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Foreign exchange interventions under a one-sided target zone regime and the Swiss franc

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Non-technical summary

Research Question

From 6 September 2011 to 15 January 2015, the Swiss National Bank (SNB) implemented a one-sided exchange rate target zone vis-à-vis the euro. During this period, the SNB accumulated large foreign exchange (FX) reserves, which ultimately raised concerns about the balance sheet risks that it was incurring and led to strong political pressure to abandon the minimum exchange rate regime. Against this background, this paper proposes a model to determine the expected size of FX interventions under a one-sided target zone.

Contribution

The paper presents a theoretical model in closed form embedded within the Krugman (1991) target zone framework. The model allows monetary authorities to determine the size of FX interventions that are expected to be necessary for implementing and maintaining a minimum exchange rate regime using only observable variables. Furthermore, an empirical application of the model to the SNB's FX rate policy vis-à-vis the euro in the aforementioned period adds new insights into the functioning of minimum exchange rate regimes.

Results

The empirical application of the proposed model to the period of the SNB's minimum exchange rate regime shows that it is well suited for explaining the actual size of FX interventions. In addition, the results suggest that the SNB's euro purchases might indeed have been large without the abandonment of the minimum exchange rate regime, which is in line with the SNB's official statements in the aftermath of that episode.

Nichttechnische Zusammenfassung

Fragestellung

Vom 6. September 2011 bis zum 15. Januar 2015 ließ die Schweizerische Nationalbank (SNB) den Wechselkurs des Schweizer Franken gegenüber dem Euro in einer einseitig begrenzten Zielzone schwanken. In diesem Zusammenhang kam es bei der SNB zum Aufbau hoher Devisenreserven, was letztlich Bedenken hinsichtlich der von der Bank eingegangenen Bilanzrisiken hervorrief und unter anderem zu der Forderung führte, das Mindestkursregime wieder aufzugeben. Vor diesem Hintergrund wird im vorliegenden Beitrag ein Modell zur Bestimmung des erwarteten Umfangs der Deviseninterventionen in einem System mit einseitig begrenzter Zielzone vorgeschlagen.

Beitrag

Es wird ein in das Zielzonenmodell von Krugman (1991) eingebettetes theoretisches Modell entwickelt. Dieses Modell erlaubt es, den Umfang der zur Einführung und Aufrechterhaltung eines Mindestkursregimes notwendigen Deviseninterventionen ausschliesslich auf Basis beobachtbarer Variablen vorherzusagen. Darüber hinaus liefert eine empirische Anwendung des Modells auf die von der SNB im vorgenannten Zeitraum verfolgte Wechselkurspolitik gegenüber dem Euro neue Erkenntnisse über die Wirkungsweise von Mindestkursregimes.

Ergebnisse

Die empirische Anwendung des entwickelten Modells auf den Zeitraum des Mindestkursregimes der SNB zeigt, dass es gut geeignet ist, den tatsächlichen Umfang der Deviseninterventionen zu erklären. Zudem deuten die Ergebnisse darauf hin, dass es ohne Aufgabe des Mindestkursregimes möglicherweise tatsächlich zu umfangreichen Euro-Käufen der SNB gekommen wäre, was mit den offiziellen Verlautbarungen der SNB nach Ende dieser Phase im Einklang steht.

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Foreign Exchange Interventions under a One-Sided Target Zone Regime and the Swiss Franc

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Abstract

From September 2011 to January 2015, the Swiss National Bank (SNB) implemented a minimum exchange rate regime (i.e. a one-sided target zone) vis-à-vis the euro to fight deflationary pressures in the aftermath of the Great Financial Crisis. During this period of unconventional monetary policy, the SNB faced mounting criticism from the media and the public on the sizable balance sheet risks that it was incurring. Motivated by this episode, I present a structural model embedded within the target zone framework developed by Krugman (1991) that allows monetary authorities to determine ex-ante the maximum size of foreign exchange market interventions that are expected to be necessary to implement and maintain a one-sided target zone. An empirical application of the proposed model to the aforementioned episode reveals that it is well suited to explain the actual size of these interventions and that, in January 2015, the SNB's euro purchases might indeed have been large without the abandonment of the minimum exchange rate regime, which is consistent with the official statements of the SNB in the aftermath of that episode.

JEL classification: C43, C51, E32, E37, E43, G12, R21, R28, R31.

Keywords: Foreign exchange interventions; minimum exchange rate; reaction function; reflected Brownian motion; Swiss franc; Swiss National Bank; target zone; unconventional monetary policy.

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1 Introduction

From September 6, 2011 to January 15, 2015, the Swiss National Bank (SNB) implemented a one-sided exchange rate target zone vis-à-vis the euro, the currency of its most important trading partner. During this episode, the SNB accumulated large foreign exchange (FX) reserves, which ultimately raised concerns about the balance sheet risks that it was incurring and led to strong political pressure to abandon the minimum exchange rate regime.[1] When the SNB finally abandoned this regime, it argued that it had taken this decision after having compared the costs[2] and benefits[3] of this unconventional monetary policy measure. Motivated by this episode, this paper generalizes the structural model proposed by Hertrich (2016a) to determine the expected size of FX interventions under a unilateral one-sided target zone by embedding the model within the Krugman (1991) target zone framework, which has become one of the standard tools in this strand of literature (Rodríguez and Rodríguez, 2007).[4] At this point, readers may argue that the theoretical predictions of the Krugman model could not be confirmed in earlier empirical studies that analyzed other target zone regimes, but "this time is different!"[5] There is strong empirical evidence indicating that the Krugman (1991) exchange rate target zone model (hereinafter referred to as the "Krugman model") is well suited to describe the EUR-CHF exchange rate dynamics in the period of interest.[6] In line with these findings, an empirical application of the proposed model to the aforementioned episode reveals that it is well suited to explain the actual size of these interventions and that, in January 2015, the SNB's euro purchases might indeed have been large in the short term without the abandonment of the minimum exchange rate regime, which is consistent with the official statements of the SNB in the aftermath of that episode.[7]

The advantages of the proposed model are threefold. First, contrary to Hertrich (2016a), it is assumed that the economic fundamental (and not the exchange rate) follows a reflected geometric Brownian motion (RGBM), in line with a large body of the target zone literature. By contrast, assuming that the exchange rate follows an RGBM as a first-order approximation may lead to sizable distortions (e.g. when pricing currency options;

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[1] Under Switzerland's political system, the SNB faced a public referendum on the composition of its balance sheet on November 30, 2014 (the so-called "Swiss Gold Initiative") that would have obliged the SNB to invest 20% of its assets in gold. This, however, was rejected by a majority of voters (see e.g. Christensen, López, and Rudebusch (2015) and Jermann (2017) for more details).

[2] For instance, with more FX interventions (and therefore larger balance sheet risks), the volume of foreign currency reserves would have rapidly exceeded the Swiss GDP (Lera and Sornette, 2016).

[3] For instance, the strong impact that the existence of a target zone has on expectations (Krugman, 1991) in view of the SNB's motivation to implement a minimum FX rate regime to depreciate its "massively overvalued" currency (Swiss National Bank, 2011).

[4] For alternative models, see the surveys of the exchange rate target zone literature provided by Kempa and Nelles (1999) and Duarte, Andrade, and Duarte (2013).

[5] Quoting the famous phrase of Carmen M. Reinhart and Kenneth S. Rogoff in a different context.

[6] See Hertrich (2016b), Lera and Sornette (2016) and Janssen and Studer (2017), who analyze the suitability of the Krugman model in terms of its main empirical implications (see Svensson (1991a) and Svensson (1992a) for details on the latter) and report results that are in line with the implications of the Krugman model. Fore more information, see Subsection 3.1.

[7] The SNB governing board member Fritz Zurbrügg, for instance, admitted in an interview one week after the "Swiss franc shock" that without the abandonment, the SNB would have had to intervene with 100 billion Swiss francs in January 2015 alone (Schätti, 2015). This statement suggests that the timing of the abandonment was associated with the fear of otherwise accumulating excessive balance sheet risks.

see Veestraeten (2000) for numerical simulations). Therefore, the generalized model is better suited as a tool for monetary authorities to determine the size of FX interventions that are expected to be necessary to implement and maintain a minimum exchange rate regime vis-à-vis a specific currency. Second, by taking advantage of the results in Lera and Sornette (2016) who propose an explicit approximation for the unobservable fundamental as a function of observable variables (e.g. the spot exchange rate), an upper limit[8] for the expected size of FX interventions can be estimated. This expression paves the way for a novel testable implication of the Krugman model for the case of a one-sided target zone. Third, the proposed approach allows an assessment of the empirical validity of the model by analyzing the EUR-CHF target zone regime in the aforementioned period of interest. The paper therefore contributes to a growing literature on unconventional monetary policy measures and a revived exchange rate target zone literature.

The paper is structured as follows. Section 2 shows how the exchange rate can be modeled when the monetary authorities of the domestic country commit to enforcing a minimum exchange rate regime. In Section 3, I demonstrate within this theoretical framework how the size of FX interventions can be estimated ex-ante and during the period in which such a regime is implemented. Section 4 analyzes how well the proposed model fits with the actual size of FX interventions in the case of the SNB's exchange rate policy vis-à-vis the euro from September 6, 2011 to January 15, 2015 and discusses the timing of the SNB's decision to abandon this policy. Section 5 concludes.

2 The Krugman Target Zone Model

2.1 Monetary Model of Exchange Rates

The Krugman model assumes that the log of the spot exchange rate at time t, $s(t)$,[9] is determined by the sum of the log of the economic fundamental,[10] $f(t)$, and a speculative term proportional to the expected percentage change of the former (i.e. reflecting the forward-looking behavior of financial market participants):

$$s(t) = f(t) + \gamma \frac{\mathrm{E}[ds(t)]}{dt}, \gamma > 0, \tag{1}$$

where γ captures (the absolute value of) the semi-elasticity of money demand to the (nominal) domestic interest rate (in years) in a monetary exchange rate model for a small open economy (for details on the economic foundations of the model, see e.g. footnote 4 on page 29 in Svensson (1991a) or Section 2 in Lin (2008)). Within this setting, γ is derived from a log-functional form of the money demand equation.[11]

Notice that the approach that is presented in this paper can easily be adapted to a

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[8] As the approximation holds for a spot exchange rate close to the minimum exchange rate, where FX interventions are necessary even under a perfectly credible target zone, the expected size of necessary FX interventions is a maximum (see Subsection 2.3 for details).

[9] Following the exchange rate convention, the spot exchange rate equals the number of domestic currency units per unit of foreign currency (Reiswich and Wystup, 2010).

[10] See Belessakos and Loufir (1993) for an alternative micro-based monetary exchange rate target zone model where the log exchange rate is a non-linear function of the current value of the fundamental.

[11] See Lucas Jr. (2000) for alternative specifications.

two-country monetary model of exchange rates in the spirit of Flood and Garber (1983) and Froot and Obstfeld (1991a). In the two-country case, the economic fundamental is defined as a scalar indicator of macroeconomic fundamentals and the drift rate must be adjusted accordingly to account for the foreign risk-free interest rate. Nevertheless, as the empirical section analyzes an episode with a small open economy (i.e. Switzerland) that commits unilaterally to maintaining a minimum exchange rate regime vis-à-vis a large currency union,[12] it is preferable to develop all the analytical results within the Krugman framework instead.

The economic fundamental $f(t)$ is modeled as the sum of the domestic money supply (in logs), $m(t)$, which is directly controlled by the domestic central bank and reflects the endogenous component of the fundamental, and a term $v(t)$ that captures exogenous "velocity" shocks (also in logs) and can be represented as the negative of a linear composite of money demands:[13]

$$f(t) = m(t) + v(t). \tag{2}$$

The exogenous velocity term $v(t)$ is assumed to follow a Brownian motion (BM)[14] with drift and diffusion coefficients μ and σ, respectively:[15][16]

$$dv(t) = \mu dt + \sigma dz(t),\ \mu \in \mathbb{R} \text{ and } \sigma > 0, \tag{3}$$

where $z(t)$ denotes a standard Wiener process.

2.2 Free Float Regime

In line with the target zone literature, it is assumed that the monetary authorities refrain from intervening with unsterilized interventions in FX markets in the absence of a minimum exchange rate regime[17] and therefore maintain the money supply constant (i.e., $m(t) \equiv m =$ const., e.g. normalized to zero for simplicity).[18] Hence, under a free float regime, the "demeaned" fundamental $k(t)$ equals the exogenous velocity term and

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[12] As a consequence, the economy of the large currency union is unaffected by this peg regime in terms of inflation, trade flows, etc.

[13] See Appendix A for details on how Equations 1 and 2 are derived.

[14] For the period of interest, Janssen and Studer (2017) show in a earlier version of this paper that their proxy variable for $v(t)$ indeed follows a random walk, which adds support to the assumption of a BM that underlies the structural model of FX interventions that is proposed in this paper.

[15] In the Krugman model, the drift coefficient μ is set equal to zero.

[16] As shown in Section 3.3. in Froot and Obstfeld (1991b), the stochastic process for the fundamental can easily be adapted to a mean-reverting process, thereby adding some degree of generalization to the structural model for the expected size of FX interventions that I propose in this paper.

[17] Which is also the standard in the literature on speculative attacks, see e.g. Grilli (1986). For Switzerland, this assumption is also in line with the actual intervention data that is used in Bieri (2001) and reveals that the SNB only intervened on two days vis-à-vis the German Mark - which is often used as the predecessor of the euro. Hence, for the EUR-CHF FX rate this assumption seems to be an appropriate approximation.

[18] This assumption can be generalized by assuming, for instance, that the monetary authorities follow the k-percent money supply rule developed by Friedman (1948)'s .

therefore also follows a BM, the continuous-time representation of a random walk:

$$k(t) \equiv f(t) - m = v(t). \tag{4}$$

This implies that $k(t)$ and therefore also $f(t)$ are both normally distributed. Specifically, the probability distribution of $f(t)$ conditional on $f(0)$ at time zero is normal with mean $f_0 + \mu t$ and variance $\sigma^2 t$. Therefore, I can focus on $f(t)$ and follow the standard target zone literature below.

In this regard, it can easily be shown that the exchange rate under a free float regime follows a BM and is equal to:[19]

$$\hat{s}(t) = f(t) + \gamma\mu. \tag{5}$$

Hence, in such a regime the conditional exchange rate volatility is equal to the instantaneous standard deviation of the fundamental. Notice that especially for high income countries and for short horizons, assuming that the log of the nominal exchange rate follows an BM is an appropriate approximation.[20]

2.3 Minimum Exchange Rate Regime

2.3.1 The Fundamental as a Function of its Counterpart under a Free Float Regime

In the following, it is assumed that the domestic monetary authorities enforce a fully credible[21] minimum level for the exchange rate[22] vis-à-vis a specific currency[23] and that it only affects the money supply with unsterilized FX interventions (so-called "marginal interventions") in periods where Krugman's "honeymoon effect"[24] is insufficient to prevent the economic fundamental (and therefore the exchange rate) from moving below a targeted level $\underline{f} \equiv \ln \underline{F}$ (i.e. the level of the fundamental that accords with the officially announced minimum exchange rate $\underline{s} = s(\underline{f})$) even under perfect credi-

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[19] See Equation 6 in Svensson (1991a) or Equation 18 in Froot and Obstfeld (1991a).

[20] See e.g. Clements and Lan (2010), Rossi (2013), Byrne, Korobilis, and Ribeiro (2016), Cheung, Chinn, Pascual, and Zhang (2019), Engel (2019) or Engel, Lee, Liu, Liu, and Wu (2019). Moreover, Kugler (2017) shows that the EUR-CHF FX rate exhibits a unit root from January 2009 to June 2017.

[21] The credibility of the minimum exchange rate regime is defined as the probability that it is maintained, following the definition of Drazen and Masson (1994).

[22] In the Krugman framework, for example, it is assumed that the domestic monetary authorities publicly announce the exchange-rate band. Nevertheless, it does not matter whether the monetary authorities announce a specific band (or e.g. a minimum level) for the exchange rate or a band (or e.g. a lower bound) for the economic fundamental, as there is a one-to-one correspondence between the exchange rate and the economic fundamental, i.e. any minimum exchange rate regime determines a unique target zone for the fundamental and vice versa; see Froot and Obstfeld (1991a) or Equation 10 in the present paper.

[23] For instance, the currency of the most important trading partner of the home country.

[24] This self-correction mechanism arises within the Krugman framework, making the exchange under a target zone regime less responsive to the fundamentals than under a free float. Those readers that are not familiar with this concept are referred to Figure B.1 in Appendix B, where it can be seen how the slope of the curve that relates the FX rate s to the velocity term v decreases, the closer the market is to the edge of the target zone.

bility.[25] As a consequence, the log of the fundamental under the minimum exchange rate regime, $\widetilde{f}(t)$, will be greater or equal to its counterpart under a free float regime (i.e. $f(t)$):

$$\widetilde{f}(t) = f(t) + \max\left\{0, \max_{0\leq s\leq t}\left[\underline{f} - f(s)\right]\right\}, \text{ for } 0 \leq t \leq \infty. \tag{6}$$

Notice that as long as there are no interventions, $\widetilde{f}(t)$ will be equal to $f(t)$. In the case of actual FX interventions, these will be captured by the second summand in Equation 6.

After subtracting $\underline{f}$, the stochastic process $\{\widetilde{f}(t) - \underline{f}\}$ results from the (scaled) stochastic process $\{f(t) - \underline{f}\}$ under a free float regime by introducing a reflecting barrier at zero.[26] Following the steps in Graversen and Shiryaev (2000) or Ko, Shiu, and Wei (2010), it can be shown that the stochastic process $\{\widetilde{f}(t) - \underline{f}\}$ is a representation of a reflected (or regulated) Brownian motion (RBM) with the initial level $f_0 \equiv \{\widetilde{f}(0) - \underline{f}\}$ and drift and diffusion coefficients μ and σ, respectively.[27] Hence, the expected size of FX interventions for a specific forecast horizon of T periods can be estimated using the transition probability density of a RBM.

For readers more familiar with the target zone literature, it is worth mentioning that, within the Krugman framework, it can easily be shown that the fundamental under the minimum exchange rate regime can be modelled as a RBM with FX interventions represented by the regulator L, such that

$$dm(t) = dL(t), \tag{7}$$

where dL represents increases in the supply of money due to FX interventions, is non-negative and positive only when $\widetilde{f}(t) = \underline{f}$, following the definition of the so-called "reflection functions" in Skorokhod (1961), where he shows how to construct one-dimensional diffusions with reflection. Notice that these properties lead to reflection functions that are uniquely determined (see e.g. Skorokhod (1961), Harrison and Reiman (1981) and Zhang and Du (2010)). As a consequence, the continuous-time process of the FX interventions is also uniquely determined.

The fundamental $\widetilde{f}(t)$ then follows the process:

$$\widetilde{f}(t) = \mu dt + \sigma dz(t) + dL(t). \tag{8}$$

2.3.2 Lower Bound for the Fundamental

Froot and Obstfeld (1991a), Froot and Obstfeld (1991b) and Svensson (1991a) derive a general expression for the saddle path exchange rate (i.e. a solution that rules out bubbles) for the case where market participants expect a departure from a free float regime in the future (see Equations 8, 8 and 13 in the aforementioned three papers, respectively). To account for the presence of a two-sided target zone, these authors impose a value-matching condition at the edges of the target zone, the so-called smooth pasting condition. Letting

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[25] For an explanation why FX interventions may arise in perfectly credible FX rate target zones, see the accompanying explanation to Figure B.1 in Appendix B.

[26] See p. 1478 in Carr and Kakushadadze (2017) for an intuitive explanation.

[27] See also Theorem 2.1 in Peskir (2005).

the upper bound of the resulting equation[28] go to infinity yields the following expression:

$$s(t) = \widetilde{f}(t) + \gamma\mu + \frac{1}{\rho}\exp^{\rho[\underline{f}-\widetilde{f}(t)]}, \tag{9}$$

with

$$\rho = \frac{1}{\sigma^2}\left(\mu + \sqrt{\mu^2 + \frac{2\sigma^2}{\gamma}}\right) > 0,$$

which is the positive root of the quadratic equation in Equation 8, 9 and 14 in Froot and Obstfeld (1991a), Froot and Obstfeld (1991b) and Svensson (1991a), respectively. Re-arranging and validating the expression in Equation 9 at $\widetilde{f} = \underline{f}$, I get the following expression for $\underline{f}$:[29]

$$\underline{f} = \underline{s} - \gamma\mu - \frac{1}{\rho}. \tag{10}$$

2.4 Derivation of Observables: A Generalization of Lera and Sornette (2016)

In this subsection, I follow the steps in Lera and Sornette (2016) and generalize their solutions for both the economic fundamental and the instantaneous conditional exchange rate volatility.

