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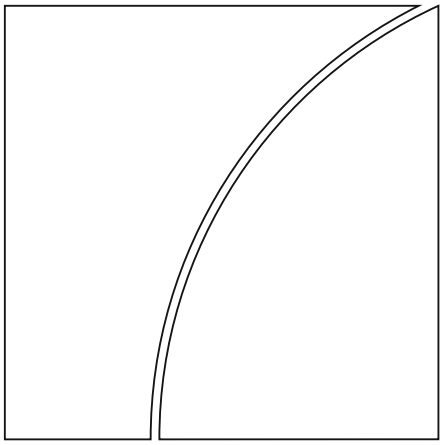

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by Nuttathum Chutasripanich and James Yetman

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Foreign exchange intervention: strategies and effectiveness

Nuttathum Chutasripanich and James Yetman[1]

Abstract

Foreign exchange intervention has been actively used as a policy tool in many economies in Asia and elsewhere. In this paper, we examine two intervention rules (leaning against exchange rate misalignment and leaning against the wind), utilised with varying degrees of transparency, based on a simple model with three kinds of agents: fundamentalists, speculators and the central bank. We assess the effectiveness of these rules against five criteria: stabilising the exchange rate, reducing current account imbalances, discouraging speculation, minimising reserves volatility and limiting intervention costs. Overall we find no dominant intervention strategy. Intervention that reduces exchange rate volatility, for example, also reduces the risks of speculation, creating a feedback loop and potentially leading to high levels of speculation, reserves volatility and intervention costs. These intervention costs will be especially large when exchange rate movements are driven by interest rate shocks, although some degree of opaqueness can help to reduce them. Survey evidence from BIS (2005, 2013) indicates that central banks follow a range of different strategies when intervening in foreign exchange rates. Given the trade-offs that different strategies entail in our model, this is not surprising.

JEL classifications: E58, F31.

Keywords: foreign exchange intervention; exchange rates; speculation.

[1] Bank of Thailand and Bank for International Settlements, respectively. Corresponding author: james.yetman@bis.org. This paper was written while the first author was visiting the BIS Representative Office for Asia and the Pacific. The views expressed here are those of the authors and are not necessarily shared by the Bank of Thailand or the Bank for International Settlements. We thank, without implication, Aaron Mehrotra, Carlos Montoro, Frank Packer, Philip Turner and seminar participants at the BIS (Hong Kong) for helpful comments and Bat-el Berger for excellent research assistance.

1. Introduction

A growing body of literature suggests that central banks – especially those in emerging market economies – may have an important role to play in stabilising exchange rates. Garcia et al (2011) argue that a central bank response to exchange rate movements may be desirable, especially in economies with relatively under-developed financial systems such that consumption co-moves more strongly with income than intertemporal optimisation would imply. Héricourt and Poncet (2015) show that firms export less when faced with greater exchange rate volatility, an effect that is magnified for those that are financially vulnerable. Engle (2011) demonstrates that if home and foreign households pay different prices for the same goods, due to currency misalignment, policies to reduce that misalignment may be welfare-improving. And Devereux (2004) shows that even if flexible exchange rates could serve as an effective shock absorber in response to shocks, then stable exchange rates may still be desirable due to the presence of nominal rigidities.

In this paper, we take the potential benefits of foreign exchange intervention as given, at least for some countries at some times, and examine different intervention strategies. We review the previous literature on foreign exchange intervention. We then build on existing analytical models to illustrate the factors that are likely to make intervention more or less effective when measured against five different criteria.

Our analytical model builds on Carlson and Osler (2000). We assume that there is an underlying fundamental demand for foreign exchange transactions that is subject to random shocks. We then add to this rational risk-averse speculators and a central bank that intervenes according to one of two rules: either to lean against the wind of exchange rate change or to drive the exchange rate closer to its fundamental value. We examine interactions between these three sets of players as we vary the nature of shocks, the size of the speculative market, the intervention rule of the central bank and the transparency of their interventions. Our model is partial equilibrium, which simplifies the analytics and allows us to address a number of questions associated with foreign exchange intervention that would be more difficult in a general equilibrium framework.[2]

The main contribution of our paper is that we extend a simple analytical model developed elsewhere and use this to illustrate some of the challenges associated with foreign exchange intervention. We are able to demonstrate the trade-offs inherent in different intervention strategies, based on the multiple objectives of policymakers. Our key results can be summarised as follows:

- The actions of speculators can reduce the volatility of exchange rates but, even then, they tend to increase current account imbalances in our model, for two reasons. First, in a world with persistent shocks, speculators trading on expected future movements tend to move the exchange rate away from its

[2] The trade-off is that we ignore general equilibrium effects. For a recent example of a paper addressing similar issues in a general equilibrium framework, see Montoro and Ortiz (2013). Among other results, they find that rule-based intervention tends to be more stabilising than discretionary intervention because of a stronger effect on expectations, and intervention can be an effective way to strengthen the link between exchange rates and fundamentals when agents have heterogeneous information.

fundamental value. Second, the actions of speculators tend to smooth the exchange rate which slows the rate of reversion towards its' fundamental value

- Intervention that reduces exchange rate volatility also reduces the risks faced by speculators, thereby encouraging greater speculation.
- Central bank uncertainty about the fundamental value of the exchange rate results in foreign exchange intervention being less efficient; beyond some level of uncertainty, intervention is generally destabilising.
- Leaning against the wind (ie systematically intervening against the direction that the exchange rate is moving), which avoids the problem of having to estimate the fundamental value of the exchange rate, is no panacea. It reduces the volatility of the exchange rate, encouraging speculation, and also works against market forces that would tend to move the exchange rate towards its' fundamental value.
- The costs of foreign exchange intervention will be especially large when exchange rate movements are driven by shocks to the differential between home and foreign interest rates since these drive a positive correlation between the stock of reserves and the carrying costs of those reserves.
- Relative to transparent intervention, adding an element of opaqueness offers both costs and benefits. It tends to increase the volatility of exchange rates, current account balances and reserves, but reduces the size of speculative flows and the costs of carrying reserves.

In the next section, we summarise the literature on how central banks intervene in foreign exchange markets. In section 3, we discuss related previous contributions to modelling and analysing exchange rates. In section 4 we build on this literature to develop our own analytical model that we can use to examine foreign exchange intervention. Section 5 discusses the results of our model. Finally, in section 6, we conclude.

2. How do central banks intervene in foreign exchange markets?

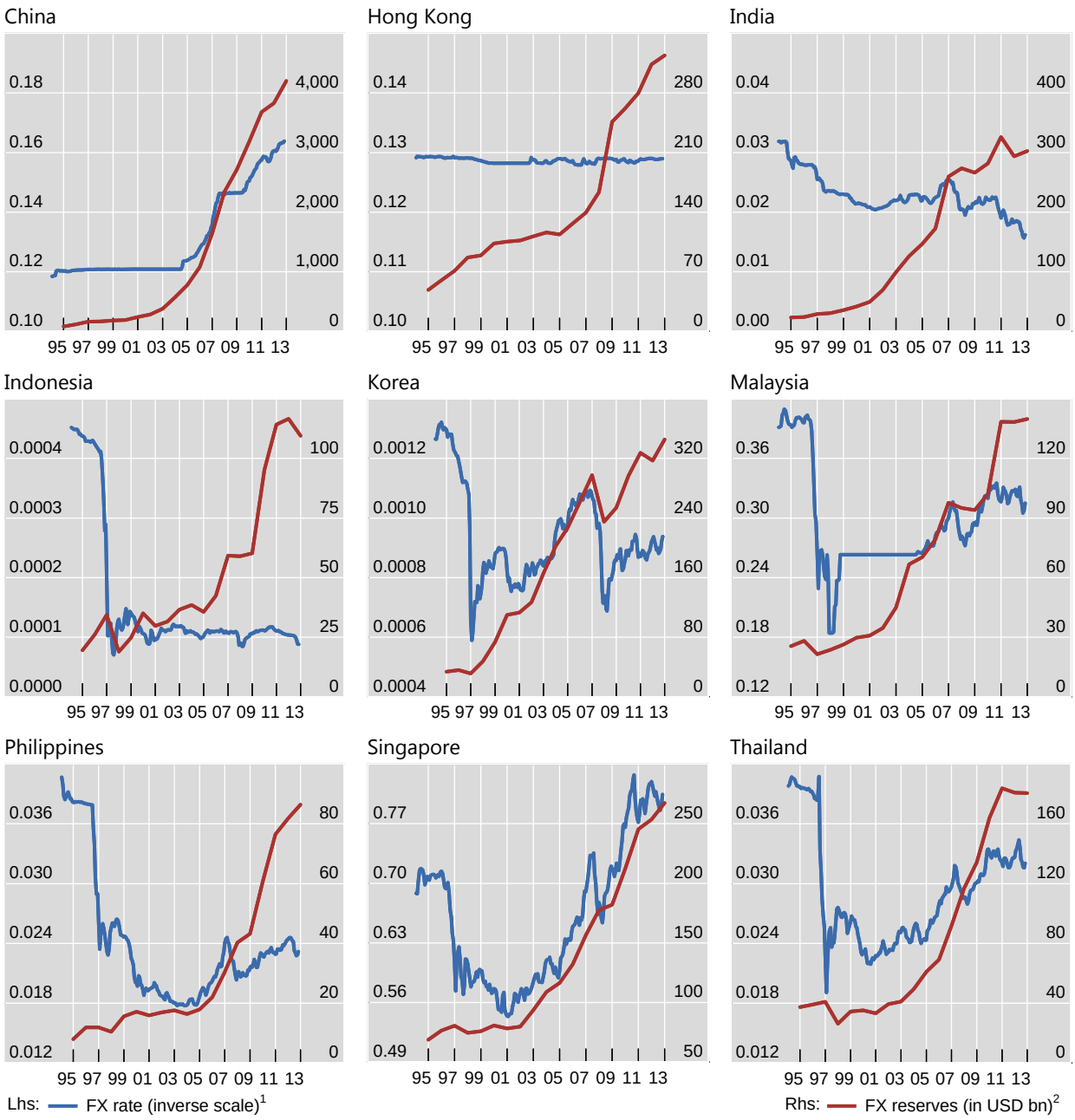
2.1 Intervention in Asia

Focusing on some of the major economies in Asia, Graph 1 plots foreign exchange reserves in US dollars and the bilateral exchange rate against the US dollar.[3] In the lead up to the Asian Financial Crisis (1997-1998), foreign exchange reserves were at modest levels in many economies in the region. Then, at various points during the financial crisis, specific regional economies suffered sharp declines in their stocks of reserves and sudden exchange rate depreciations – by around 50% in the cases of Korea, Malaysia, the Philippines and Thailand, and even more for Indonesia.

