. Second, the comparison of the *J*-curves in the different panels reveals that a less (more) likely regime change leads to smaller (larger) cross-impacts. As a result, the importance of the regime that is in place at a particular point in time is substantially reduced when taking into account the possibility of future regime changes. Thus, accounting for potential cross-regime effects appears to be an important element of a good policy design. Based on this model with regime changes, effective central bank communication about the target zone bands may be helpful in reducing exchange rate volatility from such cross-regime effects. Third, occurrences which look like speculative attacks on the Swiss franc may be associated with market perceptions of a policy regime switch having taken place.[22]

The numerical results indicate that perceived possible regime switches and speculative attacks may put the central bank under strain, even though it has not changed its foreign exchange market policies yet. Effective central bank communication may be helpful in order to anchor exchange rate expectations and reduce exchange rate volatility.

This ability of the univariate Markov-switching model to generate non-trivial connections between the dynamics of the exchange rate in both regimes represents a promising feature and opens the door to study the link between exchange rate uncertainty and real activity in a multivariate setting.[23] This might be useful in future research in light of the attention that uncertainty has recently received in the profession following the seminal contribution of Bloom (2009).

5. Summary and Conclusions

This paper develops a new theoretical model with an asymmetric informal (unofficial) one-sided target zone, using Switzerland as an example. The model incorporates the notion that a target zone can be seen as a partially credible commitment device. Analytically, the modelling approach lies at the crossroads of the literature on exchange rate target zones originated by Krugman (1991) and that on intervention in the foreign exchange market. With the aim of parsimony in mind, but also with the aim of ensuring afair degree of reality, we extend and generalize the standard target zone model by introducing perceived uncertainty about the lower band following the removal of the minimum exchange rate of CHF 1.20 per euro in January 2015.

We find that informal soft edge target zone bands lead to weaker honeymoon effects, wider target zone ranges and higher exchange rate volatility than formal target zone bands. As discussed in Section 3, the honeymoon effect stabilises the exchange rate relative to its fundamentals. It refers to the phenomenon that, if the Swiss franc is close to the informal floor, the probability increases that the Swiss franc will hit the floor, which leads to perceived interventions by the central bank. Consequently, the probability that the Swiss franc will depreciate is higher than the probability that it will appreciate further, and therefore the Swiss franc will appreciate less than is given by the fundamentals alone. Our model suggests that it would be beneficial for exchange rate policy intentions to be stated clearly to reduce misinterpretation, in order to anchor exchange rate expectations and reduce exchange rate volatility. However, transparency about foreign exchange intervention and exchange rate policy may also have adverse effects, which would need to be weighed against the potential benefits of transparency about exchange rate policy and intervention implied by our model. Moreover, there may be uncertainty and misperceptions about fundamentals, which are not modelled here.

We also study how exchange rate dynamics can be characterized in models in which financial markets are aware of occasional changes in the policy regime. We show that expected changes in the central bank's exchange rate policy may lead to exchange rate oscillations, providing an additional source of exchange rate volatility. To capture this effect, it is important to take into account the possibility of regime changes in exchange rate policy. The ability of the univariate Markov-switching model to generate non-trivial connections between the dynamics of the exchange rate in both regimes represents a promising feature and opens the door to study the link between exchange rate uncertainty and real activity in a multivariate setting.

It is clear that target zone regimes vary from one country to another and within countries over time. Our extension of the original Krugman model is, therefore, only one example of how such a regime might work. Exchange rate economics is an exceptionally exciting subject. We hope that the model presented above can contribute to it.

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Appendix A: Derivation of Equations (20) and (21) for and $s_0 \geq s_0^{le}$

We need to solve equations (17) and (19) which are coupled with parameters from both states. It is obvious that the solutions to equation (19) in the text can be obtained as follows:

(A1) $$s_1 = \frac{f}{1+\lambda\phi} + \frac{\lambda\phi s_0^{le}}{1+\lambda\phi} + A_1 e^{-\sqrt{\frac{2(1+\lambda\phi)}{\lambda\sigma_1^2}}f} = \frac{f}{1+\lambda\phi} + \frac{\lambda\phi s_0^{le}}{1+\lambda\phi} + A_1 e^{-r_1 f},$$

where

(A2) $$r_1 = \sqrt{\frac{2(1+\lambda\phi)}{\lambda\sigma_1^2}}$$

We guess that the general solution for s_0 has the following form

(A3) $$s_0 = af + b + A_{00}e^{-r_0 f} + A_{01}e^{-r_1 f},$$

where a, b, A_{00}, A_{01}, and are unkonwn variables to be determined, and parameter r_1 follows equation (A2). Substituting equations (A1) and (A3) back into equation (17) in the main text yields