2.4.1 Economic Fundamental

To express the economic fundamental as an expression of observable variables, I follow the approach in Lera and Sornette (2016), who use a Taylor series up to the second-order term to obtain the following relationship that also holds in the general case of $\mu \neq 0$:

$$\widetilde{f}(t) = \sqrt{\frac{2}{\rho}}\sqrt{s(t) - \underline{s}} + \underline{f}. \tag{11}$$

For the EUR-CHF case, Lera and Sornette (2016) show in their Section 4 using high-frequency data that this approximation empirically holds well in the period of interest. Combining Equation 10 with Equation 11, I get:

$$\widetilde{f}(t) = \sqrt{\frac{2}{\rho}}\sqrt{s(t) - \underline{s}} + \underline{s} - \gamma\mu - \frac{1}{\rho}. \tag{12}$$

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[28] See Equations 16, 15 and 13 plus 18a plus 18b in the aforecited papers, respectively.

[29] As emphasized in Lera and Sornette (2016), the following expression must be interpreted as an equality that holds in the limit when $\widetilde{f}$ approaches $\underline{f}$, as the domestic central bank will intervene in the FX market whenever the FX rate touches the minimum exchange rate, thereby changing m and $\widetilde{f}$. Therefore, in general, the value for $\underline{f}$ will be non-unique.

2.4.2 Conditional Volatility of the Fundamental

As shown in Equation 38 in Svensson (1991a), applying Ito's lemma to the conditional exchange rate volatility yields:

$$\sigma^s(\widetilde{f}(t)) = \sigma \frac{\partial s(\widetilde{f}(t))}{\partial \widetilde{f}(t)}. \tag{13}$$

Following the steps in Subsection 3.1 in Lera and Sornette (2016), the following expression emerges for the conditional volatility of the fundamental in the general case of $\mu \neq 0$:[30]

$$\sigma = \frac{\sqrt{\gamma}\sigma^s}{\sqrt{2\left[s(t) - \underline{s}\right]}} \sqrt{\frac{(\sigma^s)^2}{4\left[s(t) - \underline{s}\right]} - \mu}. \tag{14}$$

Hence, if we know γ, μ and σ^s, the unobservable economic fundamental $\widetilde{f}(t)$ can be expressed as a function of observable variables whenever monetary authorities publicly announce their commitment to implement a permanent minimum exchange rate regime.

3 Methodology, Data and Estimation

3.1 Excursus: Uniqueness of the EUR-CHF Minimum Exchange Rate Regime

There is ample empirical evidence indicating that several theoretical predictions of the Krugman model[31] are fulfilled in the period of interest, which contrasts with the experience of previous exchange rate target zones (see the detailed surveys in Kempa and Nelles (1999) and Duarte et al. (2013)).

3.1.1 Marginal Interventions

Hertrich (2016b) and Lera and Sornette (2016) empirically show that the shape of the (unconditional) exchange rate distribution of the EUR-CHF spot rate in the period of interest is \-shaped, as theoretically predicted by the Krugman model. This shape suggests that the SNB implemented its commitment to maintain a minimum exchange rate with only marginal FX market interventions.

3.1.2 Smooth Pasting

Lera and Sornette (2016) derive an expression for the conditional FX rate volatility after invoking the smooth pasting condition. Using tick data of the EUR-CHF spot rate, they show empirically that not invoking this condition in their expression does not significantly improve their fit. They conclude, therefore, that the EUR-CHF spot market was arbitrage-free in the period of interest, which is the economic interpretation of this condition.[32]

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[30] Notice that the following expression corrects an error in Equation 3.6 in Lera and Sornette (2016), where the scalar 2 should be raised to the power of 3/4 instead of being raised to the power of 1/4.

[31] See Svensson (1991a) for a detailed derivation of these theoretical implications.

[32] See Dumas (1991) for details.

Similarly, Janssen and Studer (2017) document that the EUR-CHF spot rate behaved as predicted by the Krugman model. Starting with the stylized fact that the Swiss currency is a safe haven currency, i.e. a currency that systematically increases in value when global risk aversion is high, Janssen and Studer (2017) cite several studies that document the role of global risk factors for the value of the Swiss currency (e.g. Hoffmann and Suter (2010), Ranaldo and Söderlind (2010) and Grisse and Nitschka (2015)), propose the global market risk state variable VIX as a proxy for the exogenous macroeconomic component of the fundamental value of the EUR-CHF exchange rate and demonstrate the high explanatory power of the VIX for the latter in five different periods from January 2008 to July 2016. Then, focusing on the minimum exchange rate regime, they demonstrate empirically that the theoretical predictions of the Krugman model with respect to the exchange rate behavior are fulfilled in practice for levels close to the minimum level, i.e. the closer the EUR-CHF spot rate was to the minimum level, the weaker was its co-movement with the VIX (reflecting the "honeymoon" effect), which is how the FX rate should evolve according to the smooth pasting condition that underlies the Krugman model.

3.1.3 Perfect Credibility

To assess the credibility of the EUR-CHF minimum exchange rate regime, Janssen and Studer (2017) apply the "simplest test of target zone credibility" that was first proposed by Svensson (1991b). The test consists of checking whether forward exchange rates for different maturities exceed the minimum exchange rate throughout the period of interest. If this condition is fulfilled, a target zone is deemed to be perfectly credible (Siklos and Tarajos, 1996). The intuition of this test is the following: as forward outright exchange rates reflect the expected change of exchange rates, they should never exceed the implemented minimum FX rate level in the case of a fully credible target zone regime. As shown in Figure 5 in Janssen and Studer (2017), only the forward exchange rates for a maturity of one month pass the "Svensson test" (see also Figure B.2 in Appendix B). A similar picture emerges when looking at the one-quarter ahead consensus forecasts for the EUR-CHF FX rate based on the combined estimates of large financial institutions (mainly banks) that are active in FX markets.[33] During the period of interest, the consensus estimates consistently exceeded the minimum FX rate level (see Figure B.3 in Appendix B).

These observations are in line with the findings in Hanke, Poulsen, and Weissensteiner (2015), Hui, Lo, and Fong (2016), and Jermann (2017), who document that the credibility of the SNB's commitment to maintain the minimum exchange rate regime was indeed large in the period of interest. This claim is also in line with the findings documented in Danielsson (2015) who shows that the risk models that are currently used by financial institutions predicted that the probability of an abandonment on the event day was at most once a century. In a similar vein, Section 8 in Lleo and Ziemba (2015) reports that the total loss incurred by Citigroup, Deutsche Bank and Barclays as an aftermath of the unexpected regime switch amounted to USD 400 million. One of the largest and longest-standing private investors in emerging markets, Everest Capital, had to be closed after a "large portion of the fund's USD 830 million assets were wiped out" (Delevigne, 2015).

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[33] See Bloomberg for details.

Other empirical studies, however, find that financial market participants priced in a relatively large probability of an abandonment (see e.g. Hertrich and Zimmermann (2017) and Hanke, Poulsen, and Weissensteiner (2019)). Hence, more empirical research seems to be warranted to answer this critical issue.

How do the implications of the Krugman model change under imperfect credibility? From a theoretical point of view, the effect of an imperfectly credible minimum exchange rate regime has already been analyzed in Krugman (1991).[34] Under the assumption that the monetary authority switches to a free-float regime after an abandonment, he shows that imperfect credibility leads to a weaker "honeymoon effect".[35] The extent of this "instability" is thereby increasing in the degree of "imperfect credibility". A similar result emerges in the informal target zone model developed by Chen, Funke, and Moessner (2018) that is embedded within the Krugman framework and can easily be merged with my structural model, e.g. using their modification in their Subsection 4.2. Nevertheless, due to strong empirical support for the Krugman model in the case of the EUR-CHF minimum FX rate regime, it seems appropriate to use the Krugman model in combination with the aforecited results of Lera and Sornette (2016) in the following.

3.1.4 Infinite Lifetime

In the Krugman model, it is implicitly assumed that the target zone is implemented forever. In line herewith, Dumas and Svensson (1994) show that the expected survival time of FX target zones is rather large in theory and may equal several decades, unless real disturbances are important and if the elasticity of aggregate demand to the real FX rate is rather low (Broome, 2001). Indeed, the empirical results in Lera and Sornette (2016) point to a rather long lifetime. They first expand the aforementioned saddle path FX rate (see Subsection 2.3.2) up to the second order term,[36] but refrain from imposing the smooth-pasting condition. Second, using high-frequency data, they are not able to falsify the resulting null hypothesis. In other words, financial market participants traded in the EUR-CHF spot market, as if they were using the Krugman model.[37]

Nevertheless, the assumption of an infinite lifetime can easily be replaced by a finite lifetime, as shown in Ajevskis (2011) or Lera and Sornette (2019). In the former case, Ajevskis (2011) imposes a terminal condition at a finite future date; this simply weakens the honeymoon effect, but does not alter the qualitative implications of the Krugman model at all. The honeymoon effect is weaker, the closer the finite future date is. In the latter case, Lera and Sornette (2019) show that there is a one-to-one correspondence between the Krugman model and target zones modelled in terms of perpetual options. Within this option pricing framework, the assumption of a infinite lifetime can easily be relaxed and replaced by a finite option-market's implied lifetime.

To conclude this subsection: Given ample evidence in favor of the Krugman model for the EUR-CHF minimum FX rate regime in the period of interest, it seems appropriate

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[34] See Duarte et al. (2013) for alternative models that allow for imperfect credibility.

[35] Hence, imperfect credibility goes hand in hand with larger FX interventions while a target zone is in place.

[36] Hence, implicitly assuming marginal interventions, perfect credibility and more importantly, an infinite lifetime of the minimum FX rate regime.

[37] Ignoring third- and higher-order terms.

to embed the proposed model in this framework.

3.2 Model of Expected Exchange Interventions

In the following, it is assumed that the monetary authority of the domestic country announces its commitment to implement a minimum FX rate regime and that it uses both a short and an infinitely long forecast horizon to assess the size of FX interventions that it expects to be necessary to maintain this regime. In addition, it is assumed that the domestic central bank does not have to intervene in the FX market just after publicly announcing its commitment to enforce a minimum exchange rate (i.e. $\widetilde{F}(0) = F(0)$). This assumption is in line with how the exchange rate market responded to other major monetary policy shocks, such as the unexpected[38] announcement of the Plaza Agreement among the Group of Five (G5) nations in 1985; according to Ito (1987), the initial jump of the yen against the US dollar was caused by the official communiqué itself. Hence, as the official communiqué of the SNB's minimum exchange rate regime was also unexpected, it is reasonable to assume that the initial jump of the EUR-CHF exchange rate on September 6, 2011 reflects a pure "announcement effect".[39]

Let $V(F(0), T)$ denote the discounted size of expected FX interventions for a period of T years, i.e. the extra amount of foreign currency (measured in units of the domestic currency) that a central bank expects to need to buy over the next T years due to its commitment to implement a minimum exchange rate regime for infinite years. Hence, $V(F(0), T)$ can be modeled as the difference between the discounted expected level of the fundamental under its commitment and its counterpart under a free float regime:[40]

$$\begin{aligned} V(F(0), T) &= \exp^{-r(t)T} \left\{ \mathrm{E}^{Q^{RBM}} \left[\widetilde{F}(T) \right] - \mathrm{E}^{Q^{BM}} \left[F(T) \right] \right\}, \\ &= \exp^{-r(t)T} \left\{ \underline{F} \int_0^{\infty} \exp^{x} p(x; f_0, T) dx - \mathrm{E}^{Q^{BM}} \left[F(T) \right] \right\}, \end{aligned} \tag{15}$$

with $x = \ln \left[\widetilde{F}(T) / \underline{F} \right]$ and where $p(x; f_0, T)$ denotes the transition probability density of a RBM with drift and equals (Equation 91 on p. 224 in Cox and Miller (1965)):[41]

$$\begin{aligned} p(x; f_0, T) &= n\left(x; f_0 + \mu \cdot T, \sigma^2 \cdot T\right) + \left(\frac{\underline{F}}{F(0)} \right)^{\theta} \cdot n\left(x; -f_0 + \mu \cdot T, \sigma^2 \cdot T\right) \\ &- \theta \cdot \exp^{\theta x} \cdot \left[1 - \Phi\left(\frac{x + f_0 + \mu \cdot T}{\sigma \cdot \sqrt{T}} \right) \right], \end{aligned} \tag{16}$$

with $\theta = \frac{2 \cdot \mu}{\sigma^2}$, where $n(x; \mu, \sigma^2)$ denotes the normal probability density function with mean μ and standard deviation σ and where $\Phi(x)$ denotes the cumulative distribution function

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[38] See Ito (2015), who describes in detail how the Japanese Finance Minister managed to keep the meeting of the involved finance ministers and central bank governors confidential.

[39] Otherwise, the proposed model can easily be adjusted to account for the expected size of initial FX interventions.

[40] In a two-country setup, the discount factor must be adjusted accordingly.

[41] The transition probability density $p(x; f_0, T)$ also corresponds to Equation 2.4 in Gerber and Pafumi (2000), Equation 2.5 in Ko et al. (2010) and can also be found in Appendix 1, Section 16 on pp. 133-134 in Borodin and Salminen (2015).

of the standard normal distribution.

After plugging the transition probability density $p(x; f_0, T)$ into Equation 15 and following the steps in Gerber and Pafumi (2000) or Ko et al. (2010), the expression for the expected size of FX interventions (as of time $t = 0$) can be written as:

$$\begin{aligned} V_{0,T} \equiv{} & V\left[F(0), T\right] = \underline{F}\exp^{-r(0)T}\frac{\mu}{r(0)}\Phi\left(\frac{\ln\left[\underline{F}/F(0)\right]-\mu T}{\sigma\sqrt{T}}\right) \\ & +\frac{\underline{F}}{\theta+1}\left(\frac{\underline{F}}{F(0)}\right)^{\theta+1}\Phi\left(\frac{\ln\left[\underline{F}/F(0)\right]+\left(\mu+\sigma^2\right)T}{\sigma\sqrt{T}}\right) \\ & +F(0)\Phi\left(\frac{\ln\left[F(0)/\underline{F}\right]+\left(\mu+\sigma^2\right)T}{\sigma\sqrt{T}}\right)-F(0). \end{aligned} \tag{17}$$

For a forecast horizon of $\widetilde{T} \equiv T - t$ years , the expected size of FX interventions equals the difference between the expected value of the fundamental under a minimum exchange rate regime for $\widetilde{T}$ periods and its counterpart under a free float regime:[42][43]

$$\begin{aligned} V_{t,\widetilde{T}} \equiv V\left[\widetilde{F}(t), \widetilde{T}\right] ={} & \underline{F}\exp^{-r(t)\widetilde{T}}\frac{\mu}{r(t)}\Phi\left(\frac{\ln\left[\underline{F}/\widetilde{F}(t)\right]-\mu\widetilde{T}}{\sigma\sqrt{\widetilde{T}}}\right) \\ & +\frac{\underline{F}}{\theta+1}\left(\frac{\underline{F}}{\widetilde{F}(t)}\right)^{\theta+1}\Phi\left(\frac{\ln\left[\underline{F}/\widetilde{F}(t)\right]+\left(\mu+\sigma^2\right)\widetilde{T}}{\sigma\sqrt{\widetilde{T}}}\right) \\ & +\widetilde{F}(t)\Phi\left(\frac{\ln\left[\widetilde{F}(t)/\underline{F}\right]+\left(\mu+\sigma^2\right)\widetilde{T}}{\sigma\sqrt{\widetilde{T}}}\right)-\widetilde{F}(t). \end{aligned} \tag{18}$$

Hence, conditional on an estimate for γ, the expected size of FX interventions can be fully expressed in terms of observable variables after substituting Equations 10, 11 and 14 in Equations 17 and 18.

Furthermore, notice that when the initial log money supply in Equation 4 is normalized to zero, the measure $V_{t,\widetilde{T}}$ can be interpreted as the amount of necessary FX interventions under the minimum exchange rate regime in percent of the domestic money supply. Consequently, the initial domestic money supply $M(0)$ can simply be multiplied by $V_{t,\widetilde{T}}$ to get an estimate of the expected size of FX interventions over a forecast horizon of $\widetilde{T}$ years (in monetary units).[44]

The expected size of FX interventions for an infinite lifetime of the minimum exchange rate regime results from letting T go to infinity, assuming that the drift rate μ is non-

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[42] See Equations 2.11 and 5.2 in Gerber and Pafumi (2000).

[43] Notice that the expected size of FX interventions under a minimum exchange regime for a finite forecast horizon is equal to zero at $t = T$, which can be easily proved by setting $t = T$ in Equation 18 (see also page 33 in Gerber and Pafumi (2000)).

[44] In the two-country setup, the foreign money supply must be included accordingly.

negative:

$$\lim_{T \to \infty} V_{t,\widetilde{T}} = \frac{\underline{F}}{\theta + 1} \left(\frac{\underline{F}}{\widetilde{F}(t)} \right)^{\theta+1} . \tag{19}$$

In theory, this expression paves the way for a novel testable implication of the Krugman model for the case of a one-sided target zone, as it is well known that the asymptotic (unconditional) probability distribution of the regulated fundamental is exponential or uniform, depending on the value of the drift rate μ.[45]

3.2.1 Sensitivity Analysis

Below, the impact of the parameters that are under the direct control of the monetary authorities of the domestic country (i.e. $\underline{S}$ and T) on the expected size of FX interventions is assessed. Table 1 and Figure 1 suggest that a higher minimum exchange rate $\underline{S}$ and a longer length of the forecast horizon T lead both to higher expected FX interventions, as it becomes more likely that the monetary authorities of the domestic country will have to intervene in FX markets. Intuitively, noting that $V_{t,\widetilde{T}}$ can be modelled as a call option[46] with a strike price equal to the targeted minimum exchange rate $\underline{S}$ when the underlying follows a RGBM process (see Equation C.2 in Appendix C in Hertrich (2016a)), a higher minimum exchange rate and a longer forecast horizon (i.e. a higher strike price and a longer time-to-maturity) both raise the value of the call option.

Focusing on the parameters that are not under the direct control of the monetary authorities of the domestic country (i.e. σ_s and γ), the evaluation of $V(S_0, T)$ (see Table 2 and Figure 2) indicates that the more volatile the exchange rate and the lower the (absolute value of the) semi-elasticity of money demand are, the higher the expected size of FX interventions will be.

It is noteworthy that all these insights are in line with the theoretical foundation of the Krugman framework. Especially the latter insight is of special interest. As can be seen from Equation 1, the larger γ ceteris paribus is, the less responsive the exchange rate will be with respect to changes in the economic fundamental. Accordingly, the volatility of the exchange rate will ceteris paribus decrease (see Equation 13), a result that is known as the "honeymoon effect" (see also Subsection 2.3.2). Hence, γ quantifies the relevance of this effect.

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[45] Similarly, for a forecast horizon $T \to 0$ the metric $V_{t,\widetilde{T}}$ is proportional to an expression that is a function of observable variables only (see Equations 3.5 and 3.8 plus 3.9 in Gerber and Pafumi (2000)). This would allow us to test another novel theoretical implication of the Krugman model using very short-term data and a statistical test of proportionality. However, as this analysis would go beyond the scope of this paper, it is left for future research.

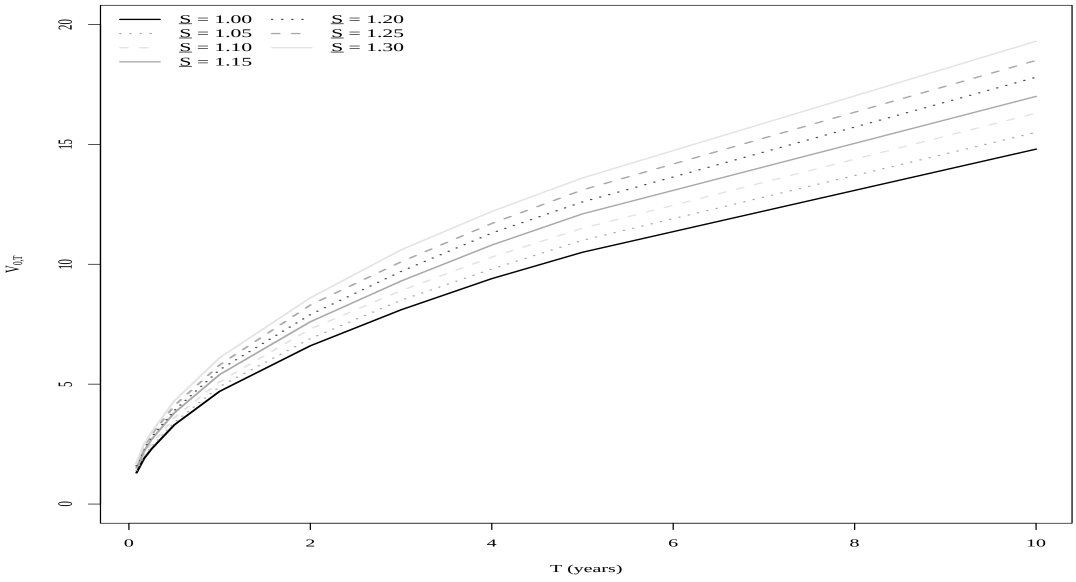
[46] Plus two additional summands that do not alter this intuitive explanation.