[3] Intervention in foreign exchange markets is by no means confined to central banks in Asia. See, for example, the contributed papers in BIS (2005) from a broad cross-section of emerging market central banks.

Foreign exchange reserves and exchange rates

Graph 1



[1] Domestic currency per USD. An increase indicates an appreciation of the domestic currency against the USD and vice versa. [2] Central bank foreign assets.

Sources: IMF, *International Financial Statistics*; national data.

In the aftermath of the Asian crisis, many regional central banks intervened in foreign exchange markets, in part to rebuild foreign reserves stocks. This accumulation of reserves continued almost monotonically for many economies. With the commencement of the more recent international financial crisis, Korea and Malaysia in particular appear to have utilised their reserves to cushion the subsequent depreciation, while the rate of reserves accumulation fell close to zero for India, Indonesia, the Philippines and Singapore.

More recently, following the crisis, massive capital inflows, perhaps stimulated by the unconventional policies of the major advanced economies, have put upward pressure on Asian currencies once again. Central banks have repeatedly expressed concerns about the potential spillovers of these measures, and the implications of heightened capital flow and exchange rate volatility for economic and financial vulnerabilities.[4,5]

Across these different episodes displayed in Graph 1, if we compare the behaviour of reserves with contemporaneous exchange rate changes, foreign exchange intervention in some economies appears to be consistent with a strategy of "leaning against the wind" to smooth exchange rate fluctuations. For example, where exchange rates and foreign exchange reserves have a positive correlation, changes in the stock of reserves have likely resulted in smaller movements in the exchange rate than would have occurred without intervention measures. For other economies, there appears to be little correlation between reserves and the exchange rate, perhaps because these central banks may have targeted some level of the exchange rate instead.[6]

Looking forward, continuing pressures on exchange rates are inevitable, but they may not be as one-sided as in the recent past. For example, in response to initial reports that the Federal Reserve might begin "tapering" its purchases of US treasuries, as a first stage of exiting from extraordinary policy measures instituted during the crisis, there was a rush for the exits from Asia. Indonesia and India were the hardest hit, with exchange rate declines of as much as 20% in the following four months. Overall, however, the relatively favourable growth prospects in Asia may see capital inflows, and appreciation pressures, continuing to predominate in the region over the longer term.

2.2 Why central banks intervene

In order to assess the effectiveness of intervention, it is helpful to identify the motives of the central banks' activities in this area. A number of papers discuss these (for example, BIS (2005, 2013), Adler and Tovar (2011), Basu and Varoudakis (2013) and Neely (2008)). Broadly speaking, these motives can be grouped as follows:

- *Leaning against the wind:* According to the recent BIS survey of central banks, the most common reason cited for emerging market central banks to intervene in foreign exchange markets was to limit exchange rate volatility and smooth

[4] See, for example, Kim (2010), Subbarao (2013) and Ruengvirayudh (2013). Carstens (2013) of Mexico also makes similar arguments.

[5] The desire to insulate regional economies from these capital inflows may itself lead to risks for the region. Recent work by the BIS has focused on possible risks arising from the link between the now-large stocks of foreign exchange reserves and the balance sheet of the domestic banking system (for example, Caruana (2012), Filardo and Yetman (2012) and Cook and Yetman (2012)). These risks include the misallocation of capital, the loss of inflation control and threats to political independence due to mark-to-market losses on the central bank balance sheet. On this final risk see, also, Vaez-Zadeh (1991) and Mohanty and Turner (2006).

[6] In the case that a central bank is completely successful at stabilising the exchange rate, the correlation between the exchange rate and reserves will be zero. In our sample, Hong Kong comes closest to that outcome, as a result of maintaining a currency board system.

the trend path of the exchange rate (BIS (2013)). This is consistent with the results of the previous survey (BIS (2005)) and other studies as well. For example, Adler and Tovar (2011) find that half of the central banks in their sample intervene to dampen exchange rate volatility.[7]

- *Reducing exchange rate misalignment:* Too high an exchange rate can reduce a country's competitiveness, and too low can lead to an unsustainable growth spurt and inflation. Therefore, central banks may wish to step into the foreign exchange market if they see that the current exchange rate appears to be either overvalued or undervalued. During 2012, only 4 out of 19 central banks acknowledged intervention being used for this reason (BIS (2013)). However, it is possible that this is an understatement, for two reasons. First, central banks know that the equilibrium value of the exchange rate is inherently hard to measure and therefore even more difficult to defend. Second, for economies seeking to generate exchange rate depreciations for this reason, it may be indistinguishable from trying to generate "beggar-thy-neighbour" exchange rate depreciations, which may attract stigma.
- *Managing or accumulating FX reserves:* as we outlined above, after the Asian financial crisis, many central banks accumulated reserves. The crisis focused the spotlight on the precautionary motive for holding reserves, and their insurance value in the face of currency pressures. Some central banks officially announced that intervention would be conducted for the purpose of building reserves, for example Turkey (CBRT (2003)), South Africa (Basu and Varoudakis (2013)) and Chile and Mexico (Adler and Tovar (2011)). Adler and Tovar argue that publicly available information points to around 50% of central banks intervening in foreign exchange markets during 2004-2010 were motivated at least in part by the desire to accumulate reserves.
- *Ensuring liquidity:* Owing to shallow foreign exchange markets, some central banks may conduct intervention to ensure adequate liquidity in order to counter disorderly markets and avoid financial stress, especially during stressful episodes. The recent BIS survey shows that, during the international financial crisis, more than half of participating central banks intervened to provide liquidity in the foreign exchange market (BIS (2013)).

Later, when we develop a model of foreign exchange intervention, we will incorporate intervention rules consistent with the first two of these – leaning against the wind and reducing exchange rate misalignment.

2.3 How intervention can work

Central bank intervention in foreign exchange markets may influence exchange rates, and the wider economy, via a number of different channels, as discussed in Sarno and Taylor (2001), Canales-Kriljenko et al (2003), BIS (2005) and Adler and Tovar (2011). We can summarise these into the following three:

[7] This explanation does not just apply to emerging market economies. Kearns and Rigobon (2005) report empirical evidence that intervention in the cases of Australia and Japan is motivated by a desire to lean against the wind, for example.

- *Portfolio-balance channel:* In economies with relatively closed financial markets the substitutability between domestic and foreign assets is likely to be low. If the central bank, as a major market player, influences the supply or demand of financial assets through its own trading activities, this is likely to result in other market participants rebalancing their financial asset portfolios. This channel may be effective for some emerging market economies, especially if the size of foreign exchange interventions is large (Sarno and Taylor (2001) and BIS (2005))
- *Signalling (or expectations) channel:* This channel works through the adjustment of expectations about future central bank policy. A highly-publicised transaction in foreign exchange markets may be interpreted as setting a precedent for future interventions, or revealing information about the level of the exchange rate that is considered desirable by policymakers (Adler and Tovar (2011) and Canales-Kriljenko et al (2003)). While there is little empirical evidence to support this channel, it might be expected to be more important where the central bank has a history of transparency and is considered highly credible. Evidence against the importance of this channel includes the fact that most interventions are not publicly revealed and many central banks act as if they believe that discreet intervention in foreign exchange markets will maximize the market impact (BIS (2005)). We will take up the issue of secrecy and foreign intervention again in section 2.4.
- *Order-flow (or microstructure) channel:* This is based on the idea that the central bank has superior information to other market participants. This could come about for a variety of reasons. For example, if other market participants only know about their own transactions but need to report these to the central bank, then the central bank may be the only market participant with a complete picture of market activity. This information advantage may then be used to the central bank's advantage to shape the market (Adler and Tovar (2011) and Canales-Kriljenko et al (2003)). One constraint for this channel to be effective, however, is that the size of intervention must be sufficiently large relative to overall market turnover (BIS (2005)).

In the model that we later develop, the central bank will observe the overall effect of other transactions in the market place on the exchange rate and use this to determine their own intervention strategy, which might be viewed as being consistent with the order-flow channel. In addition, foreign exchange intervention will influence exchange rates via the signalling channel. Central bank interventions will be assumed to follow a rule that is known by other market participants, who respond rationally in determining the size and nature of their own transactions. Our model will also imply an additional dimension to the expectations channel. To the extent that central bank intervention succeeds in reducing the variance of exchange rates, then speculation by other market participants becomes relatively less risky. Thus expectations of future central bank actions might, under some circumstances, tend to lead to more destabilising speculative transactions.[8]

[8] Similarly, if central bank intervention leads to more volatile exchange rates, that will increase the risks for speculators and may therefore reduce the level of speculation, all else equal.

2.4 How central banks intervene

The means by which central banks intervene in foreign exchange markets can vary across a number of dimensions. For example, intervention can be rule-based or discretionary, and the size and frequency of transactions can differ.

Some theoretical studies support the idea that "rule-based" intervention can be effective. Krugman (1991) developed a simple stylized model showing that if central banks clearly define exchange rate bands, or target zones, then these can influence the behaviour of exchange rates such that they remain within the bands without any intervention being required by the central bank. In his model, expectations of future central bank actions are sufficient to influence exchange rates. In a similar vein, Basu (2012) and Basu and Varoudakis (2013) show that the accumulation of foreign reserves can be avoided if central banks adopt a "schedule" intervention strategy, which amounts to making a commitment to buy or sell foreign currency to curb excessive volatility if the local currency appreciates or depreciates beyond pre-specified levels. However, these arguments depend critically on the central bank enjoying a high level of credibility.

In contrast, the study of Canales-Kriljenko et al (2003) concludes that policy rules can best serve as "rules of thumb" for intervening central banks. The applicability of any specific rule to the broad range of circumstances that a central bank might face is likely to be limited. Further, discretionary intervention, and particularly maintaining the option of surprising markets, may be useful from a tactical point of view to enhance effectiveness.

Empirical studies generally question the importance of discretion. Fatum and King (2005), in an analysis of high-frequency Bank of Canada intervention and exchange rate data, find no significant evidence that discretionary intervention is more effective than the rule-based policies. And Adler and Tovar (2011) find that the rules-versus-discretion distinction is unimportant. Rather, what matters for intervention effectiveness is the degree of capital account openness and whether the exchange rate is overvalued.