(A4) $$\begin{aligned} &af + b + A_{00}e^{-r_0 f} + A_{01}e^{-r_1 f} \\ &= f + \frac{1}{2}\lambda\sigma_0^2 r_0^2 A_{00}e^{-r_0 f} + \frac{1}{2}\lambda\sigma_0^2 r_1^2 A_{01}e^{-r_1 f} \\ &+ \lambda\theta\left(\frac{f}{1+\lambda\phi} + \frac{\lambda\phi s_0^l}{1+\lambda\phi} + A_1 e^{-r_1 f} - af - b - A_{00}e^{-r_0 f} - A_{01}e^{-r_1 f}\right). \end{aligned}$$

Rearranging yields

(A5) $$\begin{aligned} &\left(a + \lambda\theta a - 1 - \frac{\lambda\theta}{1+\lambda\phi}\right)f + \left(b + b\lambda\theta - \frac{\lambda\phi\lambda\theta s_0^{le}}{1+\lambda\phi}\right) \\ &= \left(\frac{1}{2}\lambda\sigma_0^2 r_0^2 - 1 - \lambda\theta\right)A_{00}e^{-r_0 f} + \left(\frac{1}{2}\lambda\sigma_0^2 r_1^2 - 1 - \lambda\theta\right)A_{01}e^{-r_1 f} + \lambda\theta A_1 e^{-r_1 f} \end{aligned}$$

Equation (A5) holds when we have the following relationships for a and b

(A6) $$a = \frac{1}{(1+\lambda\theta)} + \frac{\lambda\theta}{(1+\lambda\theta)(1+\lambda\phi)},$$

(A7) $$b = \frac{\lambda\phi\lambda\theta s_0^{le}}{(1+\lambda\theta)(1+\lambda\phi)},$$

where

(A8) $$r_0 = \sqrt{\frac{2(1+\lambda\theta)}{\lambda\sigma_0^2}}.$$

Substituting (A6) - (A8) into (A5), we obtain

(A9) $$\left(\frac{1}{2}\lambda\sigma_0^2 r_1^2 - 1 - \lambda\theta\right)A_{01}e^{-r_1 f} + \lambda\theta A_1 e^{-r_1 f} = 0.$$

We need some relationships between A_0 and A_1 to make equation (A9) solvable. Substituting $r_1 = \sqrt{\frac{2(1+\lambda\phi)}{\lambda\sigma_1^2}}$ back into equation (A9) gives the following relationship between A_{01} and A_1:

(A10) $$A_{01} = -\frac{\lambda\theta}{\left(\sigma_0^2\frac{(1+\lambda\phi)}{\sigma_1^2} - 1 - \lambda\theta\right)}A_1.$$

Therefore, the solution for s_0 is

(A11) $$s_0 = \left(\frac{1}{(1+\lambda\theta)} + \frac{\lambda\theta}{(1+\lambda\theta)(1+\lambda\phi)}\right)f + \frac{\lambda\phi\lambda\theta s_0^{le}}{(1+\lambda\theta)(1+\lambda\phi)} + A_{00}e^{r_0 f} + A_{01}e^{-r_1 f}.$$

This completes the proof.

Appendix B: Derivation of Solutionsto Equations (17) and (18) for $s \geq s_0^{le}$

We need to solve equations (17) and (18) in the main text which are coupled with parameters from both states for the regime $s \geq s_0^{le}$. We guess that the general solution is of the form

(B1) $$s_0 = f + A_0 e^{rf},$$

(B2) $$s_1 = f + A_1 e^{rf},$$

Note that the Markov-switching setting has no impact on the linear part of (B1) and (B2). Thus we have

(B3) $$A_0 e^{rf} = \frac{1}{2}\lambda\sigma_0^2 r^2 A_0 e^{rf} + \lambda\theta(A_1 - A_0)e^{rf}$$