Table 1: Size of FX Interventions as a Function of $\underline{S}$ and T (in %)

T	$\underline{S}$						
	1.00	1.05	1.10	1.15	1.20	1.25	1.30
1m	1.30	1.40	1.50	1.50	1.60	1.70	1.70
3m	2.30	2.40	2.50	2.70	2.80	2.90	3.00
6m	3.30	3.40	3.60	3.80	3.90	4.10	4.30
1y	4.70	4.90	5.10	5.40	5.60	5.80	6.10
3y	8.10	8.50	8.90	9.30	9.70	10.10	10.60
5y	10.50	11.00	11.50	12.10	12.60	13.10	13.60
10y	14.80	15.50	16.30	17.00	17.80	18.50	19.30

Notes: The table displays the size of FX interventions $V_{0,T}$ (e.g. in percent of the domestic money supply) that are expected to be necessary to implement and maintain a one-sided target zone for a forecast horizon T of 1 month (1m), 3 months (3m), 6 months (6m), 1 year (1y), 3 years (3y), 5 years (5y) or 10 years (10y) and different minimum exchange rate levels $\underline{S}$. For the calculation of $V_{0,T}$, the drift rate μ, the semi-elasticity of money demand γ (in years), the conditional exchange rate volatility σ^s and the initial exchange rate $S(0)$ are set equal to 0, 0.1, 6% and $\underline{S} + 0.001$, respectively.

Figure 1: Size of FX Interventions as a Function of $\underline{S}$ and T (in %)



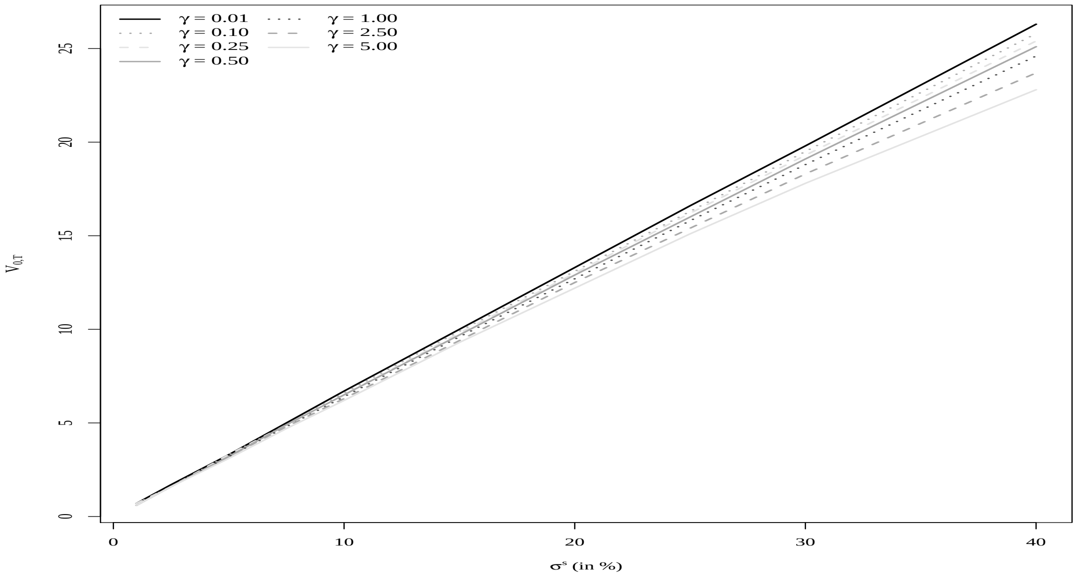
Notes: The figure displays the size of FX interventions $V_{0,T}$ (e.g. in percent of the domestic money supply) that are expected to be necessary to implement and maintain a one-sided target zone for a forecast horizon of T years and different minimum exchange rate levels $\underline{S}$. For the calculation of $V_{0,T}$, the drift rate μ, the semi-elasticity of money demand γ (in years), the exchange rate volatility σ^s and the initial exchange rate $S(0)$ are set equal to 0, 0.1, 6% and $\underline{S} + 0.001$, respectively.

Table 2: Size of FX Interventions as a Function of γ and σ^s and (in %)

σ^s (in %)	γ 0.01	0.10	0.25	0.50	1.00	2.50	5.00
1	0.70	0.70	0.70	0.60	0.60	0.60	0.60
5	3.30	3.30	3.30	3.20	3.20	3.20	3.10
10	6.70	6.60	6.50	6.50	6.40	6.30	6.20
20	13.30	13.10	13.00	12.90	12.70	12.50	12.20
40	26.30	25.80	25.40	25.10	24.60	23.70	22.80

Notes: The table displays the size of FX interventions $V_{0,T}$ (e.g. in percent of the domestic money supply) that are expected to be necessary to implement and maintain a one-sided target zone for different levels of the conditional exchange rate volatility σ^s (in %) and different values of the semi-elasticity of money demand γ (in years). For the calculation of $V_{0,T}$, the drift rate μ, the minimum exchange rate $\underline{S}$, the forecast horizon T and the initial exchange rate $S(0)$ are set equal to 0, 1.2, 0.5 and $\underline{S}$+0.001, respectively.

Figure 2: Size of FX Interventions as a Function of γ and σ^s and (in %)



Notes: The figure displays the size of FX interventions $V_{0,T}$ (e.g. in percent of the domestic money supply) that are expected to be necessary to implement and maintain a one-sided target zone for a conditional exchange rate volatility of σ^s per cent and different values of the semi-elasticity of money demand γ (in years). For the calculation of $V_{0,T}$, the drift rate μ, the minimum exchange rate $\underline{S}$, the forecast horizon T and the initial exchange rate $S(0)$ are set equal to 0, 1.2, 0.5 and $\underline{S} + 0.001$, respectively.

3.3 Data

To assess the suitability of the Krugman model in determining the expected size of FX interventions to implement and maintain a minimum exchange rate regime, the predictive power of the metric $V_{t,\tilde{T}}$ as an explanatory variable for the size of the SNB's actual FX interventions in the period from September 6, 2011 to January 14, 2015 is tested. To this end, the domestic risk-free interest rate $r(t)$ is proxied by the CHF LIBOR interest rate for a contract maturity of one week (1w), one month (1m), two months (2m), three months (3m), six months (6m) and one year (1y). Accounting for the fact that the SNB's unconventional monetary policy measure implies that FX interventions will be demand-driven, I will use financial market data for the conditional FX rate volatility σ^s and also take a forward-looking perspective, motivated by empirical evidence indicating that the predictive power of the implied volatility (IV) as a measure of the market's expected future volatility is relatively high (Jorion, 1995). Therefore, the volatility level σ^s is proxied by the option IVs for call and put options on the EUR-CHF spot FX rate with an option delta of $\Delta \pm 25\%$ and at-the-money options for the aforementioned contract maturities. In order to account for the existence of volatility smiles, the distribution-free Vanna-Volga approximation is applied.[47] In addition, and following Whaley (1993) and Bakshi, Cao, and Chen (1997), it is assumed that the domestic central bank uses the previous day's implied volatility as an estimate for today's implied volatility.

The minimum exchange rate $\underline{S}$, the initial exchange rate $S(0)$ and the forecast horizon in Equations (10), (12), (14) and (18) are set equal to EUR-CHF 1.20, EUR-CHF 1.201 and the aforementioned FX option contract maturities, respectively. All these data are from Bloomberg. Following Lera and Sornette (2016), the drift rate μ[48] and the semi-elasticity of money demand γ (in years) are set equal to zero and 0.1, respectively, where the latter value has been proposed by Flood, Rose, and Mathieson (1991) after having empirically analyzed former target zones. As γ is denominated in units of years, γ must e.g. be multiplied by 52, 12, 6, 4, 2 and 1 to get the value of γ that accords with the aforementioned contract maturities.

As there are no publicly available figures on the actual size of the SNB's FX interventions in the period of interest, I resort to a proxy measure. Following Auer (2015) and Breedon, Chen, Ranaldo, and Vause (2019), the change in total sight deposit accounts in Swiss francs that commercial banks in Switzerland hold at the SNB is used as a proxy. This data is published on a weekly basis, reflecting the average size of these accounts over the week. Hence, the proposed metric $V_{t,\widetilde{T}}$ has to be adjusted accordingly to reflect the weekly expected size of FX interventions. The motivation for this proxy measure is the fact that the SNB carries out all FX market operations via commercial banks (see e.g. Jordan (2018)). Consequently, any FX purchases (sales) will lead to an increase (decrease) in the sight deposit accounts of the involved commercial banks, reflecting changes in the SNB's liabilities that are due to FX interventions. Nevertheless, the sight deposit accounts may change also for other reasons, e.g. when banks "fly-to-safety" (Chen et al., 2018), which should be borne in mind when interpreting the empirical results. Other proxy measures, such as changes in the SNB's FX reserves, are not appropriate for at least two reasons. First, this alternative proxy measure is only available on a monthly basis. Second, empirical evidence from the mid-1980s to the mid-1990s suggests that changes in the SNB's FX reserves were only modestly correlated with the size of its actual FX

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[47] See Castagna and Mercurio (2005), Castagna and Mercurio (2007), Bossens, Rayée, Skantzos, and Deelstra (2010) or Wystup (2010) for details.

[48] See also Figures B.4 and B.5 in Appendix B that suggest that the ratio of velocity of money in Switzerland and the euro area (EA) was relatively stable from 2009 onwards in the years before and after the implementation of the minimum exchange rate regime. Hence, a drift rate of zero seems to be an appropriate choice.

interventions (Neely, 2000).

Last but not least, prior empirical evidence from the SNB reveals that the unconditional probability of an FX intervention by the SNB was rather small (around 4%), see Pierdzioch and Stadtmann (2004). Conditioning the probability on interventions in previous days, the probability increases to around 27% (Pierdzioch and Stadtmann, 2004). The latter fact suggests that interventions typically occur in clusters.[49] Therefore, clustered events are treated as single events in the event-study literature, which is implicitly also the approach followed in the present paper by assuming that FX intervention clusters end at weekends (for FX markets: lasting from 4 p.m. Eastern Standard Time (EST) on Fridays to 5 p.m. EST on Sundays) by the latest.[50] Hence, the dampening effect of averaging in the FX intervention proxy measure on its standard deviation is countervailed. Likewise, the fact that the dependent variable is only observed with some error implies that the standard error will be inflated compared to the corresponding metric associated with the the actual intervention data. To account for this shortcoming, the empirical analysis is carried out with a higher significance level of 10%, which means that the null hypothesis is rejected more often.

3.4 Estimation

To assess the validity of the proposed structural model, I want to analyze how the conditional percentiles of the FX intervention proxy variable are associated with the proposed metric $V_{t,\widetilde{T}}$. Therefore, in the following, I base the empirical analysis on quantile regression coefficients and how they accord with the model-implied parameters.

3.4.1 Preliminary Steps

Before presenting and discussing the empirical results, it is necessary to eliminate potential "sale" operations from the time series of the FX intervention proxy measure by censoring the corresponding values from below at zero. This censoring mechanism has been proposed by Demiralp and Jordá (2002) in the context of FX interventions and is also in line with one of the key assumptions of the Krugman model, namely that there are no FX interventions except on occasions when the exchange rate equals (or is infinitesimally close to) the officially announced minimum exchange rate. Hence, only marginal interventions are used to implement a minimum exchange rate regime (see Subsection 2.3). As a consequence, the monetary base remains unchanged on all other trading days. Therefore, the resulting dependent censored proxy variable exhibits a large portion of zero values and, as a function of the predictor variable $V_{t,\widetilde{T}}$, can be written as a censored regression model:

$$y_t = \max\left(0, \alpha + \beta_0 V_{t,\widetilde{T}} + \epsilon_t\right), \; t = 1, \ldots, T^*, \tag{20}$$

with unobserved parameters α and β_0, error term ϵ_t and T^* observations.

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[49] A similar observation for the SNB's past FX intervention activity can be found in Figure 1 in Fischer and Zurlinden (2004).

[50] In line with a similar assumption in Breedon et al. (2019), who use the aforecited proxy and assume that the SNB's FX interventions were evenly spread over the corresponding trading week in the period of interest.

3.4.2 Forecastability

To assess the forecast accuracy of the proposed metric $V_{t,\widetilde{T}}$, I resort to an in-sample test of predictability (i.e. using the full sample to fit the model of interest) for the following reasons. First, in-sample tests typically have higher power compared to out-of-sample tests (Inoue and Kilian, 2005),[51][52] thereby reducing the risk of type II errors (i.e. the risk of erroneously failing to reject the null hypothesis), which is the type of risk that I want to minimize, given that the null hypothesis includes the parameters that I want to test statistically.[53] Second, empirical evidence in Friederichs and Hense (2007) using precipitation time series suggests that a training period of less than three-and-a-quarter years is too short to obtain valid forecasts of the conditional distribution.

To evaluate the predictive power of $V_{t,\widetilde{T}}$ in a forecasting exercise, the censored least absolute deviation (CLAD) estimator (Powell (1984) and Powell (1986)) is applied,[54] an estimator that is asymptotically normal and consistent[55] under some regularity conditions (Powell, 1984) in the absence of normality and conditional homoskedasticity of the error term,[56] which is a major issue when using high-frequency data such as financial market data and which may seriously bias the point estimators when using non-robust methods (Wilhelm, 2008). However, the advantage of the CLAD approach with respect to departures from normality and homoskedasticity comes at the cost of some loss in efficiency compared to OLS. In the present case, nevertheless, where the dependent variable remains unchanged in more than 48% of the trading days, the OLS method would yield biased and inconsistent estimators (Maddala, 1983). Hence, for the empirical analysis, the CLAD estimator is the preferred econometric approach.

In the following, it is assumed that the error term ϵ_t is continuously distributed with conditional median equal to zero. In addition, the requirement that the conditional density function of ϵ_t is positive at zero is imposed; the conditional median of ϵ_t is therefore unique (see Figure 1 in Powell (1984) for an intuitive explanation). As shown in Powell (1984), the CLAD estimator $\hat{\beta}_{T^*}$ in the censored regression model in Equation (20) in the case of T^* observations can then be written as the estimator that minimizes the sum of the absolute deviation between the dependent variable y_t and the maximum of zero and $\alpha + \beta_0 V_{t,\widetilde{T}}$ over all observations and all possible betas; i.e. $\hat{\beta}_{T^*}$ is the estimator that minimizes

$$\sum_t \left| y_t - \max\left(0, \alpha + \beta_0 V_{t,\widetilde{T}}\right) \right|. \tag{21}$$

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[51] Assuming that their results also hold for censored quantile regressions.

[52] See also Subsection 4.4 for an additional explanation of my choice associated with model selection.

[53] Furthermore, Inoue and Kilian (2005) show that both types of forecasts are susceptible to unmodelled structural changes and data mining. Hence, these shortcomings affect both types of tests in a similar manner.

[54] See Buchinsky (1998) for a guideline on how to use this approach in empirical applications.

[55] For a proof of consistency when including lags of the dependent variable in the censored regression model, see de Jong and Herrera (2011). The small sample properties of this estimator in time-series applications are analyzed in Ordoñez-Callamand, Villamizar-Villegas, and Melo-Velandia (2018). They provide simulation evidence that the CLAD estimator outperforms the Tobit estimator in terms of bias and root-mean-square error in cases where the errors exhibit conditional heteroskedasticity or are non-normally distributed.

[56] This contrasts with the well-known Tobit regression that is typically used when analyzing FX interventions (e.g. in Demiralp and Jordá (2002) and de Jong and Herrera (2011)), a model that is not robust against, for instance, fat-tailedness.

Notice that $\max\left(0, \alpha + \beta_0 V_{t,\widetilde{T}}\right)$ equals the conditional median function for y_t, $m(V_{t,\widetilde{T}}, \alpha, \beta_0)$. In line herewith, this approach is also called "median (LAD) regression" (Powell, 1986).

The use of this estimator rests on the fact that the ordering of the data (e.g. the median) is preserved by monotonic transformations. Therefore, this estimator can easily be generalized, resulting in the θth conditional quantile of $y_t|V_{t,\widetilde{T}}$ for the censored regression model in Equation (20) with the following form (Powell, 1986):

$$q_\theta(y_t|V_{t,\widetilde{T}}, \alpha, \beta_0) \equiv \max\left(0, \alpha + \beta_0(\theta) V_{t,\widetilde{T}}\right), \; t = 1, \ldots, T^*, \tag{22}$$

with

$$\beta_0(\theta) \equiv \beta_0 + F^{-1}(\theta) \cdot e_1, \tag{23}$$

where $F^{-1}(\theta)$ and $e_1 = (1, 0, \ldots, 0)^T$ denote the θth quantile of the independent and identically distributed error terms and a unit vector, respectively. Hence, the quantiles of y_t are associated with the non-constant regressors in the same way as the median in Equation (21). For other quantiles, the CLAD estimator can therefore be determined analogously. The form of the "loss function" to be minimized is similar to Equation 21 and can be found in Equation 2.6 in Powell (1986).

3.4.3 Standard Errors

Following the strand of literature on censored quantile regression models, the standard errors are computed using the bootstrap approach proposed by Bilias, Chen, and Ying (2000). As the asymptotic covariance matrices of the censored regression quantile estimator depend on the conditional density function of ϵ_t (see Theorem 2 in Powell (1984)), computing reliable standard errors is computationally difficult (Bilias et al., 2000). To circumvent these calculations, Bilias et al. (2000) propose a modified bootstrap procedure with resampling that allows the corresponding bootstrap estimator to be computed in the same way as for the case of uncensored quantile regression.

3.4.4 Software

The software program used to analyze the data is `R`. Specifically, in the empirical section, I use the function `crq` that is available in the `quantreg` package and implements the algorithm developed by Maddala and Rao (1996) and Fitzenberger (1997), which guarantees convergence to a local minimum of the objective function. To run this algorithm, the distribution of y_t is centered at the median of the positive values of y_t, as a higher percentile will be more often informative about the true β_0 (Powell, 1986). In addition, the theoretical values of $\alpha = 0$ and $\beta = 1$ are used as the starting values, i.e. the true parameter values under the null hypothesis that the proposed model is true, unless in a very small number of cases in which these starting values did not lead to convergence. In those cases, the algorithm converged with alternative values. To assess the robustness of the empirical results, I also try out different starting values, e.g. using the median regression estimate from a standard quantile regression that ignores the censoring of the dependent variable, following Buchinsky (1994).

4 Empirical Results

4.1 Forecastability of the Size of FX Interventions

4.1.1 1-Week up to 1-Year Forecast Horizon

The empirical results in Tables 3 and 4 for the actual size of FX interventions in percent and in Swiss francs, respectively, show the estimates obtained by using the one-week lagged weighted[57] average of the proposed metric, $V_{t,\widetilde{T}}^{weekly}$, adjusted accordingly to reflect the expected size of FX interventions in the subsequent trading week (therefore the label "weekly" is added to distinguish this metric from $V_{t,\widetilde{T}}$). The (undocumented) results are similar when using the one-day lagged metric $V_{t-1,1w}^{weekly}$, also adjusted accordingly, reflecting the coefficient estimates for a remaining lifetime of one week for non-overlapping data. Nevertheless, as the one-month (and especially the three-month) FX option contracts are the most liquid ones, and to account for incoming new information in FX markets reflected in day-to-day changes of the observable variables, I prefer to present the estimates for the one-week lagged weighted average $V_{t,\widetilde{T}}^{weekly}$.