As mentioned in the previous section, secret intervention operations are unlikely to have much effect to the extent that the signalling channel is important, since this depends on the market being able to identify and correctly interpret the actions of the central bank. In concert with the empirical results summarised here, then, it is somewhat puzzling that many emerging market central banks conduct intervention operations with limited disclosure. Perhaps, as Sarno and Taylor (2001) suggest, these central banks expect to influence exchange rates via other channels, such as the portfolio-balance channel. Also secrecy may help to avoid a self-fulfilling attack on an over-valued currency by instilling doubts in market participants as to the extent that the central bank is willing to defend the exchange rate. It is also possible that less credible central banks prefer secret intervention operations since the signalling channel is likely to be weak in this case anyway.

King (2003) draws some interesting conclusions on the effectiveness of different intervention strategies, and how these may vary with different central bank objectives. He suggests that secret intervention should be conducted when central banks want to reduce the volatility of the exchange rate or to resist a short-term trend. But, for maximum impact, the intervention must be large and timed "with-the-wind". In contrast, a "leaning-against-the-wind" strategy is more suitable for targeting a specific exchange rate level, or for signalling a change in policy stance.

In our analytical model, we will focus on the case where the central bank follows a monetary policy rule, but allow for some uncertainty in the rule due to the presence of an additive noise term so that we can vary the predictability of future foreign exchange intervention as a proxy for the degree of transparency. We will also consider both "leaning-against-the-wind" and responding to the degree of exchange rate misalignment as intervention strategies.

2.5 Is intervention effective?

The effectiveness of foreign exchange intervention has been heavily debated, with the existing literature coming to mixed conclusions. In general, there appears to be a gap between the opinions of central bank policymakers and the empirical results in research papers. Surveys of central banks are generally supportive of intervention effectiveness. For example, around 70% of participating central banks believe that their intervention during the 2005-2012 period was successful (BIS, 2013). Similarly, most of the central banks included in BIS (2005) view intervention as an effective tool to calm disorderly foreign exchange markets, correct exchange rate misalignments and/or stabilise exchange rates. It concluded that central bank intervention has a temporary effect on exchange rates, although it found little connection between intervention operations and fundamental determinants of exchange rates. These results are consistent with the survey results from Neely (2001, 2008) who finds that central bankers believe that intervention operations are able to influence exchange rate levels and do not cause excessive market volatility.[9]

In contrast, empirical studies of the effectiveness of foreign exchange intervention conducted outside of the central banking community are very mixed. On the positive side, Menkhoff's (2010) empirical analysis found that foreign exchange intervention can affect the level of the exchange rate in the desired direction robustly. However, he also found that intervention may increase short-run volatility, although the effects on long-run volatility are more favourable. Adler and Tovar (2011) argue that intervention is robustly effective in terms of slowing down the pace of exchange rate appreciation, especially if capital account openness is limited. In contrast, in the case of Australia, where the foreign exchange market is deep and liquid, Newman et al (2011) find that the effect on the exchange rate is short-lived.[10] Other studies where intervention appears to have little effect include Guimarães and Karacadağ (2004), who focus on Mexico and Turkey, and Brissimis and Chionis (2004) for the euro area.

In our analysis, we will try to address this disagreement. Our model will allow us to consider a number of different characteristics of the economy and the strategy for foreign exchange intervention that we can vary to shed light on what factors may be important in determining the effectiveness of intervention.

[9] For country-level studies coming to similar conclusions, see, for example, García-Verdú and Zerecero (2013) for Mexico, Echavarría et al (2013) for Columbia and Kohlscheen (2013) for Brazil.

[10] In light of these results, showing that capital account openness reduced intervention effectiveness in Australia, it is perhaps surprising that Brissimis and Chionis (2004) find that intervention by the Bank of Japan succeeded in weakening the yen, although it also appeared to increase conditional volatility (rather than calm markets).

3. Modelling exchange rates

To analyse the effectiveness of exchange rate intervention, we first require a model of exchange rate behaviour. Some existing models have been used to explain the behaviour of exchange rates by focusing on the interactions between different kinds of agents. De Grauwe and Grimaldi (2006) develop a heterogeneous agents' model with two types of players: fundamentalists and chartists (or technical analysts). In their model, investors evaluate the relative profitability *ex post* of either type of investment and then switch to the strategy which yields higher risk-adjusted profit. Their model is successful in generating exchange rate behaviour that is disconnected from fundamentals and replicating other empirical puzzles.[11] In Beine et al (2009), this model is further developed to empirically assess the impact of central bank intervention. They find that central bank intervention can help reduce exchange rate volatility in the medium run by increasing the proportion of fundamentalists in the market. Spronk et al (2013) generalise De Grauwe and Grimaldi (2006) in a different direction by introducing carry traders, in addition to fundamentalists and chartists. They argue that interactions between these three different types of agents can explain the forward premium puzzle and other stylised characteristics of exchange rate behaviour.

The role of carry traders in Spronk et al (2013) is similar to that of rational speculators. The importance of speculators in foreign exchange markets has been widely discussed in academic studies. Some authors have suggested that speculators serve to increase volatility, while others suggest that speculators are a stabilising force for the exchange rate. In this latter category, Friedman (1953) famously argued that rational speculators must be a force for stabilisation, buying low and selling high, or they will be driven from the market on account of financial loses. However, Carlson and Osler (2000) show that this conclusion is not as self-evident as it appears. If speculators' returns depend on the behaviour of other variables in addition to the exchange rate – for example, if they were to follow a carry trade strategy so that investment returns depend on the expected behaviour of both exchange rates and interest rates – then it is quite possible for rational speculation to be destabilising for exchange rates.[12]

In our model we build on this literature. We allow for three types of agents: real activity traders, speculators and the central bank. We start with the structure of Carlson and Osler (2000), and then add a role for central bank intervention so that we can assess the effect of intervention on other market participants as well as exchange rate behaviour.

[11] See, also, Frankel and Froot (1990) who argue that an increase in the share of chartists in foreign exchange markets, in place of fundamentalists, can explain US dollar behavior in the mid-1980s.

[12] DeLong et al (1990) provide another rationale for rational speculators to be destabilising, which depends on their interaction with chartists. If rational speculators know that buying in response to good news today will lead chartists to buy tomorrow, then they will be incentivised to bid prices up further today than is warranted by the good news in order to benefit from the increased order-flow from chartists tomorrow.

4. Model

Consider a model with three kinds of agents: current account traders (or fundamentalists), rational speculators (or carry traders) and the central bank.

For current account traders, their net demand for foreign currency is given by:

$$CA_t = \varepsilon_t - Se_t, \tag{1}$$

where CA is the current account, ε is a random shock term and e is the exchange rate, defined as the number of units of domestic currency per unit of foreign currency, so that an increase is a domestic currency depreciation and would be expected to lower the foreign current account. S here is a parameter that reflects how sensitive the current account is to exchange rate changes. We will allow for persistent shocks, such that $\varepsilon_t = \rho_\varepsilon \varepsilon_{t-1} + \eta_t$.

In a world in which only fundamentalists traded the currency, we would expect the exchange rate to adjust to its fundamental value, which we model as the value consistent with a current account balance of zero:

$$e_t = \frac{\varepsilon_t}{S}. \tag{2}$$

But the presence of speculators may drive the currency away from its fundamental value, thus creating a potential role for central bank intervention to reduce exchange rate misalignment.

Suppose that there are N speculators, each of whom takes positive or negative positions in foreign money markets which realise a profit per unit of:

$$\pi_{t+1} = [e_{t+1} - e_t + \delta_t], \tag{3}$$

where δ is the differential between the foreign and home money market interest rates. (Implicitly, we are assuming that the home interest rate is the opportunity cost to a speculator who invests abroad, or equivalently that speculators are engaged in carry trade.) We will allow the interest rate differential to follow a persistent process, such that $\delta_t = \rho_\delta \delta_{t-1} + \xi_t$. Suppose speculators have a utility function given by:

$$U_{t+1} = -\exp(-\theta b_t \pi_{t+1}), \tag{4}$$

where b represents the size of the position that they take and θ is the absolute risk aversion of the speculators. Following Carlson and Osler (2000), if profits are distributed conditionally normally, speculators will act as if they are maximising:

$$W_t = b_t E_t(\pi_{t+1}) - \frac{\theta}{2} b_t^2 V_t(\pi_{t+1}), \tag{5}$$

where $V_t(\pi_{t+1})$ is the variance of speculator profits in period $t+1$ relative to period t expectations. Taking the first order condition with respect to b_t yields:

$$b_t = \frac{1}{\theta V_t(\pi_{t+1})}[E_t(e_{t+1}) - e_t + \delta_t]. \tag{6}$$

Now, given N such speculators, and with constant variance, $V_t(\pi_{t+1}) = \overline{V}$ (as we will later verify), the aggregate demand for currency from rational speculators in period t will be given by:

$$B_t = \alpha[E_t(e_{t+1}) - e_t + \delta_t], \tag{7}$$

where $\alpha = N/(\theta\overline{V})$. Note that in each period, speculators will be both taking out new positions – defined by (7) – and also receiving payment on positions taken out in the previous period. Their net demand will be given by $B_t - B_{t-1}$.

Finally, central banks are assumed to intervene in foreign exchange markets by changing the size of their shock of foreign exchange reserves. We consider two possible intervention rules:

$$\Delta FR_t = \phi(e_{t-1} - e_t), \tag{8}$$

and:

$$\Delta FR_t = \phi(e_{t-1} - e_t)\Delta FR_t = \varphi\left(\frac{\varepsilon_t}{S} - e_t\right), \tag{9}$$

where ΔFR_t is the change in foreign exchange reserves. The first rule represents leaning against the wind: increasing (decreasing) foreign exchange reserves when the domestic currency appreciates (depreciates). The second rule reflects intervening to try to drive exchange rates towards fundamental levels: if a currency depreciation would help to close the current account, then the central bank increases foreign exchange reserves to weaken the currency. We allow the parameters $\phi > 0$ and $\varphi > 0$, determining the strength of the central bank response, to vary in our analyses.