(B4) $$A_1 e^{rf} = \frac{1}{2}\lambda\sigma_1^2 r^2 A_1 e^{rf} + \lambda\phi(A_0 - A_1)e^{rf}$$

or simply

(B5) $$A_0 = \frac{1}{2}\lambda\sigma_0^2 r^2 A_0 + \lambda\theta(A_1 - A_0)$$

(B6) $$A_1 = \frac{1}{2}\lambda\sigma_1^2 r^2 A_1 + \lambda\phi(A_0 - A_1).$$

It is relatively straightforward to show that

(B7) $$\left(1 + \lambda\theta - \frac{1}{2}\lambda\sigma_0^2 r^2\right)A_0 = \lambda\theta A_1,$$

(B8) $$\lambda\phi A_0 = \left(1 + \lambda\phi - \frac{1}{2}\lambda\sigma_1^2 r^2\right)A_1.$$

This in turn implies that the solutions of r depend on the characteristic equation

(B9) $$\left(1 + \lambda\theta - \frac{1}{2}\lambda\sigma_0^2 r^2\right)\left(1 + \lambda\phi - \frac{1}{2}\lambda\sigma_1^2 r^2\right) = \lambda^2\theta\phi.$$

As the central bank only intervenes at the informal floor, we need to have two negative roots of the above characteristic equation, say , where r_0 and r_1 are both positive. Substituting r_0 and r_1 into the solutions for s_0 and s_0 yields

(B10) $$s_0 = f + A_{00}e^{-r_0 f} + A_{01}e^{-r_1 f}$$

(B11) $$s_1 = f + A_{10}e^{-r_0 f} + A_{11}e^{-r_1 f},$$

where the unknowns A_{0i} and A_{1i} satisfy

(B12) $$\left(1 + \lambda\theta - \frac{1}{2}\lambda\sigma_0^2 r_i^2\right)A_{0i} = \lambda\theta A_{1i}, \quad i = 0,1,$$

or

(B13) $$\lambda\phi A_{0i} = \left(1 + \lambda\phi - \frac{1}{2}\lambda\sigma_1^2 r_i^2\right)A_{1i}, \quad i = 0,1,$$

where $(-r_0)$ and $(-r_1)$ are two negative roots of the characteristic equation

$$\text{(B14)} \qquad \left(1+\lambda\theta-\frac{1}{2}\lambda\sigma_0^2r^2\right)\left(1+\lambda\phi-\frac{1}{2}\lambda\sigma_1^2r^2\right)=\lambda^2\theta\phi.$$

Expanding yields

$$\text{(B15)} \qquad \frac{1}{4}\lambda^2\sigma_0^2\sigma_1^2r^4-\left((1+\lambda\theta)\frac{1}{2}\lambda\sigma_1^2+(1+\lambda\phi)\frac{1}{2}\lambda\sigma_0^2\right)r^2+1+\lambda\theta+\lambda\phi=0.$$

In order to solve fully for the exchange rate dynamics, it is necessary to apply a number of familiar value matching and smooth pasting conditions, which apply at the points where the exchange rate touches the edges of the bands. The usual conditions are modified to allow for there being two states of the world. The conditions observed by market participants are:

$$\text{(B16)} \qquad s_0^{le}=f_0^{le}+A_{00}e^{-r_0f_0^{le}}+A_{01}e^{-r_1f_0^{le}},$$

$$\text{(B17)} \qquad s_0^{le}=f_1^{le}+A_{10}e^{-r_0f_1^{le}}+A_{11}e^{-r_1f_1^{l}},$$

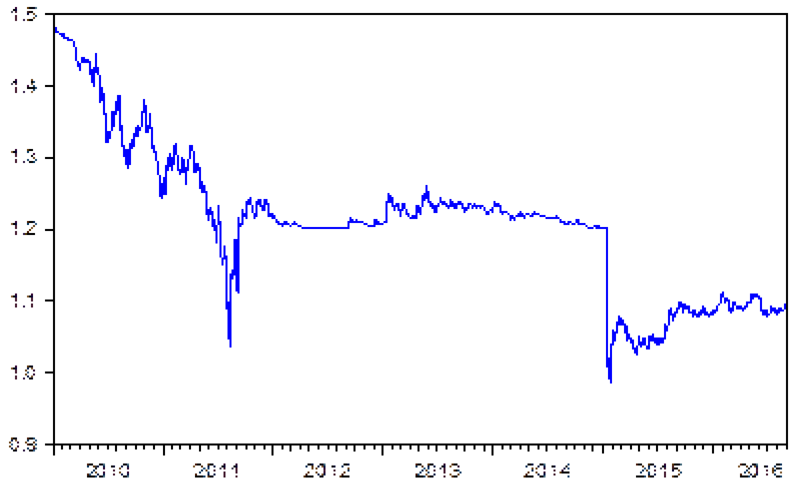
$$\text{(B18)} \qquad 0=1-r_0A_{00}e^{-r_0f_0^{l}}-r_1A_{01}e^{-r_1f_0^{le}},$$

$$\text{(B19)} \qquad slope=1-r_0A_{10}e^{-r_0f_1^{le}}-r_1A_{11}e^{-r_1f_1^{le}}.$$

where $slope$ is obtained from the results of equations (23) - (26) at s_0^{le} in the main text.