Table 3: Powell's LAD Estimates of the Size of FX Interventions (in %)

Variable	Estimate	Std. Err.	R^2 (in %)
$Const._{1w}$	-0.00572^{**}	0.00250	
$V_{t,1w}^{weekly}$	2.57726^{***}	0.38527	37.53
$Const._{1m}$	-0.00016	0.00018	
$V_{t,1m}^{weekly}$	1.02290	0.19118	48.31
$Const._{2m}$	-0.00682^{*}	0.00386	
$V_{t,2m}^{weekly}$	1.05874	0.18138	56.73
$Const_{3m}$	-0.00402^{***}	0.00141	
$V_{t,3m}^{weekly}$	0.76213^{***}	0.06307	53.68
$Const_{6m}$	-0.01679^{***}	0.00344	
$V_{t,6m}^{weekly}$	0.58823^{***}	0.08014	62.96
$Const_{1y}$	-0.02054^{***}	0.00567	
$V_{t,1y}^{weekly}$	0.42670^{***}	0.07320	56.64

Notes: The table displays Powell's LAD estimator of the censored quantile regression model with $y_t = \max\left(0, \alpha + \beta V_{t,\widetilde{T}}^{weekly} + \epsilon_t\right)$ from September 9, 2011 to January 9, 2015, where y_t denotes the maximum of zero and the percentage change in total sight deposits in Swiss francs that commercial banks in Switzerland hold at the SNB. The subscripts in column one "1w", "1m", etc. indicate the maturity of the used FX option contracts to calculate the regressor $V_{t,\widetilde{T}}^{weekly}$. ***, **, and * denote rejections of the hypothesis $\alpha = 0$ and $\beta = 1$ at the 1%, 5% and 10% significance level, respectively.

The estimates in Tables 3 and 4 show that the proposed metric $V_{t,\widetilde{T}}^{weekly}$ indeed exhibits

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[57] The five-days lagged metric $V_{t-5,\widetilde{T}}^{weekly}$ is weighted by 1/3, the four-days lagged metric $V_{t-4,\widetilde{T}}^{weekly}$ by 0.8/3, etc.

Table 4: Powell's LAD Estimates of the Size of FX Interventions (in CHF)

Variable	Estimate	Std. Err.	R^2 (in %)
$Const._{1w}$	-1.78082	0.11309	
$V_{t,1w}^{weekly}$	2.62008***	0.51048	37.42
$Const._{1m}$	-0.07560	0.07483	
$V_{t,1m}^{weekly}$	1.12807	0.22744	42.97
$Const._{2m}$	-2.16170	1.74540	
$V_{t,2m}^{weekly}$	1.09357	0.21397	55.84
$Const._{3m}$	-1.53711**	0.61663	
$V_{t,3m}^{weekly}$	0.83200**	0.08570	51.44
$Const._{6m}$	-0.56280***	0.18709	
$V_{t,6m}^{weekly}$	0.42798***	0.06320	50.73
$Const._{1y}$	0.08112	0.06425	
$V_{t,1y}^{weekly}$	0.25443***	0.04222	40.63

Notes: The table displays Powell's LAD estimator of the censored quantile regression model with $y_t = \max\left(0, \alpha + \beta V_{t,\widetilde{T}}^{weekly} + \epsilon_t\right)$ from September 9, 2011 to January 9, 2015, where y_t denotes the maximum of zero and the change in total sight deposits in Swiss francs that commercial banks in Switzerland hold at the SNB. The subscripts in column one "1w", "1m", etc. indicate the maturity of the used FX option contracts to calculate the regressor $V_{t,\widetilde{T}}^{weekly}$. *** and ** denote rejections of the hypothesis $\alpha = 0$ and $\beta = 1$ at the 1% and 5% significance level, respectively.

an economically large predictive power for the size of FX interventions under the EUR-CHF minimum exchange rate regime, which is consistent with the model-implied null hypothesis of $H_0 : \beta = 1$, especially for shorter FX option contract maturities. By contrast, the constant is statistically and/or economically insignificant in most cases, in line with the model-implied null hypothesis of $H_0 : \alpha = 0$. As convergence of the algorithm occurs in all computations regardless of the starting values used, the documented estimates may indeed correspond to a global minimum. In addition, the coefficient of determination in Tables 3 and 4 is also relatively high, indicating that $V_{t,\widetilde{T}}^{weekly}$ indeed explains a large fraction of the variation in the FX intervention proxy measure. Similarly, computing the correlation between the predicted and actual size of FX interventions (i.e. between $\hat{y}_t$ and y_t) suggests that both measures are indeed highly correlated (Tables 5 and 6).

Table 5: Correlation between Expected and Actual Size of FX Interventions (in %)

τ	$\rho(\hat{y}_t, y_t)$	$\rho(\hat{y}_t, y_t)^2$
1w	0.862	0.743
1m	0.927	0.859
2m	0.891	0.795
3m	0.879	0.773
6m	0.902	0.813
1y	0.890	0.792

Notes: The table displays the correlation between the expected and the actual size of FX interventions in per cent of domestic money supply (proxied by the percentage change in total sight deposits in Swiss francs that commercial banks in Switzerland hold at the SNB) using weekly data in the period from September 9, 2011 to January 9, 2015.

Table 6: Correlation between Expected and Actual Size of FX Interventions (in CHF)

τ	$\rho(\hat{y}_t, y_t)$	$\rho(\hat{y}_t, y_t)^2$
1w	0.871	0.758
1m	0.899	0.809
2m	0.883	0.779
3m	0.846	0.717
6m	0.889	0.791
1y	0.901	0.812

Notes: The table displays the correlation between the expected and the actual size of FX interventions in billions of Swiss francs (proxied by the change in total sight deposits in Swiss francs that commercial banks in Switzerland hold at the SNB) using weekly data in the period from September 9, 2011 to January 9, 2015.

4.1.2 1-Week and 1-Month Forecast Horizon ("Svensson Test")

As already discussed in 3.1, only the 1-month EUR-CHF forward contract passes the "simple test of target zone credibility" (Svensson, 1991b) throughout the period of interest. According to the law of iterated expectations, this implies that the corresponding 1-week contracts should pass the test as well. Similarly, the 1-week and 1-month option contracts should be priced such that their price difference is equal to the premium for entering the corresponding 1-week and 1-month forward contract by put-call parity.[58] Consequently, the 1-week and 1-month option-implied volatilities should reflect the market's expected future volatility under a perfectly credible minimum FX rate regime in view

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[58] For a detailed discussion on put-call parity when reflection is superimposed on GBM, see Hertrich (2015).

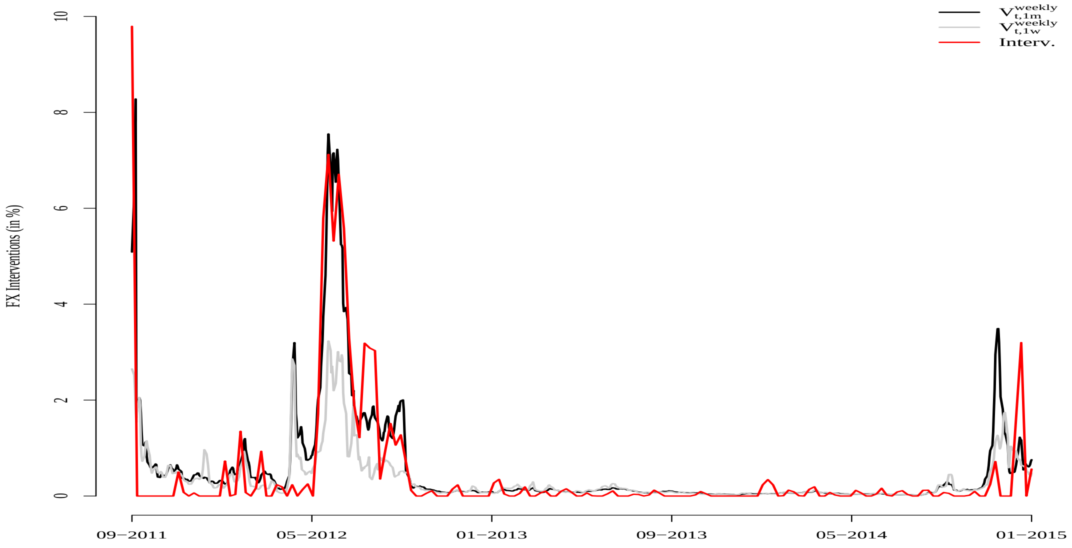
of the "Svensson test" result. Therefore, I re-estimate the censored quantile regression model for a contract maturity of one week and one month only, using the FX intervention proxy measure both in percent and in CHF, successively censoring the distribution of y_t at fifty-one different percentiles, ranging from the 49th percentile to the 99th percentile, increasing the percentiles by increments of 100bps. Using the implied volatilities of the 1w option contracts, the test results indicate that the proposed model is valid for up to the 75th percentile, as in most cases the estimated intercept and slope coefficients are in line with the model-implied null hypothesis of $\alpha = 0$ and $\beta = 1$ (Figures B.6, B.7, B.8, B.9 in Appendix B). A similar picture emerges for the 1m option contracts (Figures B.10, B.11, B.12, B.13 in Appendix B).

For smaller and higher percentiles, however, the implications of the model for the censored quantile regression coefficients are rejected, especially in the case of the one-week contract maturity. There are several possible explanations for this phenomenon. First, it may be conjectured whether liquidity issues might partially explain this phenomenon, as the market for one-week FX options is less liquid than their counterparts with larger maturities. Second, for lower quantiles, it is well known that the finite sample performance is rather poor due to the nonlinear and non-convex nature of the optimization problem (Chen, 2018). In a similar vein, at higher quantiles, the number of relevant observations becomes small, thereby "negatively" affecting the optimization procedure (Tsay, 2013).

4.2 The Size of FX Interventions from September 2011 to January 2015

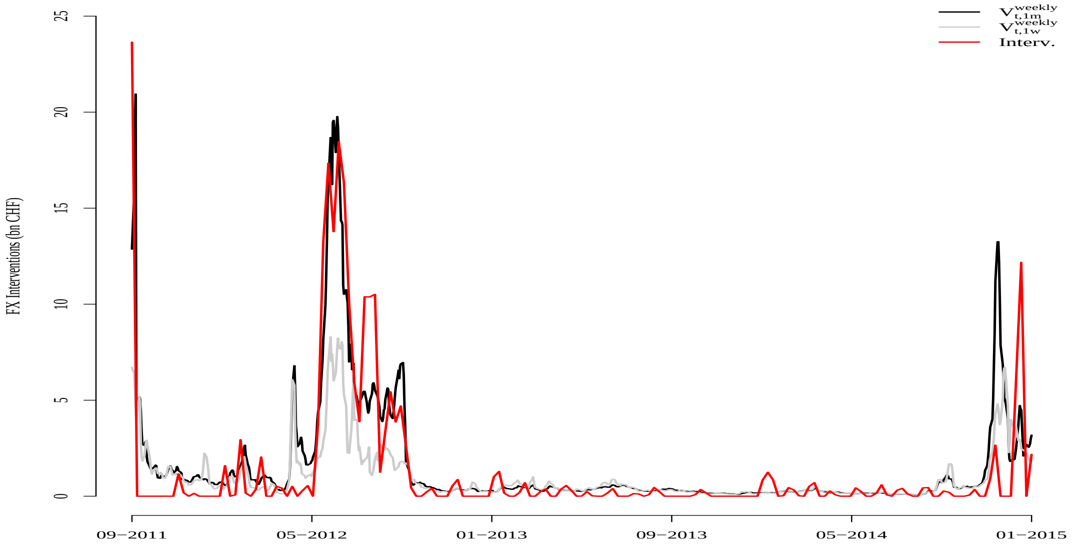
A dynamic comparison of the proposed metric $V_{t,\widetilde{T}}^{weekly}$ with the FX intervention proxy measure in Figures 3 and 4 shows that the corresponding time series indeed exhibit a large degree of covariation over time, which is in line with the correlations presented in Tables 5 and 6. Nevertheless, in view of the uncertainty with respect to the degree of credibility associated with the EUR-CHF minimum FX rate regime, despite ample empirical evidence to date indicating that all the theoretical implications of the Krugman model that have been brought to data have been "proven" empirically (see Subsection 3.1), I focus on the dynamics of the expected size of FX interventions for a short forecast horizon of one week or one month in the following (see Figure 5). Initially, i.e. in the first weeks after the introduction of the minimum exchange rate, the expected short-term "costs" of this unconventional monetary policy measure were relatively large in terms of the size of required FX interventions (for $V_{t,1w}$: CHF 1.5-8.5 billion (bn); for $V_{t,1m}$: CHF 3.2-12.7 bn). In the subsequent months and quarters the time series reflect a rather tranquil period that suddenly ended in May 2012, when the European sovereign debt crisis escalated and speculation of a "Grexit" emerged. The proposed metric $V_{t,\widetilde{T}}$ spiked accordingly, reaching a maximum of CHF 11.1 bn ($V_{t,1w}$) and CHF 50.9 bn ($V_{t,1m}$), respectively. This spike was accompanied by a comparable spike in the FX intervention proxy measure, indicating that the SNB indeed had to intervene strongly in order to maintain the minimum exchange rate, in line with the prominent role of the CHF as a safe haven currency in periods of global financial instability (see e.g. Ranaldo and Söderlind (2010), Auer (2015) and Baltensperger and Kugler (2016)). This period of heightened uncertainty lasted until mid-June 2012. After that episode, all three displayed time series continue to fluctuate at

Figure 3: Expected and Actual Size of Weekly FX Interventions (in %)



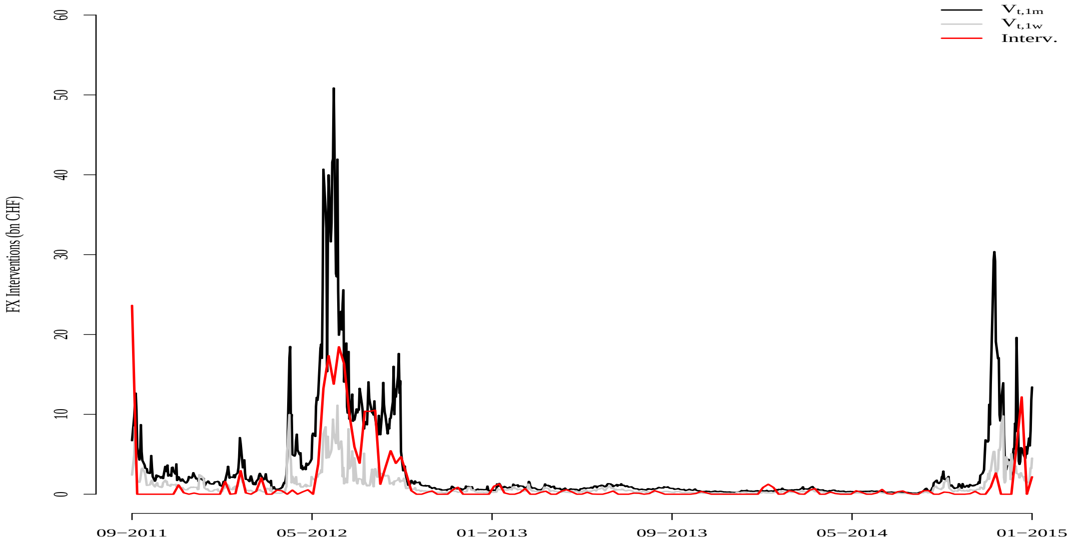
Notes: The figure displays the expected and the actual size of weekly FX interventions in percent of the domestic money supply (the former proxied by the percentage change in total sight deposits in Swiss francs that commercial banks in Switzerland hold at the SNB) using the VV-implied volatility for contract maturities of one week ($V_{t,1w}^{weekly}$) and one month ($V_{t,1m}^{weekly}$), adjusted accordingly to reflect the size of weekly FX interventions. The time series are displayed for the period from September 9, 2011 to January 9, 2015.

Figure 4: Expected and Actual Size of Weekly FX Interventions (in CHF)



Notes: The figure displays the expected and the actual size of weekly FX interventions in billions of Swiss francs (the former proxied by the change in total sight deposits in Swiss francs that commercial banks in Switzerland hold at the SNB) using the VV-implied volatility for contract maturities of one week ($V_{t,1w}^{weekly}$) and one month ($V_{t,1m}^{weekly}$), adjusted accordingly to reflect the size of weekly FX interventions. The time series are displayed for the period from September 9, 2011 to January 9, 2015.

Figure 5: Expected and Actual Size of FX Interventions for a Forecast Horizon of One Week and One Month (in CHF)



Notes: The figure displays the expected and the actual size of weekly FX interventions in billions of Swiss francs (the former proxied by the change in total sight deposits in Swiss francs that commercial banks in Switzerland hold at the SNB) using the VV-implied volatility for contract maturities of one week ($V_{t,1w}$) and one month ($V_{t,1m}$), reflecting the expected size of FX interventions for a forecast horizon of one week and one month. The time series are displayed for the period from September 9, 2011 to January 9, 2015.

a higher level than before the escalation. In this regard, it is noteworthy that Mario Draghi's "Whatever it takes" statement on July 26, 2012 only had a minor effect on the displayed time series. It was not until the ECB "put its money where its mouth was" by launching the Outright Monetary Transaction (OMT) program on September 6, 2012 that the expected and the actual FX intervention measures decreased significantly and a calm period started that lasted until November 2014, when the predicted FX intervention measures started to go back up to levels not seen since the escalation of the European sovereign debt crisis. This increase indicated that maintaining the minimum exchange rate regime would force the SNB to continue accumulating (presumably excessive) balance sheet risks in the short term as an aftermath of the necessary FX interventions to maintain the unconventional monetary policy regime (e.g. around CHF 30.4 billion according to $V_{t,1m}$ on November 19, 2014). Indeed, the following two Figures 6 and 7 that display the ratio of the expected size of FX interventions over a short forecast horizon to the same metric for an infinite forecast horizon[59] (i.e. Equation 18 divided by Equation 19) indicate that the SNB would have had to intervene heavily from that date onwards, especially in the short term.

The information that is revealed by the metric $V_{t,\widetilde{T}}$ (and the corresponding ratio) on the timing of abandoning the peg is qualitatively in line with the SNB's decision to abandon the minimum exchange rate regime on January 15, 2015.[60] Without explicitly

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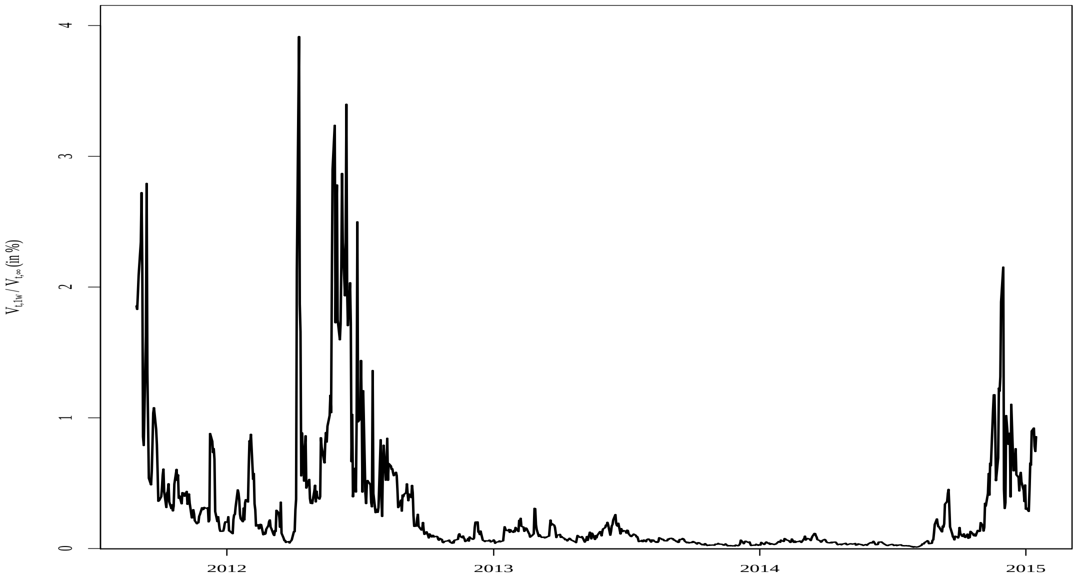
[59] I.e. the lifetime of the minimum FX rate regime.