Note that we are assuming here that foreign exchange intervention has no effect on our model other than those working through its effect on the exchange rate. This is consistent with assuming that intervention is fully sterilised. Empirical estimates in Cavoli and Rajan (2006), Aizenman and Glick (2009) and Ouyang and Rajan (2011) indicate that sterilisation is close to complete for many Asian economies.[13]

Combining these elements together, we can solve for the equilibrium exchange rate as the solution for e_t that solves:

$$CA_t + \Delta B_t + \Delta FR_t = 0. \tag{10}$$

In general, this takes the form:

$$e_t = a_1\varepsilon_t + a_2\varepsilon_{t-1} + a_3\delta_t + a_4\delta_{t-1} + a_5 e_{t-1}, \tag{11}$$

with the exact form of the coefficients depending on all the parameters of the model. For example, if the central bank follows intervention rule (9) above, then:

[13] See, also, the discussion in Filardo and Yetman (2012). Full sterilisation also implies that the cost to the central bank of intervention is the sum of the interest rate differential and exchange rate change multiplied by the size of their foreign exchange position, a fact that we will later utilise in comparing the cost to the central bank of different intervention strategies.

$$
\begin{aligned}
a_1 &= \frac{(S+\varphi)(2\alpha+\varphi+S-\alpha a_5)}{[S(2\alpha+\varphi+S-\alpha a_5)(\alpha+\varphi+S-\alpha a_5-\alpha\rho_\varepsilon)+S\alpha^2\rho_\varepsilon]},\\
a_2 &= \frac{-\alpha\rho_\varepsilon(S+\varphi)}{[S(2\alpha+\varphi+S-\alpha a_5)(\alpha+\varphi+S-\alpha a_5-\alpha\rho_\varepsilon)+S\alpha^2\rho_\varepsilon]},\\
a_3 &= \frac{\alpha(2\alpha+\varphi+S-\alpha a_5)-\alpha^2}{[(2\alpha+\varphi+S-\alpha a_5)(\alpha+\varphi+S-\alpha a_5-\alpha\rho_\delta)+\alpha^2\rho_\delta]},\\
a_4 &= \frac{-\alpha(\alpha+\varphi+S-\alpha a_5)}{[(2\alpha+\varphi+S-\alpha a_5)(\alpha+\varphi+S-\alpha a_5-\alpha\rho_\delta)+\alpha^2\rho_\delta]},\\
a_5 &= \frac{(2\alpha+\varphi+S)-\sqrt{(2\alpha+\varphi+S)^2-4\alpha^2}}{2\alpha},
\end{aligned}
\tag{12}
$$

where $|a_5|$, $|\rho_\varepsilon|$ and $|\rho_\delta|<1$ and $\alpha>0$.[14] Note that, given this form,

$$
\begin{aligned}
V_t(\pi_{t+1}) &= a_1^2 V_t(\varepsilon_{t+1}) + a_3^2 V_t(\delta_{t+1})\\
&= a_1^2\sigma_\eta^2 + a_3^2\sigma_\xi^2\\
&= \bar{V},
\end{aligned}
\tag{13}
$$

which is time-invariant.

Another dimension of intervention that we explore is the cost of sterilised intervention. Many central banks in emerging market economies have seen a steady accumulation of reserves as a result of foreign exchange intervention, and the carrying costs and exchange rate risks of these can be considerable: see, for example, the discussion in Cook and Yetman (2012). Additionally, as Cassino and Lewis (2012) argue, unprofitable intervention may damage a central bank's credibility in financial markets or attract undesirable political scrutiny.

To capture the costs of sterilisation, we compute the unconditional expected costs from holding foreign exchange reserves, starting from a steady state where, at time zero, foreign exchange reserves are zero. This is given by:

$$
C_t = E[-FR_t(e_{t+1}-e_t+\delta_t)]. \tag{14}
$$

This sterilisation cost is the product of the stock of foreign exchange reserves (with a negative sign, given how variables are defined in our model) and the sum of the exchange rate appreciation and the interest rate differential. The final component reflects the fact that we are assuming that foreign exchange intervention is sterilised, so that there may be a carry cost associated with running a foreign exchange reserves balance. For leaning against the wind, this cost takes the form:

$$
C_t = \phi\big(\mathrm{Cov}(e_t, e_{t+1}) - \mathrm{V}(e_t) + \mathrm{Cov}(e_t, \delta_t)\big), \tag{15}
$$

and for leaning against exchange rate misalignment:

$$
C_t = -\varphi\left(\mathrm{V}(e_t) - \frac{1}{S}\mathrm{Cov}(e_t, \varepsilon_t) - \frac{\mathrm{Cov}(e_t, \delta_t)}{1-\rho_\delta}\right). \tag{16}
$$

[14] A full mathematical appendix, outlining all the results used in this paper, is available on request from the authors.

When evaluating the effectiveness of intervention policies, we assume that policymakers are likely to focus on five variables:

- The variability of the change in foreign exchange reserves, which is a measure of how heavily the central bank intervenes in markets, $\mathrm{V}(\Delta FR)$. Intervening more heavily, all else equal, is likely to be undesirable from the point of view of the central bank.
- The expected cost of intervention, which is the product of the stock of reserves and the sum of the exchange rate change and the interest rate differential, δ, under the assumption that intervention is fully sterilised.
- The variability of deviations in the exchange rate relative to its fundamental value, which is isomorphic to the variability of the current account, $\mathrm{V}(CA)$.
- The variability of the exchange rate, $\mathrm{V}(e)$.
- The degree to which speculators are attracted to the market, measured by $\mathrm{V}(B)$. Higher levels of speculative activity are undesirable, all else equal.

Each of these variables can each be derived as functions of the parameters of the model, along with $a_1, \ldots, a_5$.[15]

5. Results

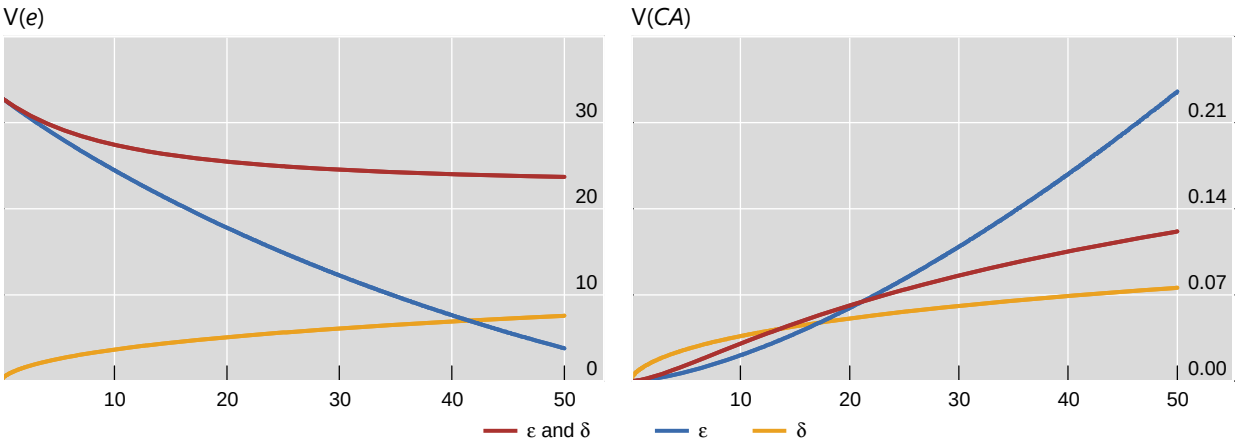
We now report results of the model based on simulations in which we vary some of the parameters in order to assess the effectiveness and desirability of foreign exchange intervention. We calibrate the key parameters as $S = 0.1$ (controlling the sensitivity of the current account to the exchange rate), $\rho_\varepsilon = \rho_\delta = 0.9$ (shocks are highly persistent) and $\theta = 1.0$ (representing the risk aversion of speculators). Given the highly stylised nature of our model, it is perhaps not surprising that the results are qualitatively robust to alternative parameterisations.

The first issue we address is whether speculators are stabilising or destabilising. Graph 2 presents evidence for this for the case where there is no central bank intervention. We examine three sets of shocks: 1) shocks to both the fundamental value of the exchange rate and the interest rate differential (ε and δ); 2) shocks only to the fundamental value of the exchange rate (ε); and 3) shocks only to the interest rate differential (δ). The horizontal axis gives the number of speculators in the market, and provides a simple way of incorporating increased speculation in the context of our model.

[15] See Appendix 1 for details of the variances that result from policy rules (8) and (9) above.

Effect of speculation on variance

No central bank intervention — Graph 2



Horizontal axis: *N* (number of speculators)

Source: Authors' calculations

The left-hand panel illustrates the arguments of Friedman (1953) and the challenge to those results in Carlson and Osler (2000). If there are only shocks to the fundamental value of the exchange rate (labelled ε), then an increase in the number of rational speculators will make the exchange rate more stable, in the sense of lowering its variance. Rational speculation in this case amounts to taking a long position in the currency when it is expected to appreciate, and taking a short position when it is expected to depreciate. This is akin to buying low and selling high, and evens out the behaviour of the exchange rate over time.

But, once we add another source of returns to speculators to the model – in addition to the exchange rate change – the stabilising role of speculation diminishes (labelled ε and δ). And if speculators' returns are solely based on shocks other than the exchange rate (labelled δ), then speculation induces increased volatility in the exchange rate.

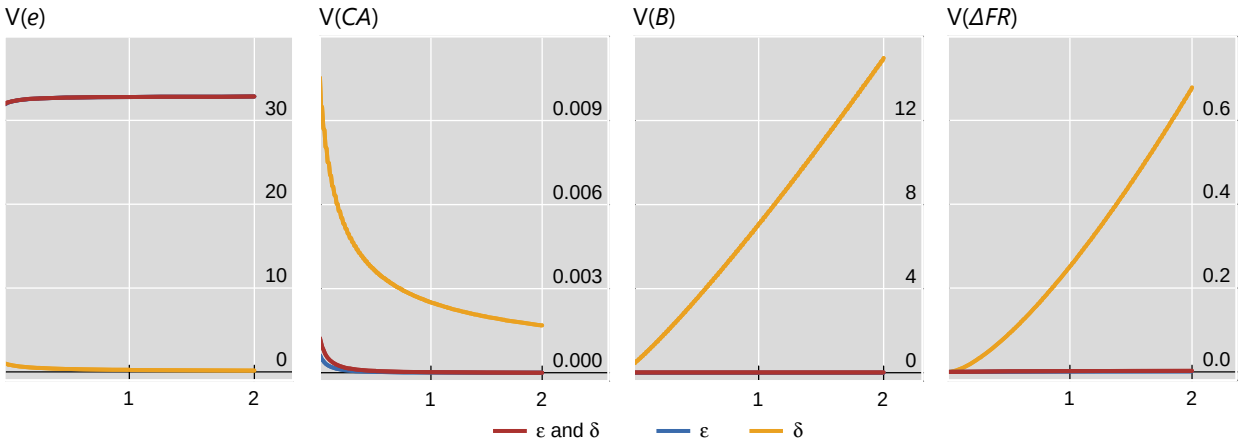
However, this may actually overstate the stabilising effects of speculators. Perhaps what policymakers care about is not the volatility of the exchange rate *per se*, but rather its volatility relative to the fundamental value of the currency. In our case, this fundamental value is given by the level of the exchange rate that would eliminate the current account deficit, and is isomorphic to the current account balance itself.