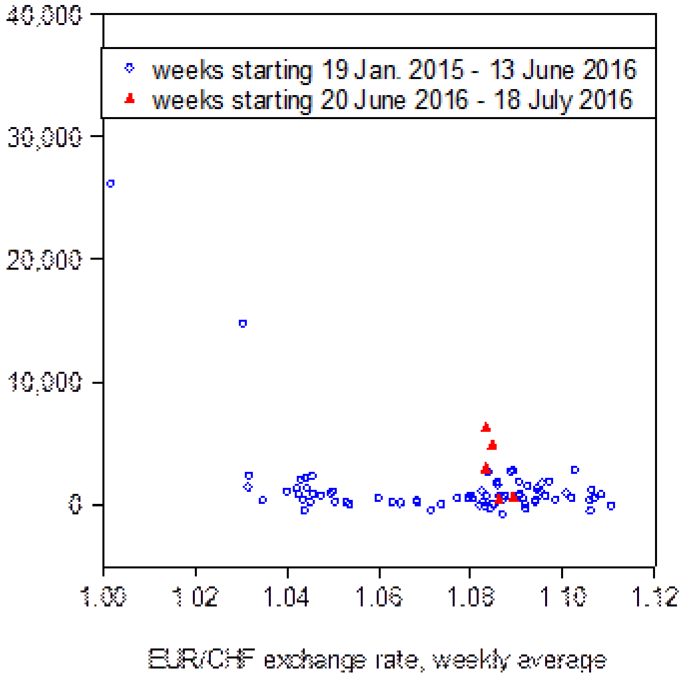
FIGURES

Figure 1: EUR/CHF exchange rate, daily data from 1 January 2010 to 31 August 2016



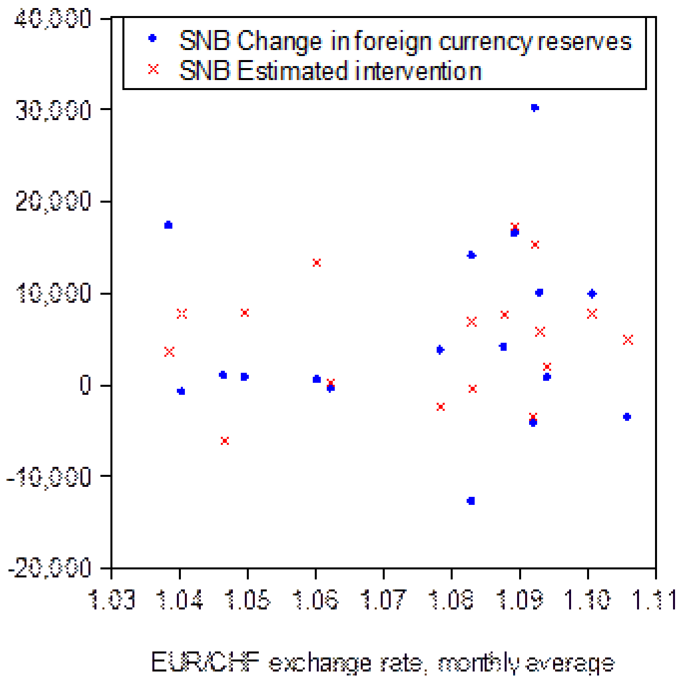
Source: Bloomberg.