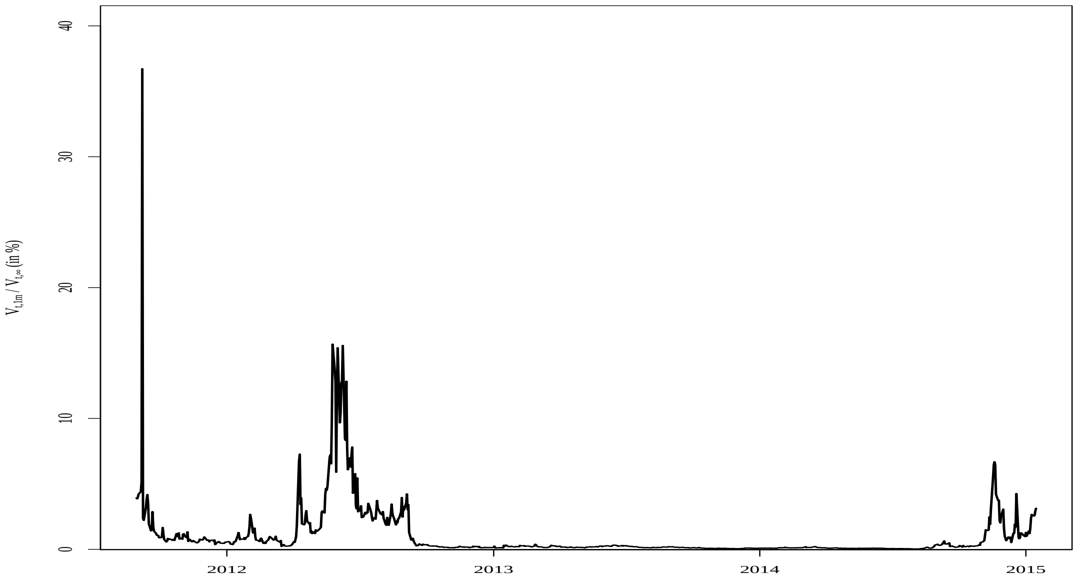
[60] Specifically, on the previous day, the expected size of FX interventions for a forecast horizon of one month equalled CHF 14.8 billion.

Figure 6: Ratio of the Expected Size of FX Interventions: 1-Week vs. Infinite Lifetime



Notes: The figure displays the ratio of the expected size of FX interventions for a forecast horizon of one week and an infinite lifetime (in %), i.e. Equation 18 divided by Equation 19. The data used cover the period from August 30, 2011 to January 15, 2015.

Figure 7: Ratio of the Expected Size of FX Interventions: 1-Month vs. Infinite Lifetime



Notes: The figure displays the ratio of the expected size of FX interventions for a forecast horizon of one month and an infinite lifetime (in %), i.e. Equation 18 divided by Equation 19. The data used cover the period from August 30, 2011 to January 15, 2015.

specifying the SNB's preferences in form of an ad-hoc objective function, which would go beyond the scope of this paper,[61] we can infer from an interview with the SNB governing board member Fritz Zurbrügg one week after the "Swiss franc shock" in which he admitted that without the abandonment, the SNB would have had to intervene with 100 billion Swiss francs in January 2015 alone (Schätti, 2015) that the timing of the abandonment was associated with the fear of otherwise accumulating excessive balance sheet risks over a rather short-term horizon, which would have entailed political costs. In theoretical papers that analyze the credibility of currency boards, political costs indeed play a major role. Contrary to e.g. the seminal work of Feuerstein and Grimm (2006), political costs are then not the costs that arise after a peg regime has been abandoned (e.g. reputation costs), but refer to e.g. the increased risk of a second referendum that might have constrained the SNB's independence.[62][63]

It may be argued that the jump in the proposed metric and the accompanied spike in actual FX interventions by the SNB are related to the elevated probability of abandoning the minimum exchange rate regime. This contrasts, however, with the aforecited results in Subsection 3.1.3 and general consensus that the abandonment came as a big shock (see e.g. Brunnermeier and James (2015), Danielsson (2015), Cukierman (2019), the event study in Mirkov, Pozdeev, and Söderlind (2019) or the fact that the abandonment has been classified as a "black swan scenario" by Lleo and Ziemba (2015)).[64] Similarly, the intra-day appreciation of the Swiss franc against the euro by more than 40% and the intra-day return of -14% of the Swiss Market Index on the day of the abandonment[65] are two facts that also suggest that the removal came as a big surprise for financial market participants. Hence, assuming perfect credibility also in the quarter before the abandonment seems to be a reasonable assumption.

All these results suggest that $V_{t,\widetilde{T}}$ might indeed be an adequate tool for monetary authorities to assess the consequences of implementing and maintaining a minimum ex-

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[61] Interested readers are referred to Amador, Bianchi, Bocola, and Perri (2016) who develop a theoretical framework to assess the adequacy of the timing of the SNB's decision to abandon the minimum exchange rate regime. A much more stylized approach that also covers the minimum exchange rate period can be found in an unpublished manuscript of Zhu (2016). Rodríguez and Rodríguez (2007) also develop a model that includes a loss function for a two-sided target zone, which can be adapted to the EUR-CHF episode.

[62] As already mentioned in footnote 1, the fact that the SNB indeed faced the risk of a public referendum on the composition of its balance sheet in late 2014 adds support to my claim.

[63] In the aforementioned work Feuerstein and Grimm (2006) show that pegs (i.e. regimes that can be instantaneously be abandoned) in economies where the flexibility to be able to react immediately to exogenous shocks are highly volatile and play a dominant role compared to e.g. the need to solve the time-inconsistency problem of monetary policy (i.e. the incentive of monetary authorities to create surprise inflation by stimulating output above the natural level, see Kydland and Prescott (1977), Barro and Gordon (1983) and Lohmann (1992)) exhibit a higher credibility than currency boards, defined as a long-term commitment to maintain a fixed exchange rate regime that is introduced by law. In the case of Switzerland, the fact that the SNB had introduced a minimum exchange rate regime to combat deflationary pressures, the SNB's track record of keeping inflation low and stable over decades, and the ECB's announcement in late 2014 that it would start a period of a more accommodative monetary policy in early 2015 all suggest that flexibility may have been a major concern that motivated the SNB to abandon the minimum exchange rate regime.

[64] See also Alvero and Fischer (2016).

[65] The largest negative return of the SMI ever recorded, reflecting a loss in market capitalization of around CHF 140 billion.

change rate regime in terms of FX interventions and to monitor the timing of abandoning it. The documented results are also helpful for financial market participants, whenever a currency of interest is subject to a target zone regime, as it potentially allows them to infer the policy reaction function of the monetary authorities involved.

4.3 Validation

4.3.1 Order of Integration

To assess the validity of the empirical results, I first check whether the documented results might be spurious by investigating the integration property of the FX intervention proxy and the metric $V_{t,\widetilde{T}}^{weekly}$ using standard unit root/stationarity tests. The (undocumented) test results give an unclear picture concerning the order of integration of the time series of interest, which may be due to insufficient power of the tests. In isolation, the test results by their own make it therefore difficult to decide on the integration properties of the two variables based on purely empirical grounds.[66] To complement the assessment of the order of integration, I also plot the sample autocorrelation function and the partial autocorrelations for both variables. The plots (not included in the paper) reveal that the corresponding coefficients are statistically insignificant at higher lags. Hence, the FX intervention proxy[67] and the metric $V_{t,\widetilde{T}}^{weekly}$ both exhibit time-series characteristics that are in line with a stationary data generating process.

4.3.2 Autocorrelation of the Residuals and Endogeneity

Autocorrelation In a second step, the residuals of the re-estimated censored quantile regressions (i.e. for the contracts with maturities of one week and one month) are checked for non-stationarity. The (undocumented) results show that the residuals are stationary, an indication that the documented results are not spurious. The Ljung-Box test statistics (not included in the paper), however, indicate that the residuals exhibit positive serial correlation. A possible cause of this serial correlation is the possibility that a small number of relevant variables (e.g. lagged dependent variables that capture the effect of subsequent interventions) with a net positive effect might not have been included in the model specification.[68]

Endogeneity To assess whether this is the case, I include up to four lags of the dependent variable (i.e. covering the previous month due to the frequency of the proxy variable) in a dynamic version of the censored quantile regression, centered at the median of the positive observations of the FX intervention proxy y_t. The use of lagged dependent

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[66] Nevertheless, as shown in Hu and de Jong (2006), the censored regression model with a single, integrated regressor of order one and using only positive observations leads to a super-consistent and (asymptotically) mixed normally distributed OLS estimator (i.e. the truncated OLS estimator). Hence, the standard test statistics remain (asymptotically) valid. Consequently, the empirical results of the censored quantile regression model should not be affected by the non-stationarity of the regressors due to the robustness property of the latter modelling approach to deviations from normality (e.g. fat-tailedness).

[67] In line with the test result reported in Kugler (2017).

[68] See e.g. p. 337ff. in Dougherty (2002) for details.

variables is standard in empirical work on FX interventions to deal with (possibly) statistical problems caused by the issue of simultaneity (Brandner and Grech, 2005), which may lead to inconsistent estimators.

Following the general-to-specific approach to model specification reveals that only the first lag of the dependent variable is statistically significant at the 5% level.[69] Economically, this result implies that there is a short-term tendency towards mean reversion in the SNB's intervention behavior (see Romer and Romer (2004)). In other words, interventions seem to be serially correlated in the period of interest, in line with previous findings that FX interventions typically occur in clusters, see e.g. Ito (2002) or Pierdzioch and Stadtmann (2004) for empirical evidence from Japan and Switzerland, respectively.[70] The estimated coefficients for the first lag equal 0.87 (0.46) and 0.87 (0.53) for the one-week (one-month) FX option contracts using the data in per cent and CHF, respectively.[71]

Standard inference techniques with time series To assess the validity of the standard inference techniques associated with this model specification, I take advantage of the result in de Jong and Herrera (2011), who develop the condition under which the CLAD estimator of the dynamic censored regression model (i.e. the model with lags of the dependent variable) is asymptotically consistent and normally distributed, allowing the error term to be autocorrelated. Specifically, they show that a unique and strictly stationary solution exists (see their theorems 1 and 4), whenever the smallest root of the lag polynomial - which contains the parameters associated with the lags of the dependent variable - lies outside the unit circle. Similarly, the authors also prove asymptotic normality in their theorem 5.

The corresponding check in Figures B.23 and B.23 in Appendix B reveals that the aforementioned condition is fulfilled in more than 90% of the cases (i.e. most of the estimated coefficients of the computed dynamic censored quantile regressions have a smallest root that falls outside the unit circle.[72] The residuals of the corresponding regressions are stationary in all models (e.g. according to the Phillips-Perron test) and exhibit no serial correlation for the 49th (49th) up to the 70th (90th) percentile when using the FX intervention proxy measure in percent (in CHF). Consequently, all these diagnostic tests suggest that the dynamic version of the model is well specified, as the error term is allowed to be serially correlated within this modelling framework. It can therefore be concluded that the estimates that are obtained when using only one lag of the dependent variable are asymptotically valid. Figures B.14, B.15, B.16, B.17, B.18, B.19, B.20 and B.21 in the Appendix include the corresponding parameters estimates. Comparing these plots with Figures B.6, B.7, B.8, B.9, B.10, B.11, B.12 and B.13 reveals that the point estimates

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[69] As an interesting by-product of this approach, I obtain a dynamic censored quantile regression model that can be interpreted as a conventional central bank intervention reaction function; see Ito and Yabu (2007).

[70] See also a similar assumption that underlies the empirical work in Breedon et al. (2019), who analyze how algorithmic trading responded to the abandonment of the minimum exchange rate regime.

[71] The size of the estimates associated with the 1m contracts is comparable to the coefficient estimates in, for instance, Ito (2002) for the period from 1991 to 1995 in the case of the Japanese central bank; see his Table 8.

[72] I.e. 90.2% and 96.1% for the 1-week and 1-month VV-implied volatility metric, respectively. Unfortunately, to the best of my knowledge, no statistical test exists to assess the statistical significance of these estimates.

are numerically smaller in the case of both the intercept and the slope coefficients. The confidence intervals, on the contrary, are comparably narrow. Focusing on the parameter values under the model-implied null hypothesis (i.e. $\alpha = 0$ and $\beta = 1$), the number of the cases where the null hypothesis cannot be rejected is not affected by the inclusion of the first lag of the dependent variable. Hence, these results are in line with the empirical results in Subsection 4.1. I can therefore conclude that the proposed model is indeed well suited to predict the actual size of foreign exchange market interventions over a finite forecast horizon.

4.4 Model Comparison

As explained in Diebold (2015), it is a widespread misconception that pseudo-out-of-sample model-comparison procedures[73] are the statistically best choice when it comes to model selection. By splitting data samples, information is wasted and the procedures become suboptimal compared to their full-sample counterparts. His analysis shows that the full-sample procedures are appropriate, especially when comparing models that are not necessarily nested. Therefore, I follow the advice in Diebold (2015) and apply the Schwarz information criterion (SIC)[74] to assess the validity of my model compared to alternative specifications:

$$SIC = k \ln T^{*} - 2 \ln L_j(\hat{\psi}), \tag{24}$$

where k equals the number of parameters estimated and L_j the likelihood function associated with the j-th model that is maximized over the parameter vector $\psi = (\alpha, \beta_0)^{'}$.

The test results are shown in Tables A.1 and A.2 in Appendix C. In around 52% and of the cases, the DCQR approach is the best-fitting model, followed by the CQR approach (36% of the cases) and the AR(1) model (12% of the cases). A similar picture emerges for the DCQR approach when using the 1-month forecast horizon (i.e. 47.1%, 27.4% and 25.5%, respectively). Given the DCQR's well-founded theoretical basis and the statistical properties of its residuals, I conclude that the proposed structural model with one lag of the dependent variable[75] is indeed an appropriate choice for a perfectly credible one-sided target zone.

5 Conclusion

This paper presents a structural model that is embedded within the Krugman (1991) target zone framework to determine ex-ante - using only observable variables - the maximum size of FX interventions that are expected to be necessary to implement and maintain a minimum exchange rate regime. An empirical application of the proposed model to the EUR-CHF minimum exchange rate regime that was in place from September 2011 to

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[73] E.g. in the spirit of Diebold and Mariano (1995).

[74] Alternative model comparison procedures have been proposed, for instance, allowing for sets of model specifications that do not necessarily need to contain the (unobserved) theoretically best model (Hansen, Lunde, and Nason, 2011).

[75] Notice, as already mentioned, that including lags of the dependent variable is a standard approach in empirical work on FX interventions to deal with the issue of simultaneity.

January 2015 reveals that it is well suited to explain the actual size of FX interventions over finite forecast horizons. Consequently, in currency areas with comparable monetary policy regimes, the high predictive power of the model-implied metric proves its practical usefulness for both monetary authorities and financial market participants. An application to the euro-Czech koruna target zone that would add new insights to the strand of literature on target zones and unconventional monetary policy measures would be an interesting case study, but is left for future research.

Similarly, analyzing the timing of the SNB's decision to unexpectedly abandon the minimum exchange rate regime might add valuable insights to the strand of literature on currency crises. In this regard, an extension of the "reverse speculative attack" model developed by Amador et al. (2016) might be a fruitful starting point. Likewise, and in view of the empirical results in Breedon et al. (2019), who find that it was much more difficult for algorithmic traders than for human traders to revise their expectations with regards to the EUR-CHF FX rate after the unexpected abandonment of the minimum exchange rate regime, it might be an interesting research question to develop an FX rate target zone with two types of market participants that differ with regard to the way they form their expectations. Last but not least, it may be interesting from an academic point of view to analyze how the growth of algorithmic trading in FX markets has contributed to the EUR-CHF minimum FX rate regime being "special" compared to previous target zones, given the findings in Breedon et al. (2019), who document that algorithmic trading contributed to price efficiency in the EUR-CHF spot market in the period of interest.

Appendix

A Flexible Price Monetary Model of the Exchange Rate for a Small Open Economy[76]

A.1 Cagan-style Money Demand Equation

$$m(t) - p(t) = \psi y(t) - \gamma r(t) + \epsilon(t), \tag{A1}$$

where $m(t)$ represents the log of domestic money demand and in equilibrium equals domestic money supply, $p(t)$ the log of the domestic price level, $y(t)$ is the log of domestic output and $r(t)$ the (risk-free) domestic interest rate.

A.2 Real Exchange Rate Equation

$$q(t) = s(t) + p^*(t) - p(t), \tag{A2}$$

where $q(t)$ is the log of the real exchange rate, $s(t)$ the log of its nominal counterpart and $p^*(t)$ the log of the foreign price level.

A.3 Uncovered Interest Parity

$$r(t) - r^*(t) = \frac{\mathrm{E}[ds(t)]}{dt}, \tag{A3}$$

where $r(t)^*$ denotes the foreign risk-free interest rate. The right-hand side of the equation reflects the expected change in the log exchange rate and equals

$$\lim_{\kappa \to 0_+} \frac{\mathrm{E}[s(t+\kappa)] - s(t)}{\kappa}.$$

A.4 Asset Pricing Equation

After replacing $p(t)$ in Equation A2 by the corresponding expression that results after rearranging Equation A1 and rearranging the resulting equation to have $s(t)$ on the left-hand side of the equation, we get

$$s(t) = q(t) - p^*(t) + [m(t) - \psi y(t) + \gamma r(t) - \epsilon(t)] \,.$$

Next, we replace $r(t)$ by Equation A3 and set $v(t) \equiv q(t) - p^*(t) - \phi y_t + \gamma i^*(t) + \epsilon(t)$. As a result, we obtain Equations 1 and 2 in Subsection 2.1.

Notice that if uncovered interest parity is not invoked $v(t)$ can easily be adjusted to account for e.g. an exogenous risk premium $\rho(t)$ in FX markets by adding a term $\gamma\rho(t)$. In this case, however, FX option markets would allow for arbitrage opportunities,[77] which in the informationally highly efficient FX market is an assumption, in line with the empirical evidence in de Santis and Gérard (1998), who report small currency risk premia

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[76] See Equation (3) in Svensson (1991a) or footnote 1 in Flood et al. (1991) for more details.

[77] See Carr and Kakushadadze (2017) for details.

in international capital markets. Focusing specifically on the EUR-CHF minimum FX rate regime, the empirical evidence suggests that FX risk premia were indeed small in the period of interest.[78] Moreover, it can be shown that FX premia are theoretically small in target zones (Svensson, 1992b). Therefore, in the target zone literature, FX premia are often ignored in practice.[79]

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[78] See e.g. Funke, Loermann, and Moessner (2017) and the working paper version of Mirkov et al. (2019).

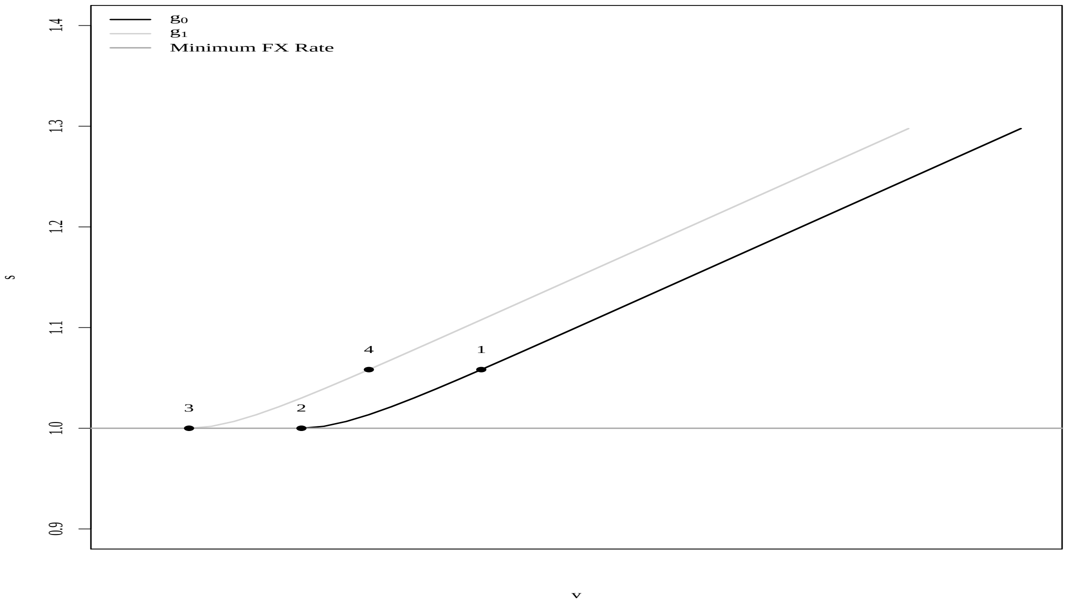
[79] See e.g. Hanke et al. (2015), Funke et al. (2017) and Mirkov et al. (2019).

B Figures

Inspired by the example on page 678 in Krugman (1991), Figure B.1 below shows how FX interventions affect the locus of the \-shaped curve that relates the velocity term v to the exchange rate s (in logs) and is a normative prediction of the Krugman framework.[80]

Assume that the FX market is at point 1 on the \-shaped curve g_0 at a given point in time and that suddenly a series of negative velocity shocks hits the market, pushing the market successively closer to the exemplary minimum exchange rate level of 1.0 along the curve g_0 until point 2 is reached. From that date onwards, any further decreases in v will be fully offset by FX interventions by the monetary authority. As a consequence, the exchange rate will remain constant at the minimum exchange rate level until a positive velocity shock (e.g. when the market is at point 3) pushes the market to an upper point 4 on a new \-shaped curve g_1.