The right-hand panel considers the effect of speculation on exchange rate misalignment and shows that more speculators are always destabilising by this metric. The intuition behind this result comes in two parts. First, because fundamental shocks in our model are persistent, when a shock hits the economy, speculators are able to forecast the likely future movement of the exchange rate and trade upon this knowledge. This has the effect of moving the exchange rate away from its fundamental value. Second, the actions of speculators tend to smooth the path of the exchange rate over time. If the exchange rate starts off away from its fundamental value, then the behaviour of speculators will slow the path of the exchange rate towards it.

We next consider the effect of intervention policy intended to reduce the misalignment of the exchange rate from its fundamental value, using the intervention rule given by equation (9). The effect of this rule on the different variances of interest, as we increase the strength of the central bank response (φ), is displayed in Graph 3.

Effect of leaning against exchange rate misalignment on variance

N = 1 Graph 3



Horizontal axis: φ (strength of intervention against exchange rate misalignment)

Source: Authors' calculations

Focusing on the second panel, we can see that this policy rule is generally successful, in the sense that exchange rate deviations from their fundamental value decline as the strength of the intervention response increases. And in both cases where there are shocks to the fundamental value of the exchange rate, with or without shocks to the interest rate, the variance of the exchange rate is little changed by the intervention (far-left panel). In both of these cases, there is little change in the level of speculation as a result of foreign exchange intervention (third panel), and foreign exchange reserves tend to be relatively stable (far-right panel). This is a wonderful environment for policymakers: they achieve their policy goals without having to intervene heavily.

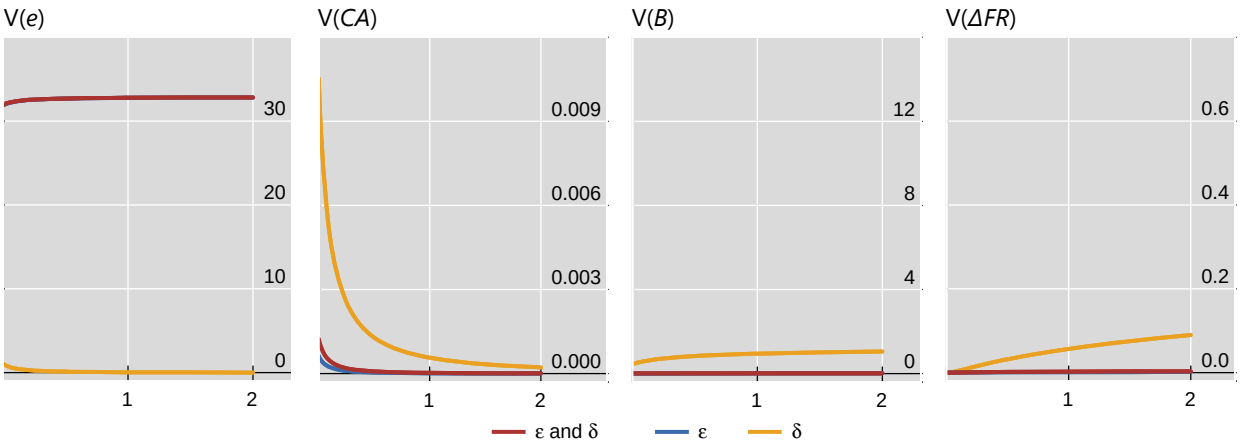
For the case of only interest rate shocks, however, intervention is less effective. On the surface it appears to be successful: the misalignment of the exchange rate declines, and further the more strongly the central bank intervenes. But this comes at a price. The intervention also reduces the volatility of the exchange rate, which reduces the risk to speculators who are taking a position in currency markets, so speculation is increasing in the size of central bank intervention. There is a feedback-loop here: intervention reduces the volatility of the exchange rate, which encourages more speculation, which drives the exchange rate further from its fundamental value, which increases the size of the central bank intervention, and so on. The end result is that foreign exchange reserves are very volatile, as shown in the far-right panel.

We can illustrate the size of this feedback loop – intervention lowering the variance of the exchange rate, encouraging speculation that requires further intervention – in the following way. We repeat the same exercise as above, but impose that the volatility of the expected future profit, given by equation (13), does

not change as we move from left to right in the panels. The results are given in Graph 4, with the vertical scale the same as in Graph 3 to ease comparison. Here intervening still induces an increase in speculation, but to nothing like the degree of the case displayed in Graph 3 above.

Effect of leaning against exchange rate misalignment on variance

$N = 1$; $V_t(\pi_{t+1})$ constant — Graph 4



Horizontal axis: φ (strength of intervention against exchange rate misalignment)

Source: Authors' calculations

The key point that we have illustrated here is that foreign exchange intervention that is intended to reduce the volatility of the exchange rate has a negative side-effect. To the extent that it succeeds, it also reduces the volatility faced by speculators and therefore improves their risk-return trade-off, encouraging them to take larger speculative positions, which tend to be destabilising.

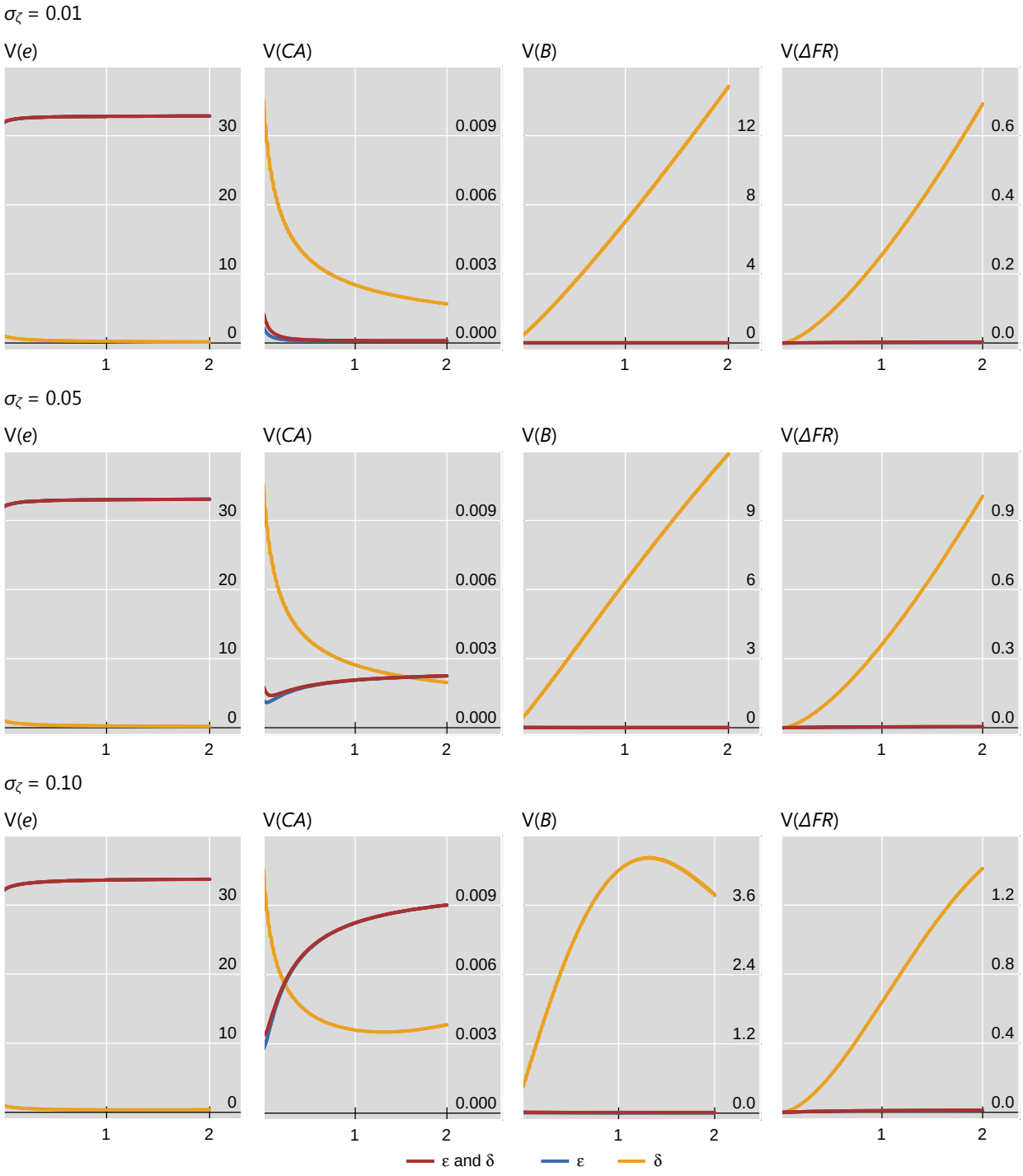
In addition to concerns about the composition of shocks to that might motivate speculation, there are other reasons to believe that intervention may be destabilising. Our results above assume that the central bank and speculators know what the fundamental value of the exchange rate is. More plausibly, the central bank may know the direction that the fundamental value of the exchange rate has changed in response to a shock, but is unlikely to know the magnitude of the change with any degree of precision. Then the best that the central bank (and speculators) can do is estimate the fundamental value of the exchange rate. We now assume that they do so, and base their decisions on an unbiased, but imperfect, estimate.[16]

The results, for three different levels of the standard deviation of the measurement error, σ_ζ, are given in Graph 5. They show that, particularly in the case where there are shocks to the fundamental value of the exchange rate, intervention can be destabilising. As the size of the measurement errors rises, the central bank is increasingly likely to be driving the exchange rate away from, rather than towards, it's fundamental value.

[16] See Appendix 2 for details.