Figure 2: Weekly SNB intervention proxy: Weekly changes in total sight deposits in Swiss francs at the SNB, in CHF million



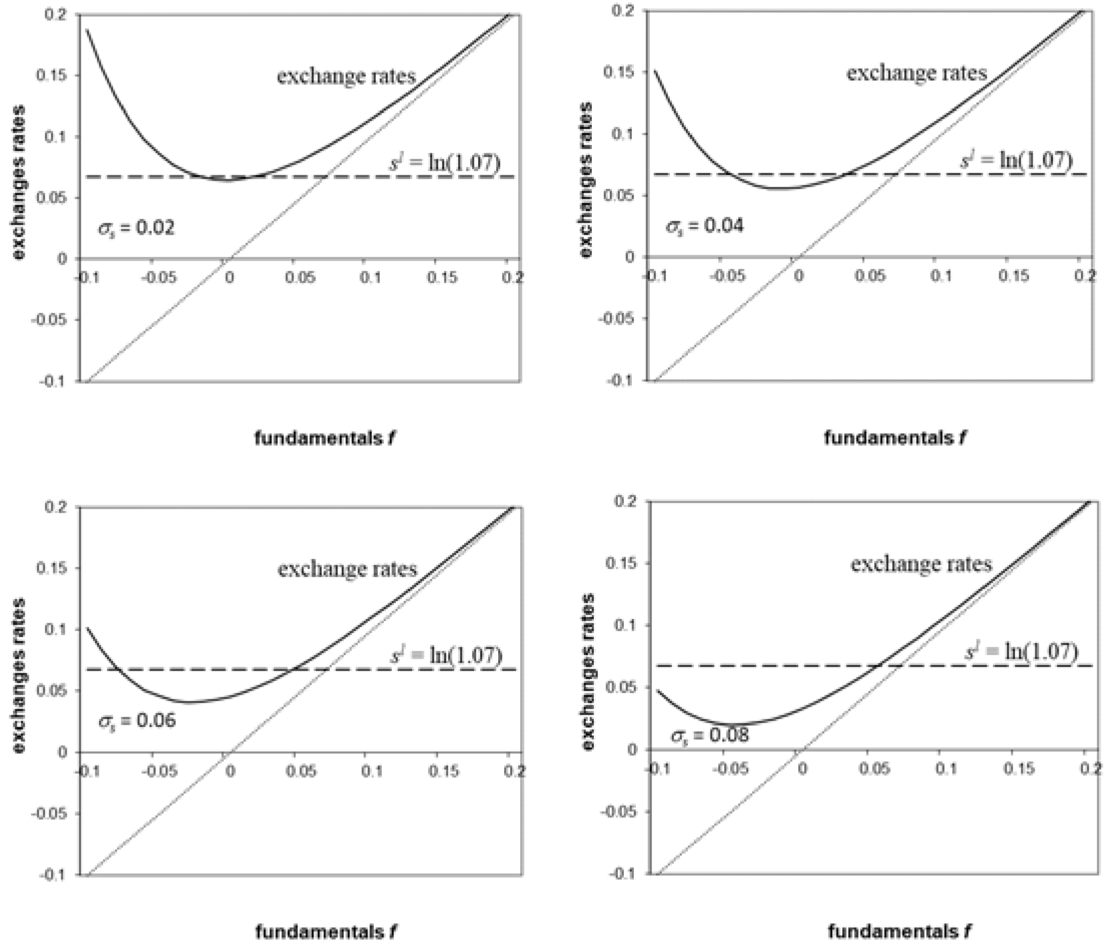
Sources: SNB, Bloomberg, authors' calculations.