Figure B.1: Money Supply Behavior (Example)



Notes: The figure displays a possible cycle to illustrate the effect that changes in the supply of money have on the \-shaped curve that relates the velocity term v to the exchange rate (in logs) s. As a by-product, it also reflects the so-called "honeymoon" effect that arises within FX rate target zones via the manifestation of one sub-component of the expectations channel of monetary policy, namely how the announcement of an explicit FX rate level that automatically triggers monetary actions (i.e. in the present case: FX interventions) forms (here: stabilizes) FX market expectations. A similar figure can be found on page 678 in Krugman (1991).

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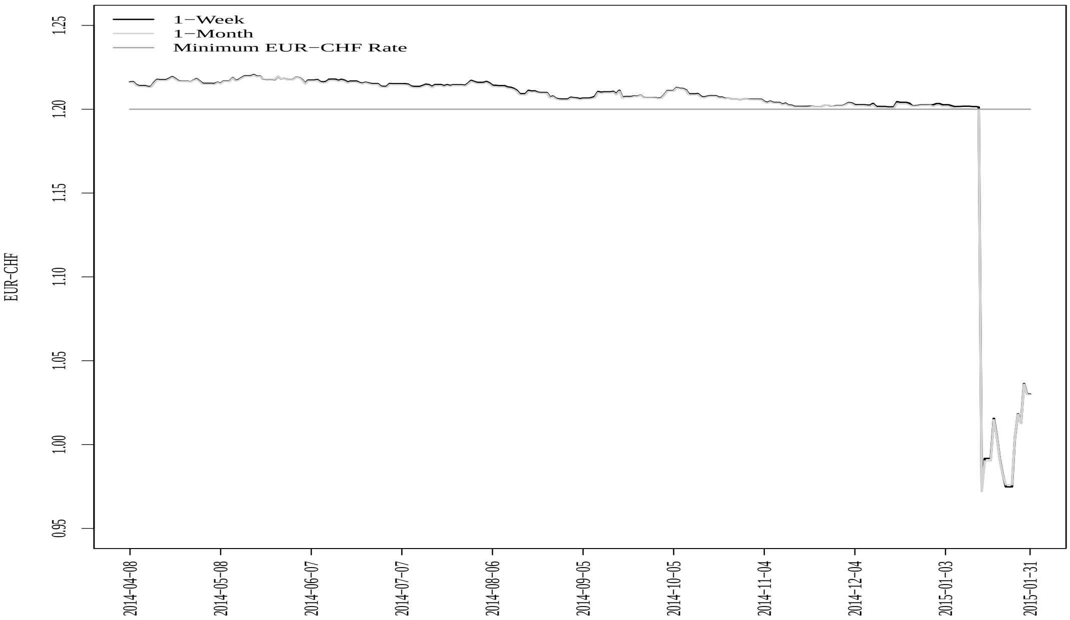
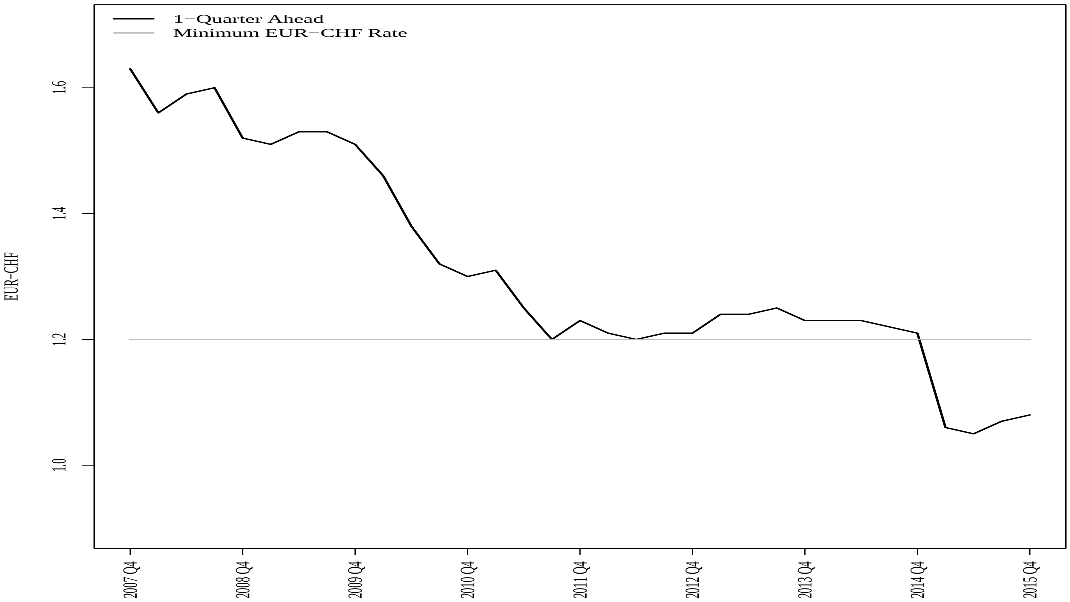
[80] Notice that this figure also reflects the so-called "honeymoon effect", a mechanism that reflects the stabilizing effect that the announcement of a target zone has on FX market expectations.

Figure B.2: 1-Week/1-Month Forward EUR-CHF FX Rate



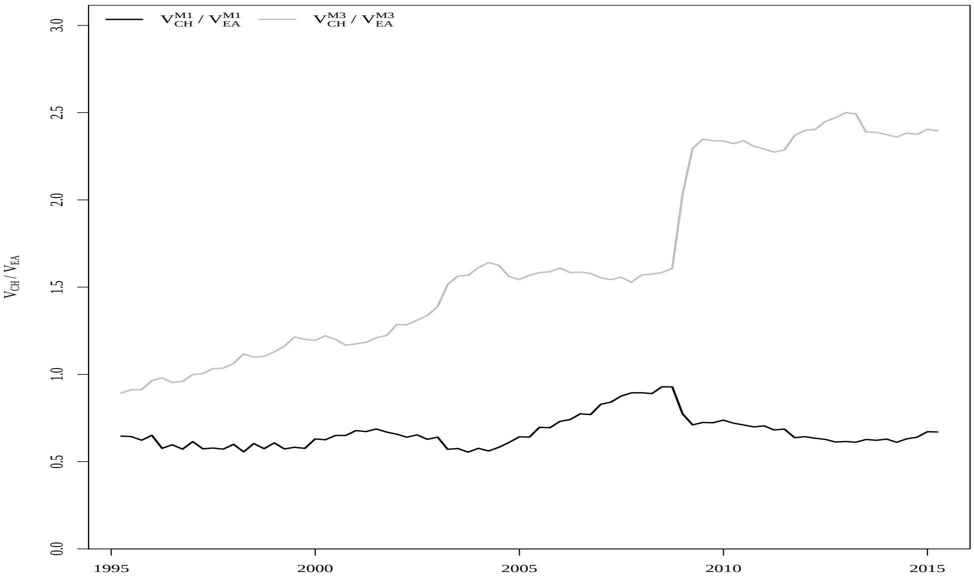
Notes: The figure displays the 1-week (black line) and 1-month (light grey line) forward EUR-CHF FX rate and the implemented EUR-CHF minimum exchange rate (grey line) from April 8, 2014 to January 31, 2015, respectively. Data source: Bloomberg.

Figure B.3: 1-Quarter Ahead Consensus Forecast for the EUR-CHF FX Rate



Notes: The figure displays the 1-quarter ahead EUR-CHF consensus forecast (black line) among large financial institutions (mainly banks) that are active in FX markets and the implemented EUR-CHF minimum exchange rate (grey line) from 2007:Q4 to 2015:Q4, respectively. Data source: Bloomberg.

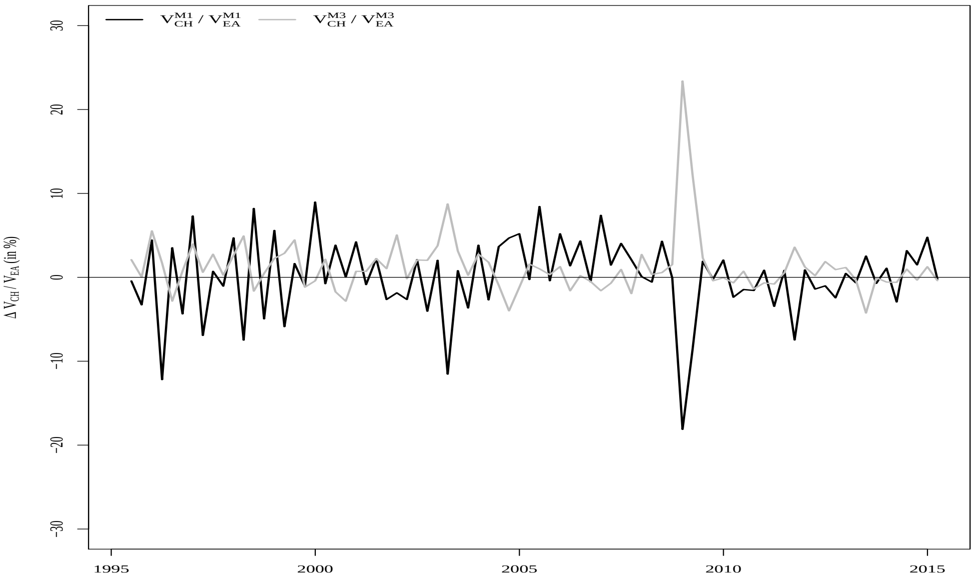
Figure B.4: Velocity of M1 and M3 Money Supply: Switzerland vs. Euro Area



EURCHF.pdf

Notes: The figure displays the ratio of velocity of money in Switzerland and the euro area (EA) for the monetary aggregates M1 (black line) and M3 (grey line) from 1995:Q1 to 2015:Q1, respectively. Data source: Federal Reserve Economic Data - St. Louis Fed for the M1 and M3 data and the nominal gross domestic product for both the EA and Switzerland (all series are seasonally adjusted), all of which are used to estimate V_{CH} and V_{EA}.

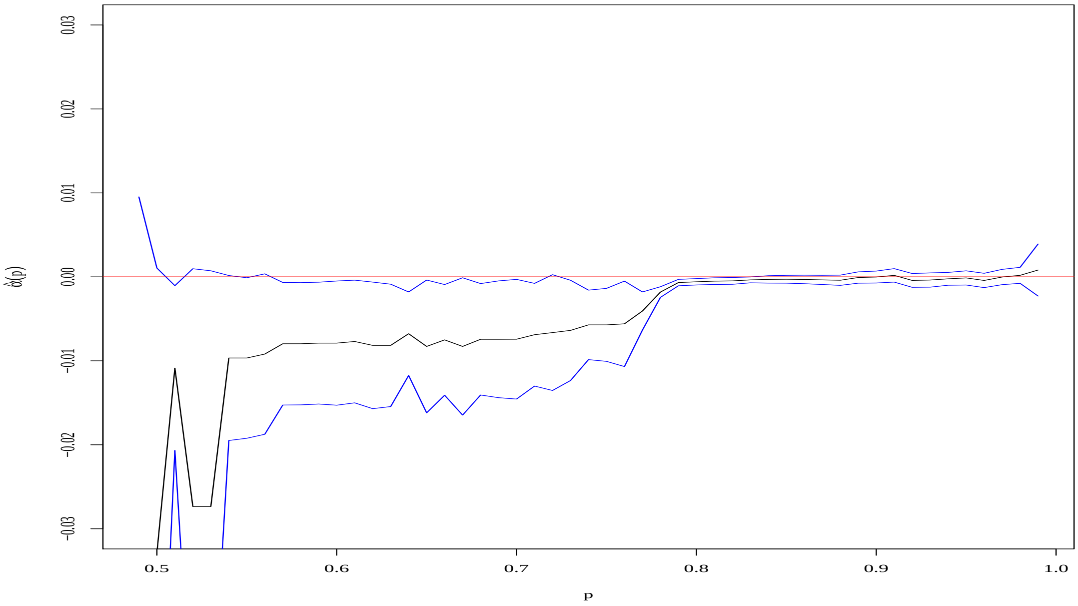
Figure B.5: Change in Velocity of M1 and M3 Money Supply: Switzerland vs. Euro Area



EURCHF.pdf

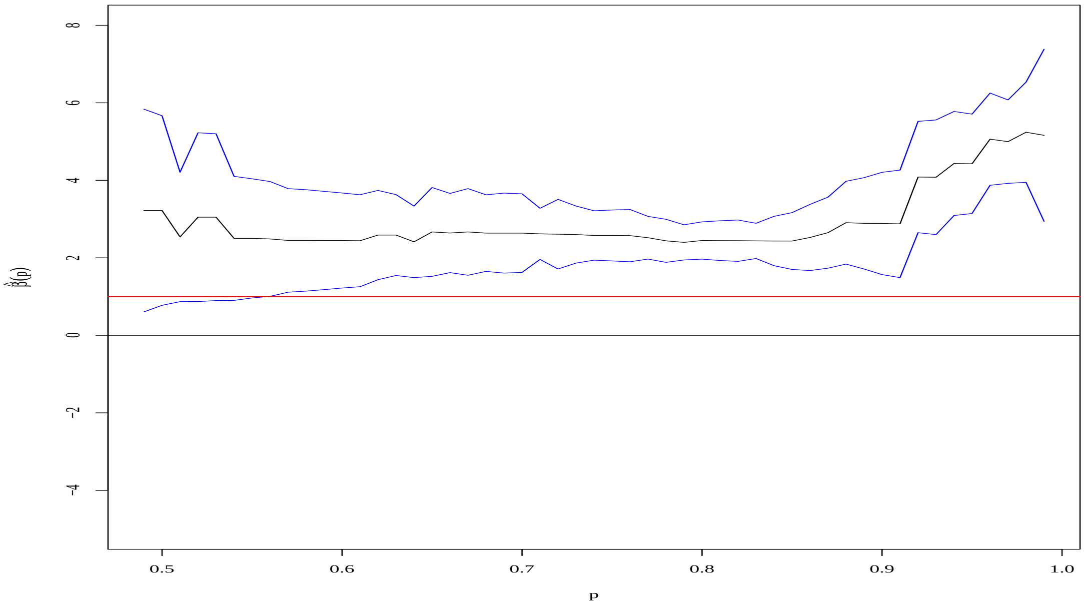
Notes: The figure displays the change in the ratio (in per cent) of velocity of money in Switzerland and the euro area (EA) for the monetary aggregates M1 (black line) and M3 (grey line) from 1995:Q1 to 2015:Q1, respectively. Data source: Federal Reserve Economic Data - St. Louis Fed for the M1 and M3 data and the nominal gross domestic product for both the EA and Switzerland (all series are seasonally adjusted), all of which are used to estimate V_{CH} and V_{EA}.

Figure B.6: Censored Quantile Regression (1w; in %): Intercept



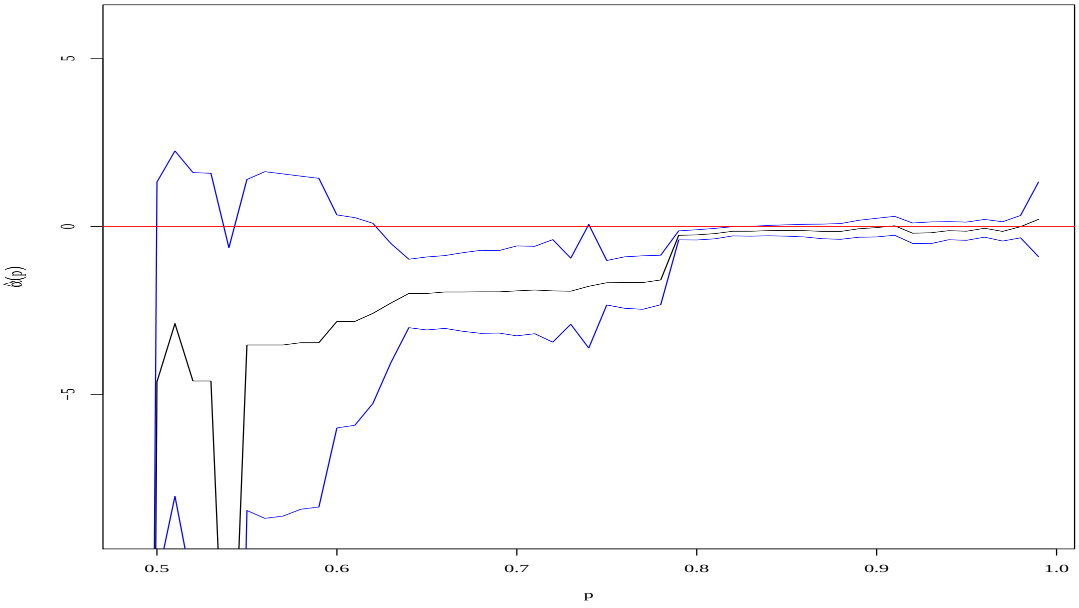
Notes: The figure displays the CLAD coefficient estimates $\hat{\alpha}(p)$ associated with the intercept of the censored quantile regression model and the corresponding 90% confidence interval for different percentiles ("p") using the VV-implied volatility for a contract maturity of one week ("1w"), adjusted accordingly to reflect the size of weekly FX interventions (in percent of the domestic money supply ("in %")). The data used cover the period from September 9, 2011 to January 9, 2015.

Figure B.7: Censored Quantile Regression (1w; in %): Slope



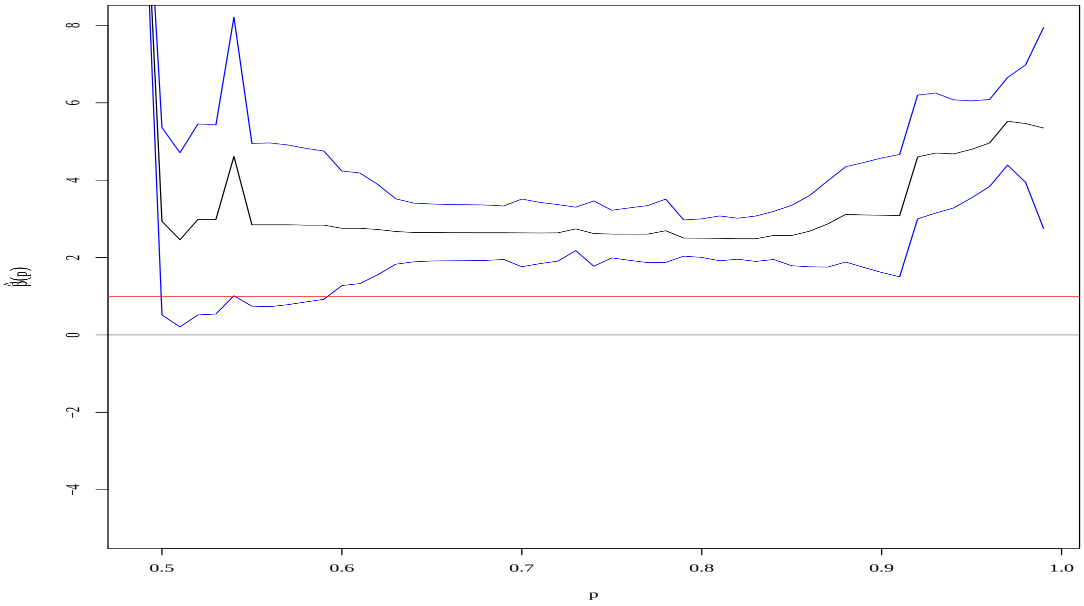
Notes: The figure displays the CLAD coefficient estimates $\hat{\beta}(p)$ associated with the slope of the censored quantile regression model and the corresponding 90% confidence interval for different percentiles ("p") using the VV-implied volatility for a contract maturity of one week ("1w"), adjusted accordingly to reflect the size of weekly FX interventions (in percent of the domestic money supply ("in %")). The data used cover the period from September 9, 2011 to January 9, 2015.