Effect of leaning against exchange rate misalignment when fundamental value is measured with error

N = 1 Graph 5



Horizontal axis: φ (strength of intervention against exchange rate misalignment)

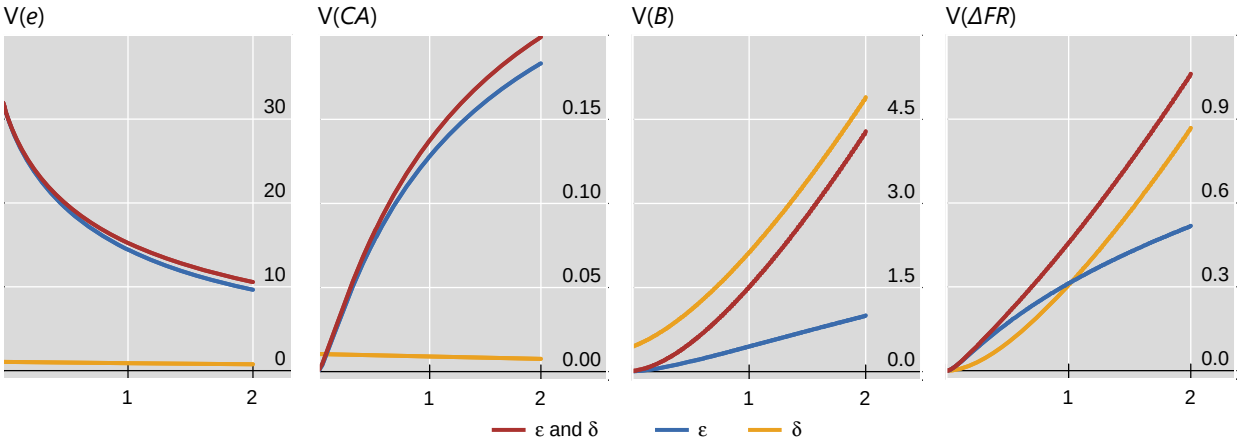
Source: Authors' calculations

In cases where measurement issues are particularly challenging, then, perhaps one solution would be to use an intervention rule that does not require an estimate of the fundamental value of the exchange rate, such as equation (8), which entails leaning against the wind, or seeking to slow the rate of change of the exchange rate in whichever direction it happens to be moving.

The results from following such a rule are given in Graph 6 below, for increasing strength of policy response (ϕ) as we move from left to right, and they indicate that such a rule is generally destabilising, for two reasons. First, it reduces the volatility of the exchange rate which encourages speculators to take larger positions. Second, it also tends to smooth the path of the exchange rate over time. Thus, when the exchange rate is hit by a shock, leaning against the wind effectively works against market forces that would tend to drive the exchange rate back towards its equilibrium value. Further, it results in highly volatile foreign exchange reserves.

Effect of leaning against the wind (responding to exchange rate change)

N = 1 Graph 6



Horizontal axis: ϕ (strength of intervention against change in the exchange rate)

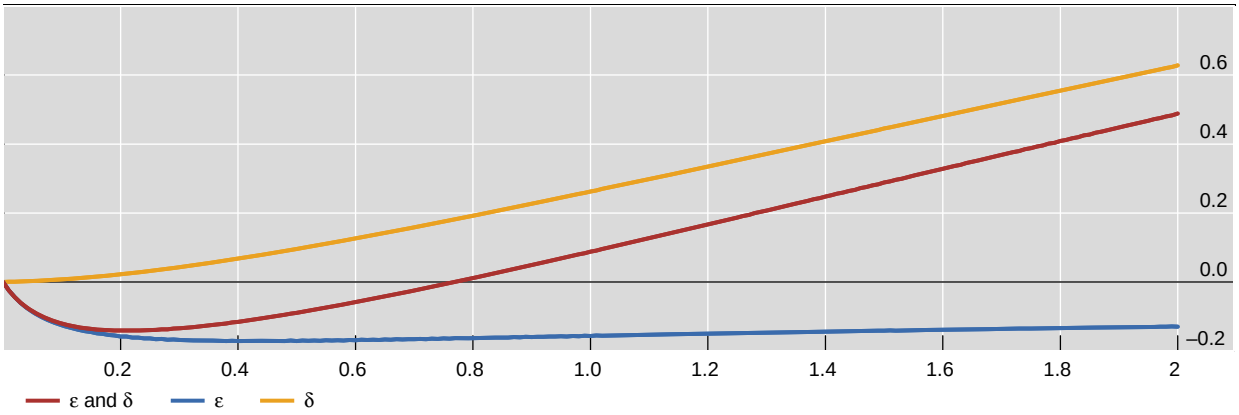
Source: Authors' calculations

All of the results presented above are for the case of a single speculator, $N = 1$. As a robustness check, we also considered different numbers of speculators (or, equivalently, different degrees of risk aversion on the part of speculators). In general, the results are very similar to those reported above. The only exception to this is when we consider the case where the fundamental exchange rate is measured with error (equivalent to the results presented in Graph 5; see Graph A1 in the Appendix). Then, even for $\sigma_\zeta = 0.10$, at least over some range, a stronger central bank response reduces the degree of exchange rate misalignment. But, as in Graph 5, as long as the fundamental value of the exchange rate is subject to shocks, beyond some point, a stronger policy response is destabilising for the exchange rate – in contrast to the monotonic relationship when there is no measurement uncertainty (as was displayed in Graph 3, for example).

One element that we have ignored in the analysis thus far is that carrying reserves can be costly to the central bank. Graphs 7 and 8 display these costs, across the different types of shocks that we consider. Note that the expected cost of

Effect of leaning against the wind on expected cost of holding reserves

N = 1 Graph 7



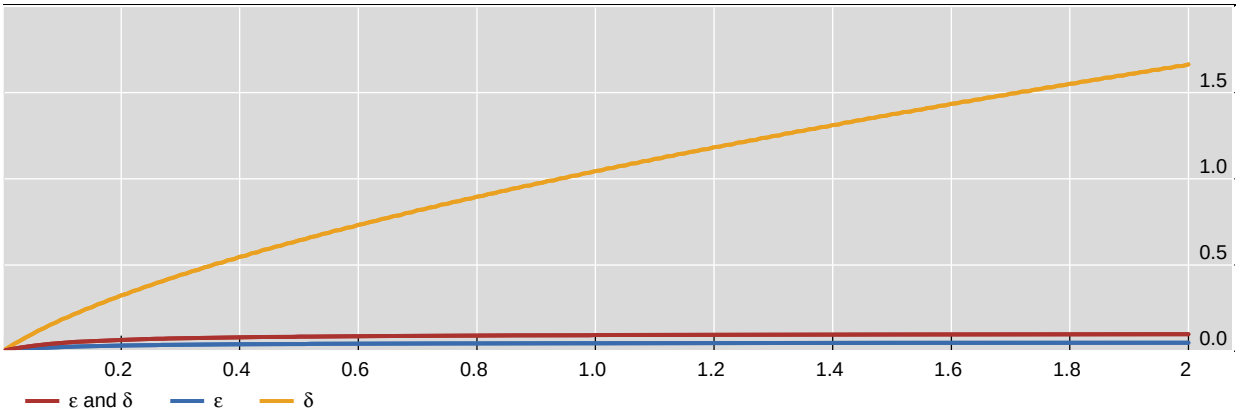
Horizontal axis: ϕ (strength of intervention against change in the exchange rate)

Source: Authors' calculations.

reserves holdings depends critically on the intervention strategy and the nature of shocks that the economy is subject to. Focusing on Graph 7, because exchange rate shocks are temporary, so that the exchange rate displays some degree of mean-reversion, a small amount of leaning against the wind generates a profit for the central bank. But, beyond a certain level, this turns into a cost if interest rate shocks drive the exchange rate process. In contrast, responding to deviations from the fundamental value of the exchange rate (Graph 8) is never profitable in expectation, and especially costly when interest rate shocks predominate.

Effect of leaning against exchange rate misalignment on expected cost of holding reserves

N = 1 Graph 8



Horizontal axis: φ (strength of intervention against exchange rate misalignment)

Source: Authors' calculations.

One key factor behind these results is that a negative interest rate differential attracts speculative inflows and causes the exchange rate to appreciate. In response, regardless of which of the two strategies it is following, the central bank will be induced to intervene to stave off the appreciation of the currency. Thus the rate of accumulation of foreign exchange reserves will be larger the more negative is the interest rate differential. But, given that the (negative of the) interest rate differential is also the carry costs per unit of foreign exchange reserves, there will be a positive correlation between the strength of the central bank's intervention and the costs to the central bank.

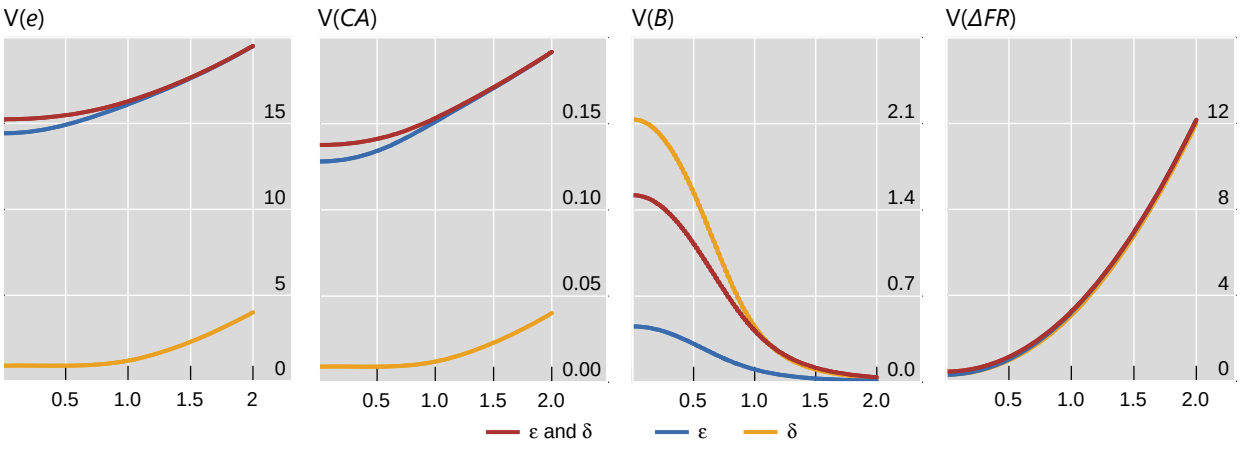
One final issue that we use our model to address is the effect of central bank transparency. Many interventions are conducted in a relatively secretive manner, perhaps to enhance the surprise effect on markets and to avoid a self-fulfilling speculative attack on the currency. We wish to see if our model can provide any insights into this practice.

We introduce an opaqueness factor, ψ_t, which is an i.i.d. shock that we add to the central bank's intervention rule (either (8) or (9) above).[17] This has the effect of ensuring that future interventions of the central bank are not fully informed by current observables and future shocks, which is our proxy for incomplete transparency.

Qualitatively, adding a given level of noise to the central bank's intervention reaction function has little effect on the variances we had earlier presented (for examples analogous to Graphs 3 and 6, see Graphs A2 and A3 in the Appendix). There are some quantitative differences, however: the noise does tend to increase the volatility of reserves, for example.