Figure 3: Monthly Intervention Proxies, February 2015-June 2016, in USD million



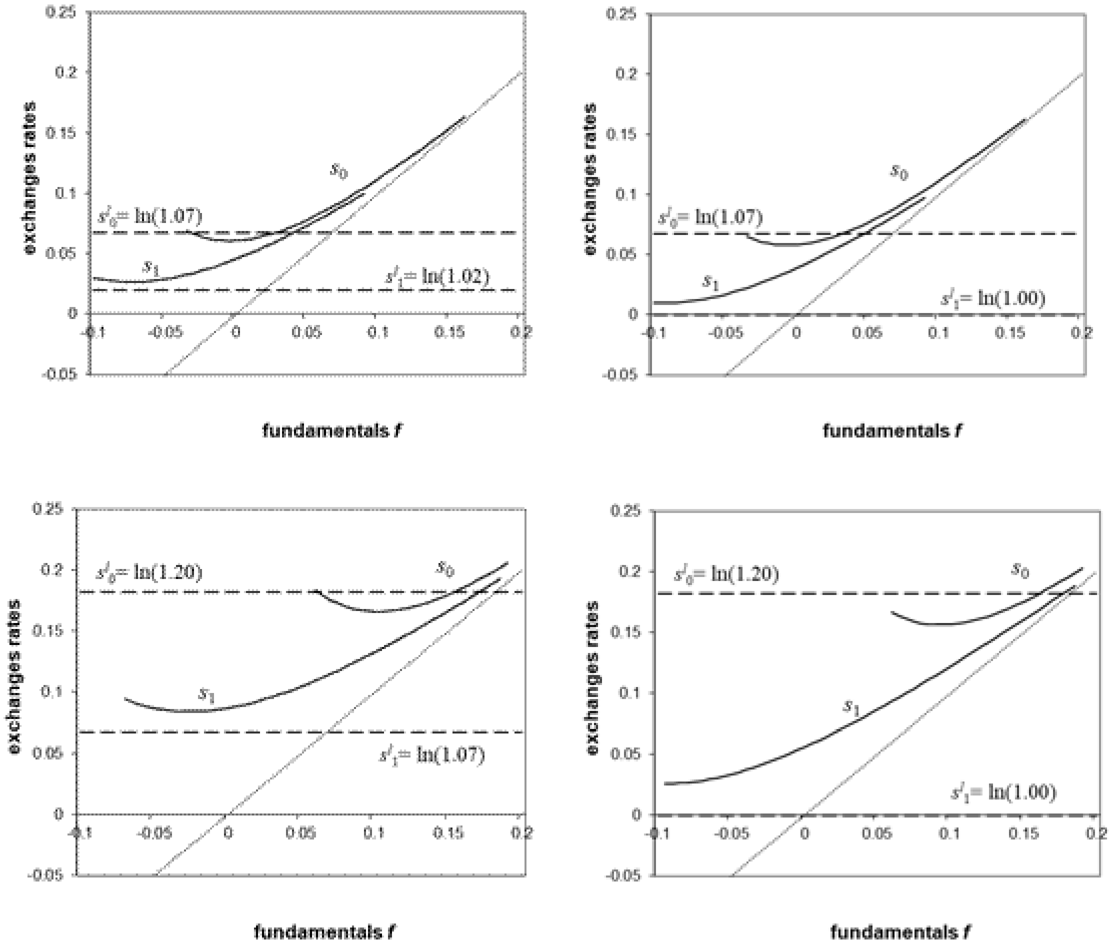
Notes: Plotted are monthly changes in foreign currency reserves and estimated intervention (estimated as changes in foreign currency reserves adjusted for valuation changes). Sources: SNB, Bloomberg, BIS calculations.

Figure 4: Informal Lower Band Target Zone Model



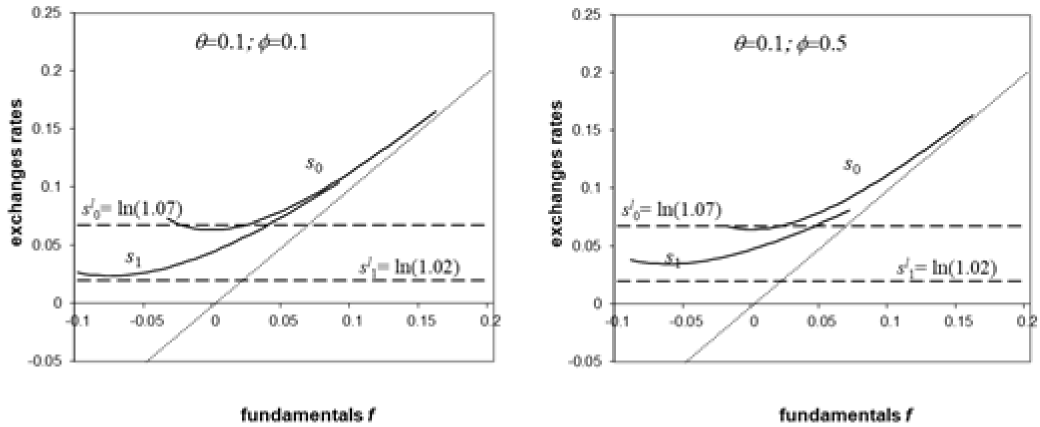
Note: measures the risk parameter and s^l measures the lower band in the model.