Figure B.8: Censored Quantile Regression (1w; in CHF): Intercept



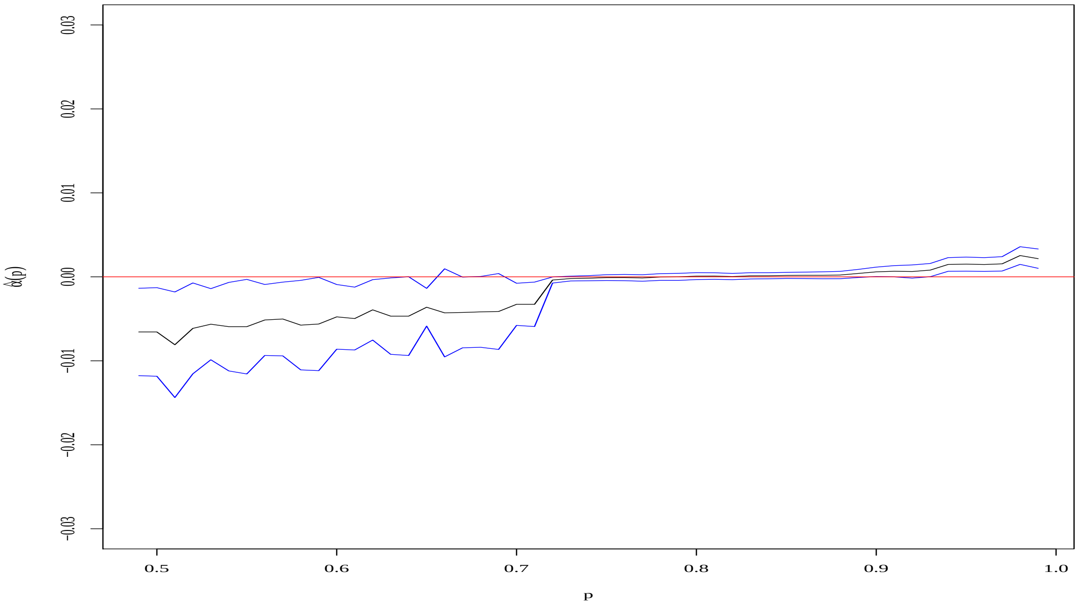
Notes: The figure displays the CLAD coefficient estimates $\hat{\alpha}(p)$ associated with the intercept of the censored quantile regression model and the corresponding 90% confidence interval for different percentiles ("p") using the VV-implied volatility for a contract maturity of one week ("1w"), adjusted accordingly to reflect the size of weekly FX interventions (in Swiss francs ("in CHF")). The data used cover the period from September 9, 2011 to January 9, 2015.

Figure B.9: Censored Quantile Regression (1w; in CHF): Slope



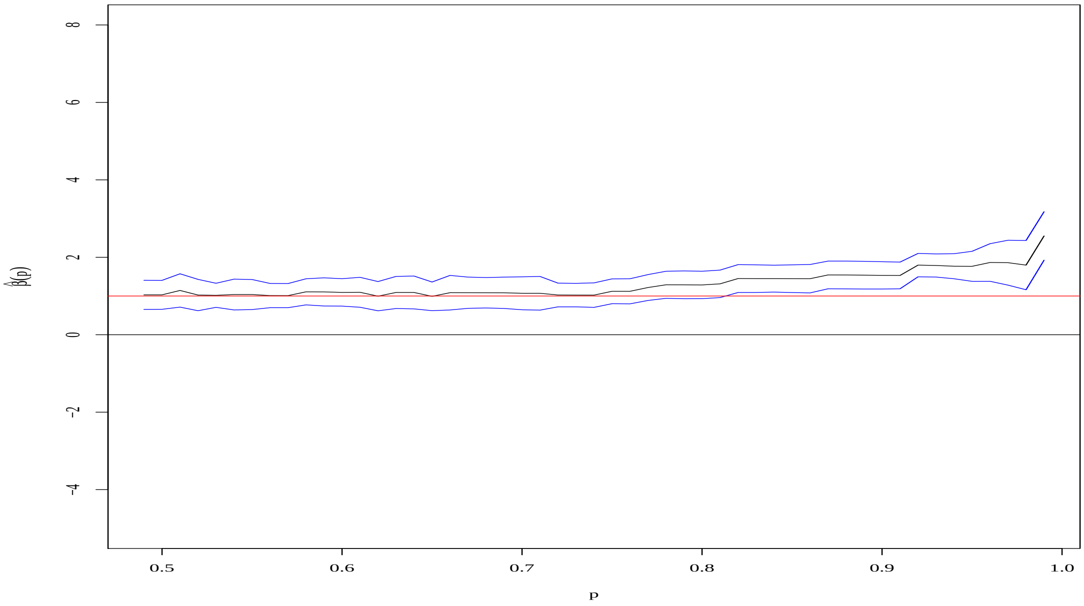
Notes: The figure displays the CLAD coefficient estimates $\hat{\beta}(p)$ associated with the slope of the censored quantile regression model and the corresponding 90% confidence interval for different percentiles ("p") using the VV-implied volatility for a contract maturity of one week ("1w"), adjusted accordingly to reflect the size of weekly FX interventions (in Swiss francs ("in CHF")). The data used cover the period from September 9, 2011 to January 9, 2015.

Figure B.10: Censored Quantile Regression (1m; in %): Intercept



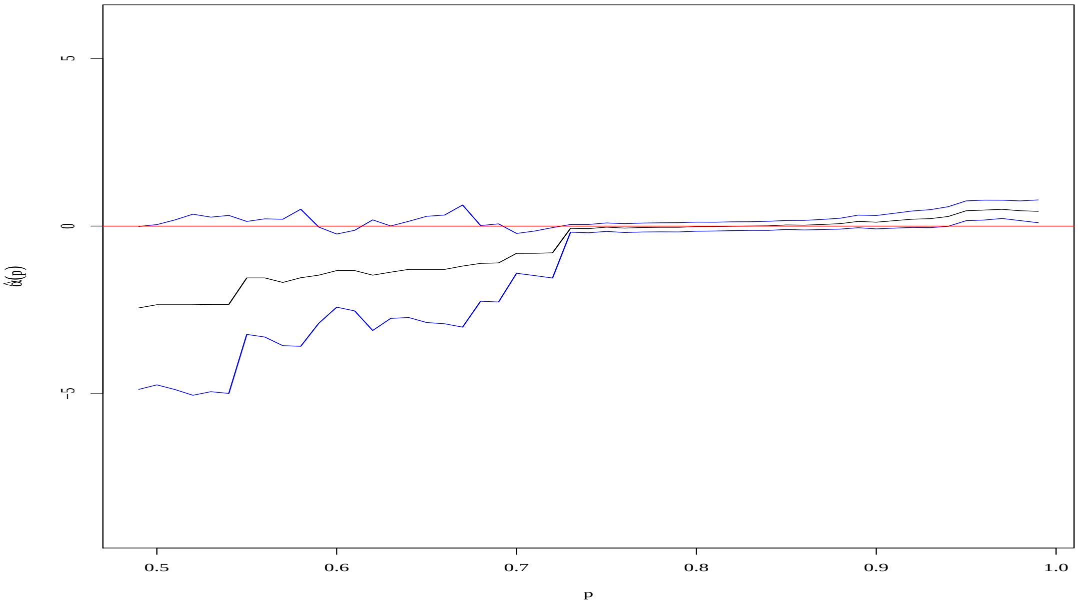
Notes: The figure displays the CLAD coefficient estimates $\hat{\alpha}(p)$ associated with the intercept of the censored quantile regression model and the corresponding 90% confidence interval for different percentiles ("p") using the VV-implied volatility for a contract maturity of one month ("$1m$"), adjusted accordingly to reflect the size of weekly FX interventions (in percent of the domestic money supply ("in %")). The data used cover the period from September 9, 2011 to January 9, 2015.

Figure B.11: Censored Quantile Regression (1m; in %): Slope



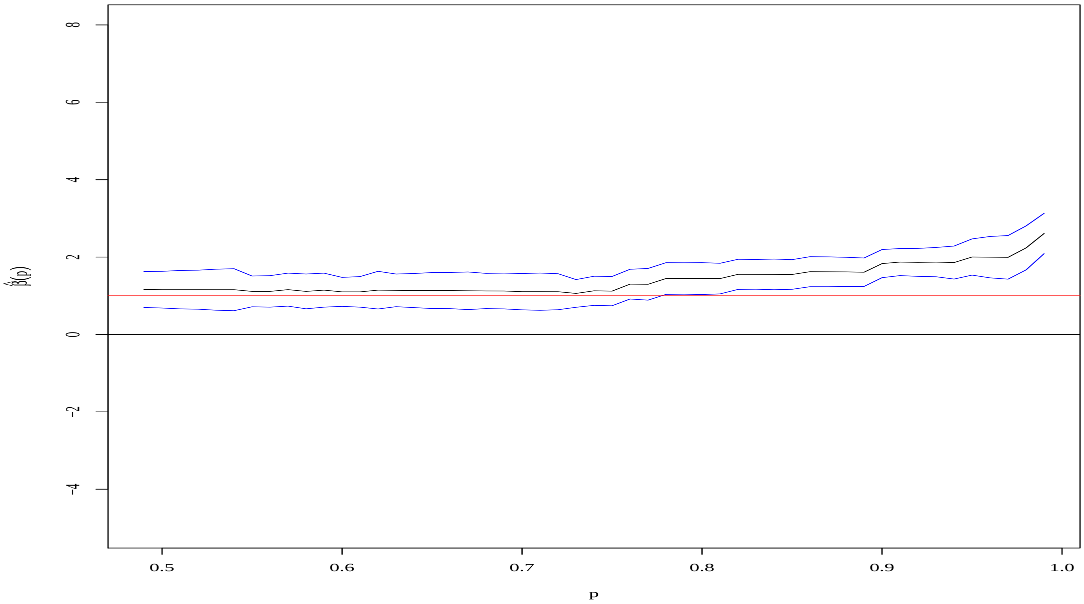
Notes: The figure displays the CLAD coefficient estimates $\hat{\beta}(p)$ associated with the slope of the censored quantile regression model and the corresponding 90% confidence interval for different percentiles ("p") using the VV-implied volatility for a contract maturity of one month ("$1m$"), adjusted accordingly to reflect the size of weekly FX interventions (in percent of the domestic money supply ("in %")). The data used cover the period from September 9, 2011 to January 9, 2015.

Figure B.12: Censored Quantile Regression (1m; in CHF): Intercept



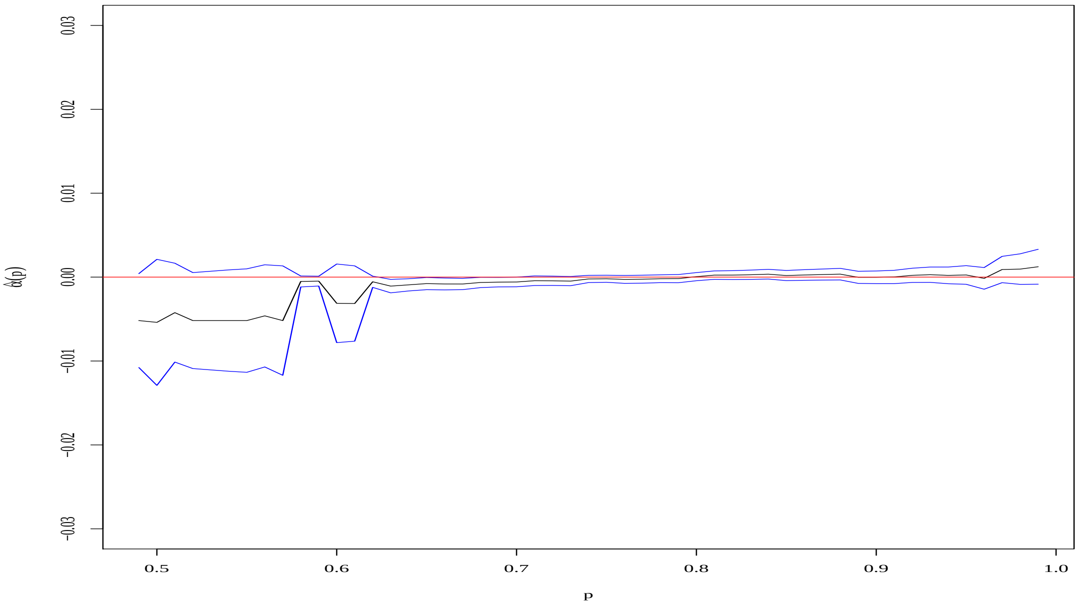
Notes: The figure displays the CLAD coefficient estimates $\hat{\alpha}(p)$ associated with the intercept of the censored quantile regression model and the corresponding 90% confidence interval for different percentiles ("p") using the VV-implied volatility for a contract maturity of one month ("$1m$"), adjusted accordingly to reflect the size of weekly FX interventions (in Swiss francs ("in CHF")). The data used cover the period from September 9, 2011 to January 9, 2015.

Figure B.13: Censored Quantile Regression (1m; in CHF): Slope



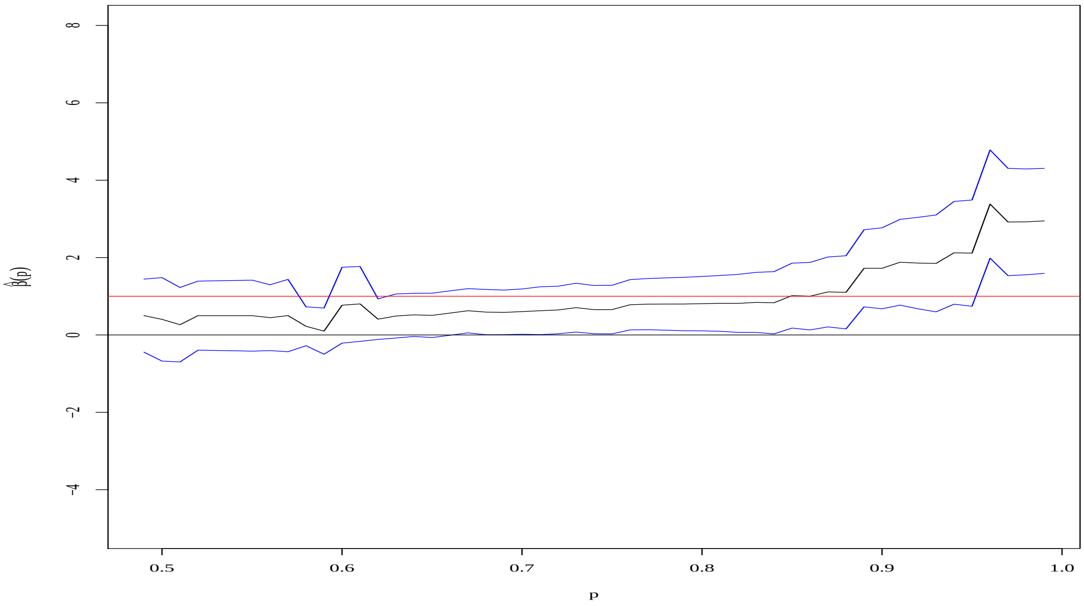
Notes: The figure displays the CLAD coefficient estimates $\hat{\beta}(p)$ associated with the slope of the censored quantile regression model and the corresponding 90% confidence interval for different percentiles ("p") using the VV-implied volatility for a contract maturity of one month ("$1m$"), adjusted accordingly to reflect the size of weekly FX interventions (in Swiss francs ("in CHF")). The data used cover the period from September 9, 2011 to January 9, 2015.

Figure B.14: Dynamic Censored Quantile Regression (1w; in %): Intercept



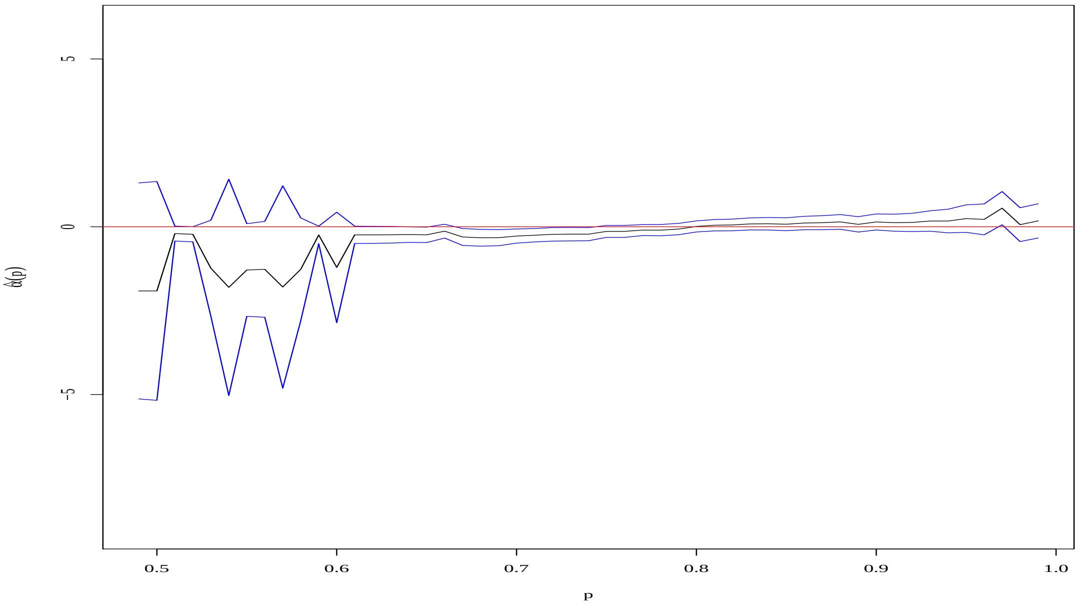
Notes: The figure displays the CLAD coefficient estimates $\hat{\alpha}(p)$ associated with the intercept of the dynamic censored quantile regression model and the corresponding 90% confidence interval for different percentiles ("p") using the VV-implied volatility for a contract maturity of one week ("$1w$"), adjusted accordingly to reflect the size of weekly FX interventions (in percent of the domestic money supply ("in %")). The data used cover the period from September 9, 2011 to January 9, 2015.

Figure B.15: Dynamic Censored Quantile Regression (1w; in %): Slope



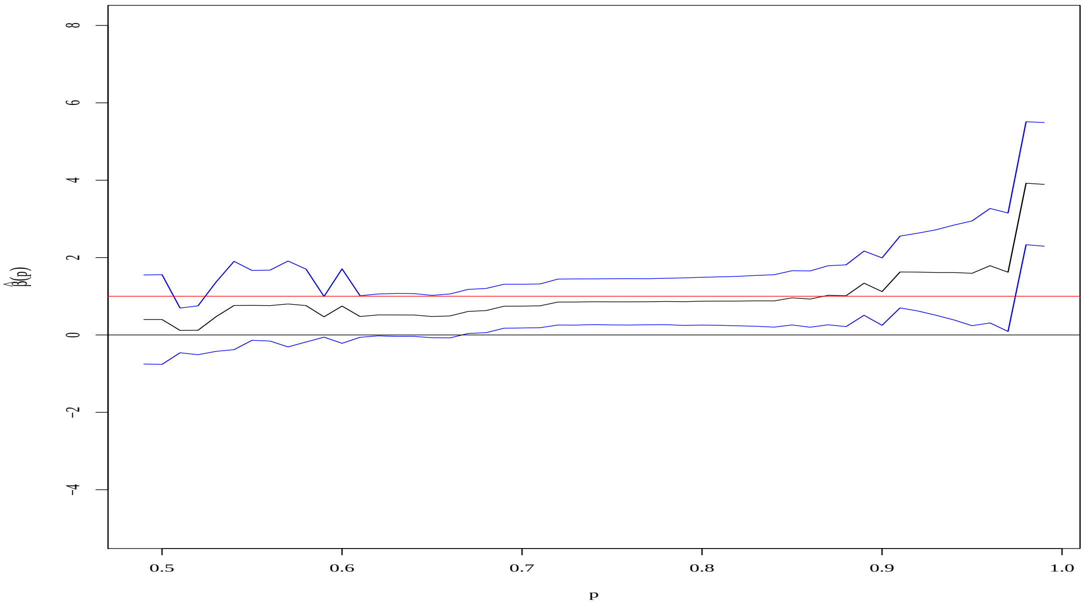
Notes: The figure displays the CLAD coefficient estimates $\hat{\beta}(p)$ associated with the slope of the dynamic censored quantile regression model and the corresponding 90% confidence interval for different percentiles ("p") using the VV-implied volatility for a contract maturity of one week ("$1w$"), adjusted accordingly to reflect the size of weekly FX interventions (in percent of the domestic money supply ("in %")). The data used cover the period from September 9, 2011 to January 9, 2015.