Effect of increasing opaqueness of intervention on variances; Leaning against the wind

$N = 1 / \phi = 1$ Graph 9



Horizontal axis: σ_ψ (degree of opaqueness of the intervention)

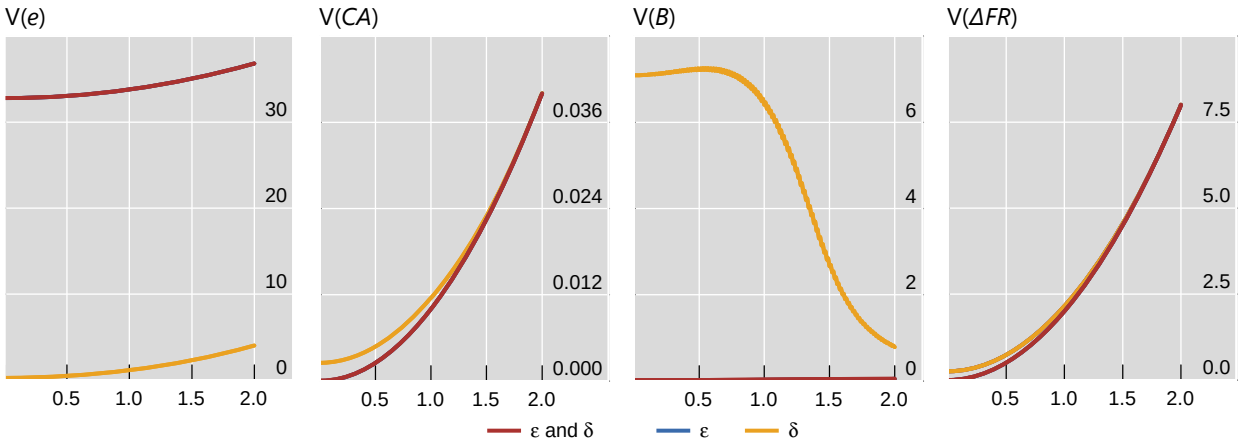
Source: Authors' calculations.

[17] Please see Appendix 3 for details.

We can demonstrate greater effectiveness of opaqueness across some dimensions when we fix the strength of the central bank response coefficient, and vary the degree of noise, σ_ψ, as presented in Graphs 9 and 10. The overall message here is that greater opaqueness can help to reduce speculation, since speculators are dissuaded by the higher risks that result from policy uncertainty. However, this is a double edged sword: a less predictable intervention policy implies that exchange rate, current account and foreign reserves volatility all increase. This is generally true whether policy is used to lean against exchange rate misalignment or lean against the wind. But there is a silver lining to this dark cloud. Because opaque intervention reduces the size of speculative flows, it also reduces the costs to the central bank of holding foreign exchange reserves, as displayed in Graphs 11 and 12 below.

Effect of increasing opaqueness of intervention on variances; Leaning against exchange rate misalignment

$N = 1 / \varphi = 1$ Graph 10

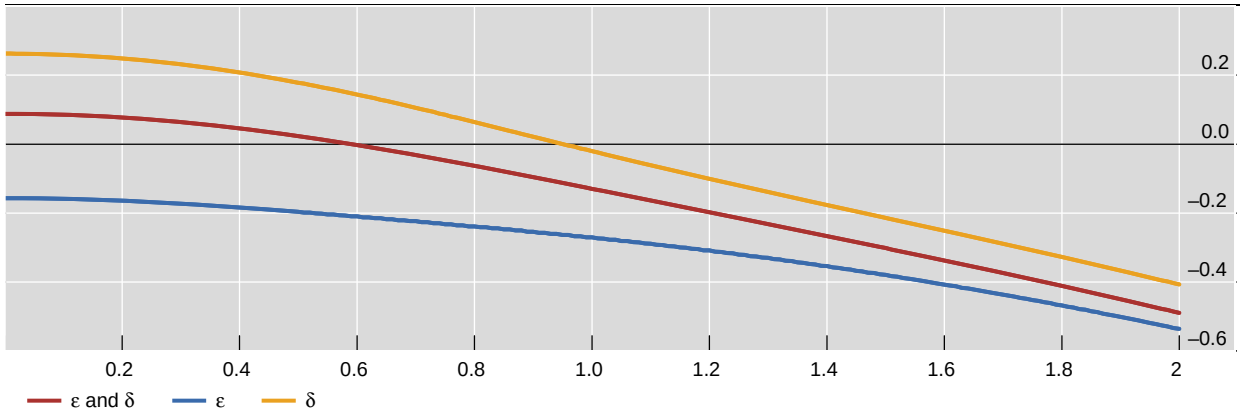


Horizontal axis: σ_ψ (degree of opaqueness of the intervention)

Source: Authors' calculations.

Effect of increasing opaqueness of intervention on cost of holding reserves; Leaning against the wind

$N = 1 / \phi = 1$ Graph 11

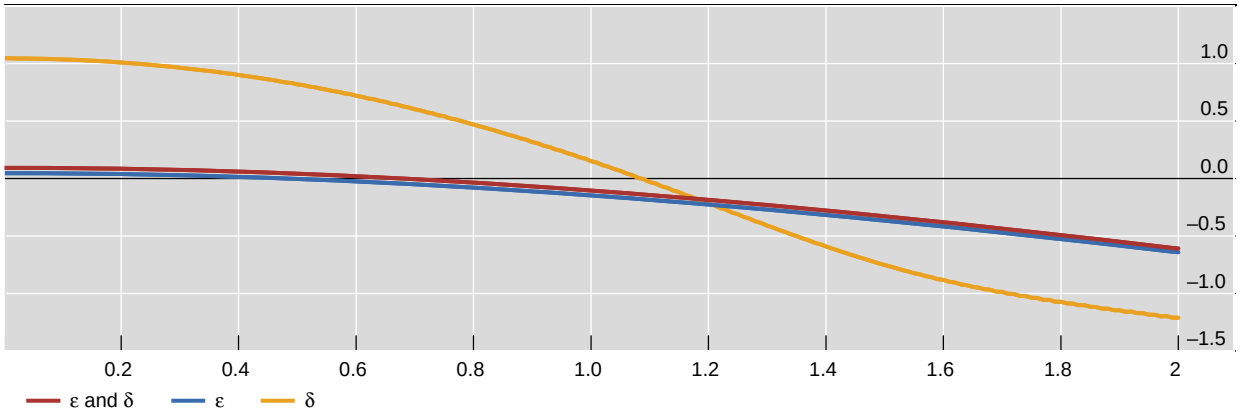


Horizontal axis: σ_ψ (degree of opaqueness of the intervention)

Source: Authors' calculations.

Effect of increasing opaqueness of intervention on cost of holding reserves; Leaning against exchange rate misalignment

$N = 1 / \varphi = 1$ Graph 12



Horizontal axis: σ_ψ (degree of opaqueness of the intervention)

Source: Authors' calculations.

We summarise our results in table 1, where a ✓ indicates favourable performance, an × indicates unfavourable performance, and • indicates little effect. Note that the "transparent" column indicates the effectiveness of the intervention strategy relative to no intervention at all, while the "opaque" column is relative to the "transparent" column, and provides an answer to the question of whether adding opaqueness causes the performance of the various metrics to improve or get worse. The key point illustrated in the table is that no one strategy dominates across the five criteria that we examine, or across the three sets of shock combinations that we consider.

6. Conclusions

Foreign exchange intervention has been actively used as a policy tool in many economies in Asia and elsewhere. In this paper, we have discussed why and how central banks intervene in foreign exchange markets, and outlined a simple analytical framework that can be used to assess the effectiveness of different intervention strategies. We have examined two different foreign exchange intervention rules: leaning against exchange rate misalignment, which requires an estimate of the equilibrium value of the exchange rate, and leaning against the wind, which does not. We have also assessed the degree to which transparency may be a help or a hindrance in achieving policy objectives.

In our model we have assumed that the fundamental value of the exchange rate is the value at which the current account is equal to zero. However, active trading by risk-averse, rational, speculators may push the exchange rate persistently away from this value, especially if their returns are influenced by variables that do not co-move with the exchange rate. For example, if speculators engage in the carry trade, their returns depend on the behaviour of both the exchange rate and interest rates.

Comparing the performance of intervention strategies

Table 1

	ε and δ	Strategies			
		Leaning against the wind		Leaning against exchange rate misalignment	
		Transparent	Opaque	Transparent	Opaque
Objectives	Stabilise exchange rate	✓	×	×	×
	Reduce current account imbalance	×	×	✓	×
	Reduce speculation	×	✓	•	•
	Reduce reserves volatility	×	×	•	×
	Minimise costs	×	✓	•	✓

	ε	Strategies			
		Leaning against the wind		Leaning against exchange rate misalignment	
		Transparent	Opaque	Transparent	Opaque
Objectives	Stabilise exchange rate	✓	×	×	×
	Reduce current account imbalance	×	×	✓	×
	Reduce speculation	×	✓	•	•
	Reduce reserves volatility	×	×	•	×
	Minimise costs	✓	✓	•	✓

	δ	Strategies			
		Leaning against the wind		Leaning against exchange rate misalignment	
		Transparent	Opaque	Transparent	Opaque
Objectives	Stabilise exchange rate	✓	×	✓	×
	Reduce current account imbalance	✓	×	✓	×
	Reduce speculation	×	✓	×	✓
	Reduce reserves volatility	×	×	×	×
	Minimise costs	×	✓	×	✓

Into this mix, we add rule-based intervention by the central bank. We have assumed that foreign exchange interventions are sterilised so that central banks are exposed to exchange rate risk and carry costs when they intervene. We then assess the effectiveness of different intervention rules across five criteria: stabilising the exchange rate, reducing current account imbalances, discouraging speculation, minimising reserves volatility and limiting intervention costs.

Our results may be summarised as follows. First, the actions of speculators can, under some circumstances, reduce the volatility of exchange rates but, even then, they tend to increase exchange rate misalignment. Second, intervention that reduces exchange rate volatility also reduces the risks of speculation, creating a feedback loop and potentially leading to high levels of speculation. Third, uncertainty about the fundamental value of the exchange rate results in foreign exchange intervention being less efficient; beyond some level of uncertainty,

intervention is destabilising. Fourth, leaning against the wind, which avoids the problem of having to estimate the fundamental value of the exchange rate, is no panacea. It reduces the volatility of the exchange rate but tends to increase exchange rate misalignment. Fifth, the costs of foreign exchange intervention will be especially large when exchange rate movements are driven by interest rate shocks since these drive a positive correlation between the stock of reserves and the carrying costs of those reserves. And sixth, relative to transparent intervention, adding an element of opaqueness offers both costs and benefits. It tends to increase the volatility of exchange rates, current account balances and reserves, but reduce the size of speculative flows and the costs of carrying reserves.