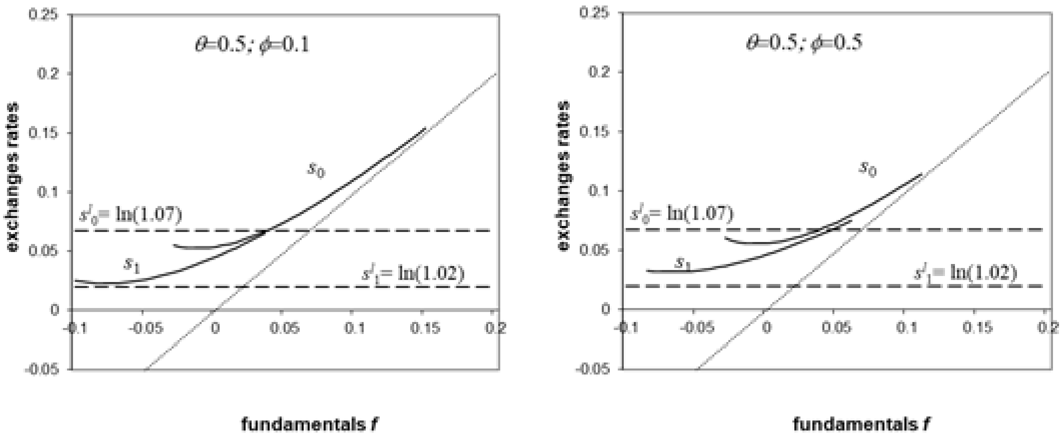
Figure 5: The Regime-Dependent Dynamics of the EUR/CHF Exchange Rate



Note: In the graphs $\phi = \theta = 0.2$ is assumed throughout, s_0^l measure the lower band for state 0 and s_1^l measure the lower band for state 1. Further benchmark values are $\sigma_0 = 0.1$, $\sigma_1 = 0.15$, and $\lambda = 0.9$, respectively;

Figure 6: The Dynamics of the Exchange Rate for Different Jump Probabilities





Note: ϕ measures the probability of state 1 jumping to state 0, θ denotes the probability of state 0 jumping to state 1, s_0^l measure the lower band for state 0 and s_1^l measure the lower band for state 1.

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[1] The Swiss franc briefly appreciated to around 1.04 against the euro in early August 2011 (with a low of 1.036 on 10 August 2011, using daily closing prices from Bloomberg, see Figure 1), as the euro area sovereign debt crisis intensified in the second half of 2011. This intensification seems to have been related to concerns about banks' possible losses on sovereign debt holdings, and to an increasing recognition that in any future crisis, banks' bondholders, and perhaps even wholesale depositors, would not be bailed out by governments. Euro area banks' CDS spreads widened following the European Council's statement of 21 July 2011 referring to a 'voluntary contribution' from the private sector to covering the financing gap of Greece (see Allen & Moessner, 2013; Moessner & Allen, 2013).

[2] Since the exit from the minimum exchange rate, it seems that the SNB has focused not just on the EUR/CHF exchange rate, but on the 'overall currency situation' (see SNB, 2016). This is consistent with our modelling approach: if the central bank targets a basket with unknown currency weights, this would still imply some distribution for the exchange rate band for each bilateral currency pair.

[3] Halting a further appreciation of the Swiss franc is not an end in itself, but a means to affect inflation, which is the SNB's main objective. If inflation is too low, depreciation can lead to higher imported inflation, and thereby to a better attainment of the inflation objective. Inflation well below target requires monetary policy easing, but with the policy rate at zero and quantitative easing not feasible due to small domestic financial markets, FX interventions and the currency floor took centre stage for preventing a further tightening of monetary conditions.

[4] One exception was following Brexit. Ahead of the referendum of 23 June whether the United Kingdom should leave the European Union (Brexit), some economists expected that the SNB would intervene in the foreign exchange market if necessary to defend a level of the EUR/CHF exchange rate of 1.07, see "Economists expect that he [Jordan] would vehemently defend a euro-Swiss franc exchange rate level of 1.07" (Neue Züricher Zeitung, 19 June 2016).

[5] As mentioned above, affecting the value of the Swiss franc is not an end in itself, but a means to affect inflation, which is the SNB's main objective.

[6] See Ranaldo and Rossi (2010) for a study on the effects of the SNB's communication in the form of monetary policy announcements, speeches and interviews on asset prices.

[7] Transparent rule-based FX intervention has sometimes been used to indicate that changes in FX reserves will be limited and predictable and that there is no explicit intention of exchange rate targeting (eg in Chile and Colombia before and after the global financial crisis) (Domanski et al., 2016).