Figure B.16: Dynamic Censored Quantile Regression (1w; in CHF): Intercept



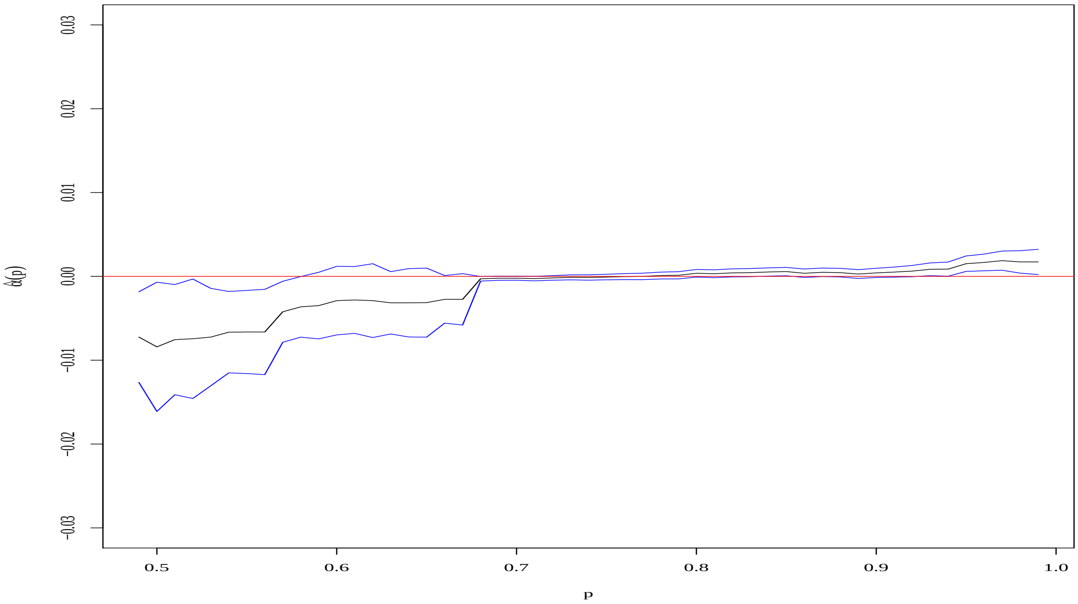
Notes: The figure displays the CLAD coefficient estimates $\hat{\alpha}(p)$ associated with the intercept of the dynamic censored quantile regression model and the corresponding 90% confidence interval for different percentiles ("p") using the VV-implied volatility for a contract maturity of one week ("$1w$"), adjusted accordingly to reflect the size of weekly FX interventions (in Swiss francs ("in CHF")). The data used cover the period from September 9, 2011 to January 9, 2015.

Figure B.17: Dynamic Censored Quantile Regression (1w; in CHF): Slope



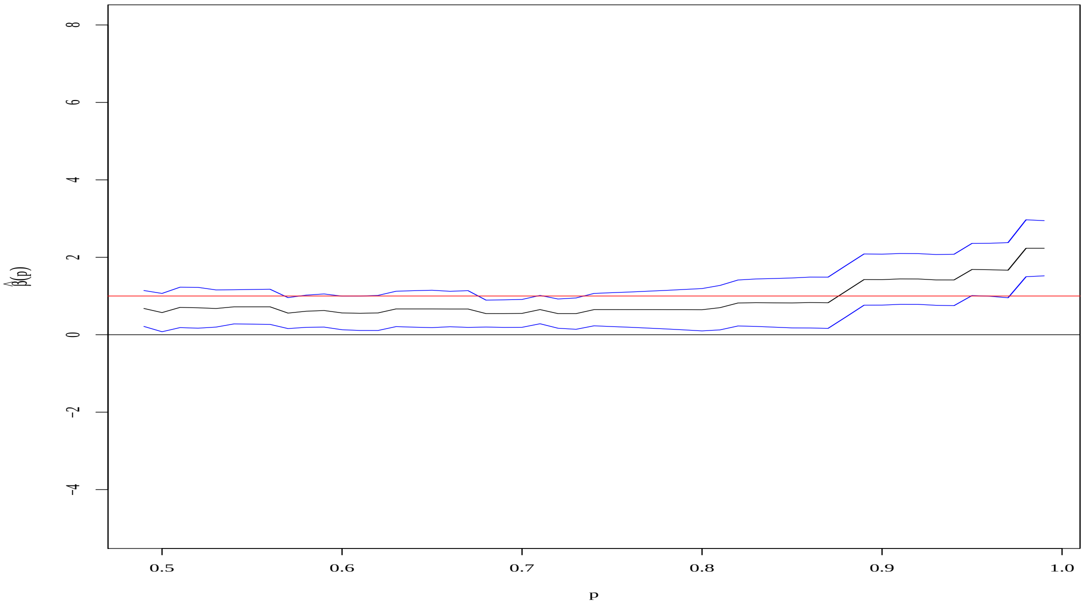
Notes: The figure displays the CLAD coefficient estimates $\hat{\beta}(p)$ associated with the slope of the dynamic censored quantile regression model and the corresponding 90% confidence interval for different percentiles ("p") using the VV-implied volatility for a contract maturity of one week ("$1w$"), adjusted accordingly to reflect the size of weekly FX interventions (in Swiss francs ("in CHF")). The data used cover the period from September 9, 2011 to January 9, 2015.

Figure B.18: Dynamic Censored Quantile Regression (1m; in %): Intercept



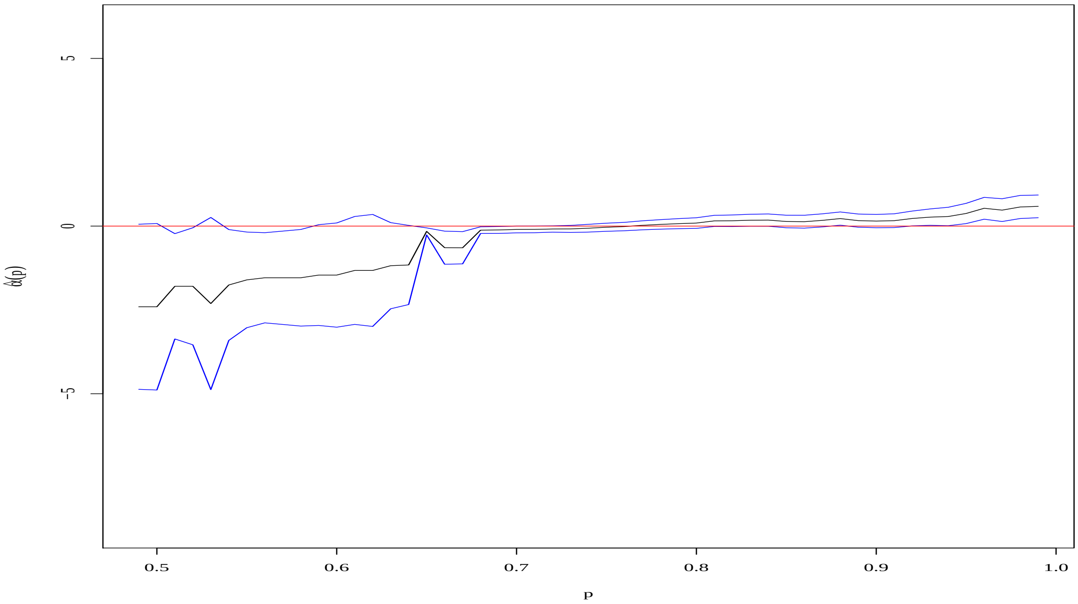
Notes: The figure displays the CLAD coefficient estimates $\hat{\alpha}(p)$ associated with the intercept of the dynamic censored quantile regression model and the corresponding 90% confidence interval for different percentiles ("p") using the VV-implied volatility for a contract maturity of one month ("1m"), adjusted accordingly to reflect the size of weekly FX interventions (in percent of the domestic money supply ("in %")). The data used cover the period from September 9, 2011 to January 9, 2015.

Figure B.19: Dynamic Censored Quantile Regression (1m; in %): Slope



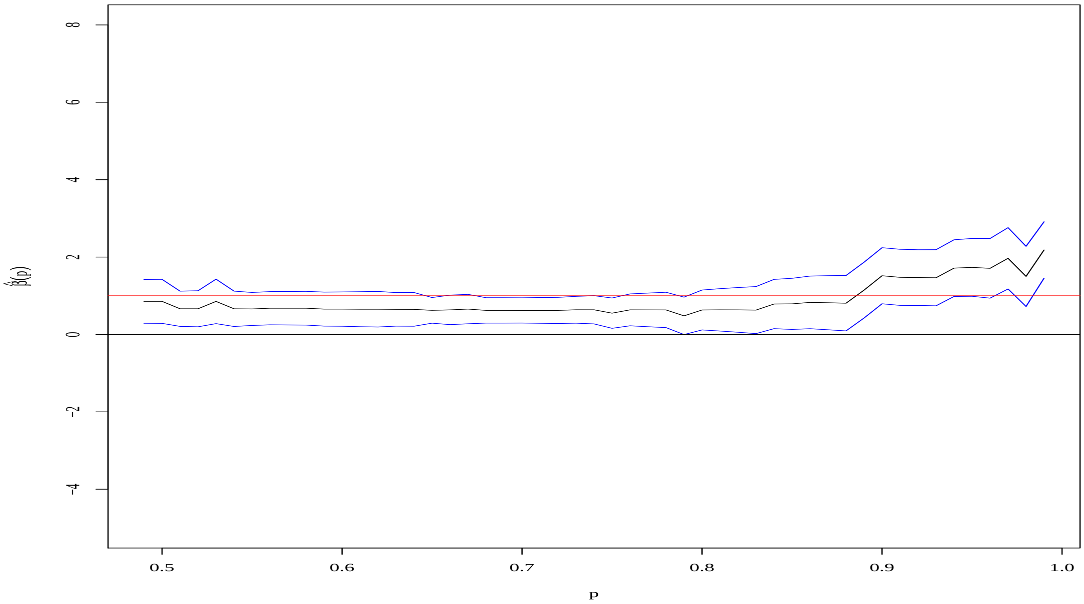
Notes: The figure displays the CLAD coefficient estimates $\hat{\beta}(p)$ associated with the slope of the dynamic censored quantile regression model and the corresponding 90% confidence interval for different percentiles ("p") using the VV-implied volatility for a contract maturity of one month ("1m"), adjusted accordingly to reflect the size of weekly FX interventions (in percent of the domestic money supply ("in %")). The data used cover the period from September 9, 2011 to January 9, 2015.

Figure B.20: Dynamic Censored Quantile Regression (1m; in CHF): Intercept



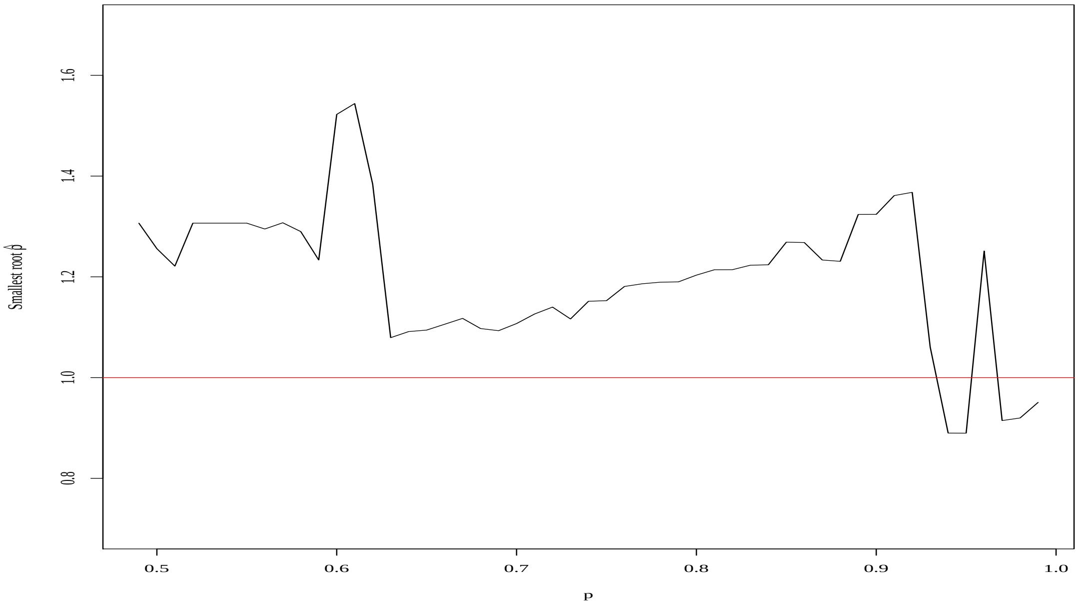
Notes: The figure displays the CLAD coefficient estimates $\hat{\alpha}(p)$ associated with the intercept of the dynamic censored quantile regression model and the corresponding 90% confidence interval for different percentiles ("p") using the VV-implied volatility for a contract maturity of one month ("1m"), adjusted accordingly to reflect the size of weekly FX interventions (in Swiss francs ("in CHF")). The data used cover the period from September 9, 2011 to January 9, 2015.

Figure B.21: Dynamic Censored Quantile Regression (1m; in CHF): Slope



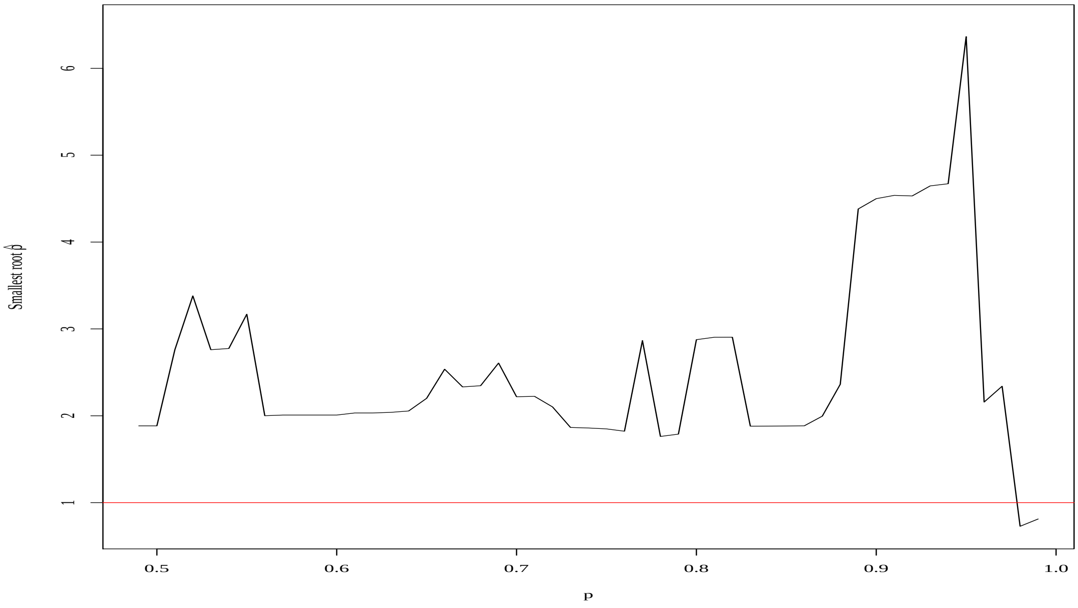
Notes: The figure displays the CLAD coefficient estimates $\hat{\beta}(p)$ associated with the slope of the dynamic censored quantile regression model and the corresponding 90% confidence interval for different percentiles ("p") using the VV-implied volatility for a contract maturity of one month ("1m"), adjusted accordingly to reflect the size of weekly FX interventions (in Swiss francs ("in CHF")). The data used cover the period from September 9, 2011 to January 9, 2015.

Figure B.22: Dynamic Censored Quantile Regression (1w; in %): Smallest Root



Notes: The figure displays the smallest root $\hat{\rho}(p)$ of the one lag polynomial for different percentiles ("p") associated with the dynamic censored quantile regression model using the VV-implied volatility for a contract maturity of one week ("1w"), adjusted accordingly to reflect the size of weekly FX interventions (in percent of the domestic money supply ("in %")).

Figure B.23: Dynamic Censored Quantile Regression (1m; in %): Smallest Root



Notes: The figure displays the smallest root $\hat{\rho}(p)$ of the one lag polynomial for different percentiles ("p") associated with the dynamic censored quantile regression model using the VV-implied volatility for a contract maturity of one month ("1m"), adjusted accordingly to reflect the size of weekly FX interventions (in percent of the domestic money supply ("in %")).

C Tables

Table A.1: Schwarz Information Criterion (1w; in %)

p	Dynamic Censored Quantile Regression	Quantile Regression	AR(1)
49	28.924	**27.942**	28.177
50	28.946	**27.943**	28.177
51	28.970	**27.945**	28.177
52	28.988	**27.950**	28.177
53	29.010	**27.956**	28.177
54	29.033	**27.961**	28.177
55	29.055	**27.967**	28.177
56	29.078	**27.973**	28.177
57	29.101	**27.980**	28.177
58	28.932	**27.990**	28.177
59	28.959	**28.000**	28.177
60	28.969	**28.012**	28.177
61	28.965	**28.024**	28.177
62	28.861	**28.037**	28.177
63	28.595	**28.058**	28.177
64	28.539	**28.082**	28.177
65	28.514	**28.106**	28.177
66	28.459	**28.131**	28.177
67	28.389	**28.157**	28.177
68	28.339	28.185	**28.177**
69	28.318	28.214	**28.177**
70	28.293	28.245	**28.177**
71	28.216	28.276	**28.177**
72	28.197	28.308	**28.177**
73	28.183	28.340	**28.177**
74	**28.068**	28.375	28.177
75	**28.042**	28.411	28.177
76	**27.897**	28.450	28.177
77	**27.849**	28.491	28.177
78	**27.804**	28.534	28.177
79	**27.782**	28.578	28.177
80	**27.643**	28.626	28.177
81	**27.532**	28.677	28.177
82	**27.513**	28.731	28.177
83	**27.443**	28.787	28.177
84	**27.406**	28.845	28.177
85	**27.223**	28.908	28.177
86	**27.193**	28.976	28.177
87	**26.937**	29.054	28.177
88	**26.907**	29.137	28.177
89	**26.321**	29.239	28.177
90	**26.300**	29.360	28.177
91	**26.118**	29.490	28.177
92	**26.060**	29.641	28.177
93	**25.753**	29.809	28.177
94	**25.324**	30.054	28.177
95	**25.297**	30.339	28.177
96	**24.760**	30.721	28.177
97	**24.600**	31.271	28.177
98	**24.573**	32.071	28.177
99	**24.513**	33.449	28.177

Notes: The table displays the value of the Schwarz Information Criterion (SIC) for different percentiles p (1st column) using the dynamic censored quantile regression approach (2nd column), the quantile regression approach (3rd column) and an AR(1) model (4th column) associated with a 1-week forecast horizon and the size of weekly ("1w") FX interventions (in percent of the domestic money supply ("in %")). The cell entries in bold indicate the row-wise optimal model in terms of the SIC.

Table A.2: Schwarz Information Criterion (1m; in %)

p	Dynamic Censored Quantile Regression	Quantile Regression	AR(1)
49	29.179	**28.010**	28.177
50	29.200	**28.009**	28.177
51	29.216	**28.013**	28.177
52	29.220	**28.022**	28.177
53	29.252	**28.033**	28.177
54	29.270	**28.043**	28.177
55	29.260	**28.054**	28.177
56	29.200	**28.067**	28.177
57	29.201	**28.080**	28.177
58	29.209	**28.094**	28.177
59	29.217	**28.111**	28.177
60	29.226	**28.132**	28.177
61	29.200	**28.153**	28.177
62	29.206	**28.175**	28.177
63	29.200	28.198	**28.177**
64	29.176	28.223	**28.177**
65	28.690	28.249	**28.177**
66	29.095	28.276	**28.177**
67	29.074	28.303	**28.177**
68	29.068	28.331	**28.177**
69	28.980	28.359	**28.177**
70	28.535	28.388	**28.177**
71	28.489	28.417	**28.177**
72	28.395	28.448	**28.177**
73	28.249	28.484	**28.177**
74	28.226	28.521	**28.177**
75	28.198	28.559	**28.177**
76	**28.146**	28.598	28.177
77	**28.041**	28.640	28.177
78	**28.025**	28.683	28.177
79	**27.974**	28.727	28.177
80	**27.924**	28.774	28.177
81	**27.735**	28.824	28.177
82	**27.715**	28.887	28.177
83	**27.309**	28.953	28.177
84	**27.280**	29.024	28.177
85	**27.242**	29.099	28.177
86	**27.183**	29.177	28.177
87	**27.075**	29.261	28.177
88	**26.872**	29.353	28.177
89	**26.396**	29.464	28.177
90	**26.332**	29.601	28.177
91	**26.288**	29.749	28.177
92	**26.235**	29.911	28.177
93	**26.143**	30.091	28.177
94	**26.108**	30.293	28.177
95	**25.801**	30.546	28.177
96	**25.447**	30.879	28.177
97	**25.416**	31.298	28.177
98	**24.605**	31.927	28.177
99	**24.302**	33.266	28.177

Notes: The table displays the value of the Schwarz Information Criterion (SIC) for different percentiles p (1st column) using the dynamic censored quantile regression approach (2nd column), the quantile regression approach (3rd column) and an AR(1) model (4th column) associated with a 1-month forecast horizon and the size of monthly ("1m") FX interventions (in percent of the domestic money supply ("in %")). The cell entries in bold indicate the row-wise optimal model in terms of the SIC.

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