[8] Commentators have also often referred to this. For example, Handelsblatt (2015) wrote that changes in sight deposits are an indicator of whether and in what amount the SNB intervenes in order to counter too strong an appreciation of the Swiss franc. Another article on Bloomberg mentioned that "Sight deposits are the cash commercial banks hold with the central bank and serve as a proxy measure for interventions. In the past, when the SNB defended its currency ceiling, the deposits were credited with the amount of francs sold" (Bloomberg, 2015). Obstfeld (1983) analysed the effectiveness of sterilized and nonsterilized interventions in a rational expectations model. The model covers, amongst other topics, structural equations for German sight deposits' demand and supply.

[9] In addition to observing the proxy measure of weekly sight deposits, FX market participants may also be able to infer information on possible FX interventions in real time to some extent by following news reports on platforms like Bloomberg and

Reuters, which might point to the possibility of or speculation about intervention.

[10] The valuation adjustment nets out currencyvaluation changes and estimated interest income gains, and includes variation of net forward positions. It accounts for changes in the exchange rates of global reserve currencies and the average foreign exchange reserve composition based on the IMF Currency Composition of Official Foreign Exchange Reserves (COFER) database, assuming that the share in each currency is remunerated at a Libor rate, following Domanski et al. (2016). The adjustment is not exact, however, since it is based on information on currency composition of foreign currency reserves which is not updated each month.

[11] However, Adler and Tovar (2011) highlight that differences between changes in reserves and actual intervention at lower-than-weekly frequencies tend to be minor.

[12] Some papers have endogenised exchange rate policy by deriving the width of the band as a rational choice of an optimising central bank. For example, Cukierman, Kiguel, and Leiderman (1994) model the choice of the bandwidth as a choice between flexibility in responding to external shocks and commitment of less devaluation and inflation. Such normative issues are beyond the scope of the paper.

[13] See Encyclopedia of Mathematics, "Wiener process", available at http://www.encyclopediaofmath.org/index.php?title=Wiener_process&oldid=26975 (accessed 2 January 2017).

[14] In mathematical terms, the smooth pastingcondition only guarantees a zero slope at f^l. For $f < f^l$ the slope is non-zero.

[15] Note that this is not necessarily the case in a multilateral band system. For example, Serrat (2000) has shown that in such an exchange rate setting, exchange rate volatility can be larger than under a free float.

[16] We are well aware of the stylised nature of the model, despite our attempts to calibrate with realistic parameters. We do not claim empirical accuracy for the model but use it rather for qualitative features and predictions.

[17] Given such discontinuities, a number of attempts have been made to relax the assumption of a given band and perfect credibility. An alternative to our modelling approach with oscillating bandwidths over time has been presented by Dibeh (2006). In his modelling approach, the periodic motion is forced by a sinusoidal function.

[18] It is clear that target zone regimes vary from one country to another and within countries over time. Our extension of the original Krugman model is, therefore, really only one example of how such a Markov-switching regime might work, but it can be modified and extended in various ways.

[19] Regime-switching models are well-established models in the exchange rate literature. Hamilton (1990), Engel (1994), and Cheung and Erlandsson (2005) have popularized the Markov-switching toolkit in exchange rate economics by showing that the Markov switching model is a relevant statistical alternative to the classical martingale model for exchange rates.

[20] The assumption of constant switching probabilities may appear unlikely. Tristani (1994) and Werner (1995) have presented targetzone models in which the realignment risk is a positive function of how far the exchange rate is located from the central parity – the closer the exchange rate is to the boundaries of the target zone, the higher is the realignment probability.

[21] The analysis here is of potentially recurrent switches of the exchange rate regime. More precisely, it allows for the possibility (but not the necessity) of a greater-than-zero probability of returning to the original state. On the contrary, Miller and Sutherland (1991) have analysed the implications of a single not-to-be-repeated jump.

[22] An important point to bear in mind is that in contrast to the Swiss case considered here, weak currencies might actually benefit from such cross-regime effects. For example, weak currencies might benefit from the stabilizing effect of the belief that a regime switch would tighten up monetary policy in the future with some probability. In other words, in this case regime switches are a stabilizing device.

[23] The modelling toolbox developed here may be combined with the framework developed by Bianchi and Melosi (2016) to characterize the evolution of expectations and uncertainty in general equilibrium models in which agents have to learn the stochastic properties of regimes. The central insight of Bianchi and Melosi (2016) consists of recognizing that the evolution of agents' beliefs can be captured by defining a set of regimes that are characterized by the degree of agents' pessimism, optimism, and uncertainty about future equilibrium outcomes.