BIS (2005, 2013), discussed earlier, outlines the strategies taken by central banks when they intervene in foreign exchange markets. One conclusion from those studies is that central banks employ a range of different approaches. Our results suggest that this should not be surprising. Across the five criteria we consider, no one approach dominates in our model. For a central bank seeking to stabilise exchange rates, leaning against the wind transparently may be optimal. To reduce exchange rate misalignment relative to some known target, a transparent policy targeting that value may be most effective. But either of these strategies may encourage speculation, although some degree of opaqueness may help to limit this and also reduce the expected costs of carrying foreign exchange reserves on the central bank balance sheet. Further, the more strongly the central bank intervenes the more volatile their reserves are likely to become, implying a natural limit on how strongly a central bank would want to act to stabilise exchange rates.

It is likely that the relative importance of the five criteria that we examine will vary from time to time, and from economy to economy. Our results suggest that intervention strategies might be expected to change correspondingly.

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Appendix 1

The variances and cost of holding reserves to central bank used to construct the graphs are given as follows:

- Variance of current account trader:

$$\mathrm{V}(CA_t) = \mathrm{V}(\varepsilon_t) + S^2\mathrm{V}(e_t) - 2S\mathrm{Cov}(e_t, \varepsilon_t).$$

- Variance of speculative bets:

$$\mathrm{V}(B_t) = \alpha^2 \begin{bmatrix} (a_5-1)^2\mathrm{V}(e_t) + (a_1\rho_\varepsilon + a_2)^2\mathrm{V}(\varepsilon_t) + (a_3\rho_\delta + a_4 + 1)^2\mathrm{V}(\delta_t) \\ +2(a_5-1)(a_1\rho_\varepsilon + a_2)\mathrm{Cov}(e_t, \varepsilon_t) + 2(a_5-1)(a_3\rho_\delta + a_4 + 1)\mathrm{Cov}(e_t, \delta_t) \end{bmatrix}.$$

- Variance of the exchange rate:

$$\mathrm{V}(e_t) = \left[\frac{a_1^2}{1-\rho_\varepsilon^2} + \frac{(a_2 + a_1a_5)^2(1+\rho_\varepsilon a_5)}{(1-\rho_\varepsilon^2)(1-a_5^2)(1-\rho_\varepsilon a_5)} + \frac{2a_1(a_2 + a_1a_5)\rho_\varepsilon}{(1-\rho_\varepsilon^2)(1-\rho_\varepsilon a_5)}\right]\sigma_\eta^2$$
$$+\left[\frac{a_3^2}{1-\rho_\delta^2} + \frac{(a_4 + a_3a_5)^2(1+\rho_\delta a_5)}{(1-\rho_\delta^2)(1-a_5^2)(1-\rho_\delta a_5)} + \frac{2a_3(a_4 + a_3a_5)\rho_\delta}{(1-\rho_\delta^2)(1-\rho_\delta a_5)}\right]\sigma_\xi^2.$$

- Variance of change in foreign exchange reserves in case that central bank:
  - Leans against exchange rate misalignment:

$$\mathrm{V}(\Delta FR_t) = \varphi^2\left(\frac{\mathrm{V}(\varepsilon_t)}{S^2} + \mathrm{V}(e_t) - \frac{2}{S}\mathrm{Cov}(e_t, \varepsilon_t)\right).$$

  - Leans against the wind:

$$\mathrm{V}(\Delta FR_t) = \phi^2\left(2\mathrm{V}(e_t) - 2\mathrm{Cov}(e_t, e_{t-1})\right).$$

- Average cost to central banks of holding reserves when central bank:
  - Leans against exchange rate misalignment:

$$C_t = -\varphi\left(\mathrm{V}(e_t) - \frac{1}{S}\mathrm{Cov}(e_t, \varepsilon_t) - \frac{\mathrm{Cov}(e_t, \delta_t)}{1-\rho_\delta}\right).$$

  - Leans against the wind:

$$C_t = \phi[\mathrm{Cov}(e_t, e_{t+1}) - \mathrm{V}(e_t) + \mathrm{Cov}(e_t, \delta_t)],$$

where:

$$\mathrm{V}(\varepsilon_t) = \frac{\sigma_\varepsilon^2}{1-\rho_\varepsilon^2},\ \mathrm{V}(\delta_t) = \frac{\sigma_\delta^2}{1-\rho_\delta^2},\ \mathrm{Cov}(e_t, \varepsilon_t) = \left[\frac{a_1}{1-\rho_\varepsilon^2} + \frac{(a_2 + a_1a_5)\rho_\varepsilon}{(1-\rho_\varepsilon^2)(1-\rho_\varepsilon a_5)}\right]\sigma_\varepsilon^2,$$

$$\mathrm{Cov}(e_t, \delta_t) = \left[\frac{a_3}{1-\rho_\delta^2} + \frac{(a_4 + a_3a_5)\rho_\delta}{(1-\rho_\delta^2)(1-\rho_\delta a_5)}\right]\sigma_\delta^2,$$

$$\mathrm{Cov}(e_t, e_{t-1}) = \left[\frac{a_1^2\rho_\varepsilon}{1-\rho_\varepsilon^2} + \frac{a_1(1+\rho_\varepsilon^2)(a_2 + a_1a_5)}{(1-\rho_\varepsilon^2)(1-\rho_\varepsilon a_5)} + \frac{(a_2 + a_1a_5)^2(a_5(1-\rho_\varepsilon^2) + \rho_\varepsilon(1-a_5^2))}{(1-\rho_\varepsilon^2)(1-a_5^2)(1-\rho_\varepsilon a_5)^2}\right]\sigma_\eta^2$$
$$+\left[\frac{a_3^2\rho_\delta}{1-\rho_\delta^2} + \frac{a_3(1+\rho_\delta^2)(a_4 + a_3a_5)}{(1-\rho_\delta^2)(1-\rho_\delta a_5)} + \frac{(a_4 + a_3a_5)^2(a_5(1-\rho_\delta^2) + \rho_\delta(1-a_5^2))}{(1-\rho_\delta^2)(1-a_5^2)(1-\rho_\delta a_5)^2}\right]\sigma_\xi^2.$$

Appendix 2

For the case of measurement error, the central bank and speculators are assumed to estimate the equilibrium value of the exchange rate imperfectly. We assume that their estimate, $\hat{\varepsilon}_t$, satisfies:

$$\hat{\varepsilon}_t = \varepsilon_t + \zeta_t,$$

where ζ_t is an i.i.d. error and intervention and speculation are given by:

$$\Delta FR_t = \varphi\left(\frac{\hat{\varepsilon}_t}{S} - e_t\right), \; B_t = \alpha[E_t(\hat{e}_{t+1}) - e_t + \delta_t],$$

where $E_t(\hat{e}_{t+1})$ is the expected value of the exchange rate next period, conditional on the measurement error. Note that now:

$$e_t = a_1\varepsilon_t + a_2\varepsilon_{t-1} + a_3\delta_t + a_4\delta_{t-1} + a_5 e_{t-1} + a_6\zeta_t + a_7\zeta_{t-1},$$

$$\hat{e}_t = a_1\varepsilon_t + a_2\varepsilon_{t-1} + a_3\delta_t + a_4\delta_{t-1} + a_5 e_{t-1},$$

$$E_t(\hat{e}_{t+1}) = (a_1\rho_\varepsilon + a_2)\varepsilon_t + (a_3\rho_\delta + a_4)\delta_t + a_5 e_t + (a_1\rho_\varepsilon + a_2)\zeta_t.$$

In this case:

$$\bar{V} = V_t(\hat{e}_{t+1}) = a_1^2\sigma_\varepsilon^2 + a_3^2\sigma_\delta^2 + \left(a_6^2 + [a_7 - (a_1\rho_\varepsilon + a_2)]^2\right)\sigma_\zeta^2.$$

When there are measurement errors, variances of exchange rate, speculative bets and the change in foreign exchange reserves take the following forms:

- Variance of the exchange rate:

$$\begin{aligned}\mathrm{V}(e) = &\left[\frac{a_1^2}{1-\rho_\varepsilon^2} + \frac{2a_1(a_2 + a_1a_5)\rho_\varepsilon}{(1-\rho_\varepsilon^2)(1-a_5\rho_\varepsilon)} + \frac{(a_2 + a_1a_5)^2(1+a_5\rho_\varepsilon)}{(1-\rho_\varepsilon^2)(1-a_5^2)(1-a_5\rho_\varepsilon)}\right]\sigma_\eta^2 \\ &+\left[\frac{a_3^2}{1-\rho_\delta^2} + \frac{2a_3(a_4 + a_3a_5)\rho_\delta}{(1-\rho_\delta^2)(1-a_5\rho_\delta)} + \frac{(a_4 + a_3a_5)^2(1+a_5\rho_\delta)}{(1-\rho_\delta^2)(1-a_5^2)(1-a_5\rho_\delta)}\right]\sigma_\xi^2 \\ &+\left[a_6^2 + \frac{(a_7 + a_5a_6)^2}{1-a_5^2}\right]\sigma_\zeta^2.\end{aligned}$$

- Variance of speculative bets:

$$\mathrm{V}(B_t) = \alpha^2\begin{bmatrix}(a_5-1)^2\mathrm{V}(e_t) + (a_1\rho_\varepsilon + a_2)^2\mathrm{V}(\varepsilon_t) + (a_3\rho_\delta + a_4 + 1)^2\mathrm{V}(\delta_t) + (a_1\rho_\varepsilon + a_2)^2\sigma_\zeta^2 \\ +2(a_5-1)(a_1\rho_\varepsilon + a_2)\mathrm{Cov}(e_t,\varepsilon_t) + 2(a_5-1)(a_3\rho_\delta + a_4 + 1)\mathrm{Cov}(e_t,\delta_t) \\ +2(a_5-1)(a_1\rho_\varepsilon + a_2)\mathrm{Cov}(e_t,\zeta_t)\end{bmatrix}.$$

- Variance of the change in foreign exchange reserves:

$$\mathrm{V}(\Delta FR_t) = \varphi^2\left(\frac{\mathrm{V}(\varepsilon_t)}{S^2} + \frac{\sigma_\zeta^2}{S^2} + \mathrm{V}(e_t) - \frac{2}{S}\mathrm{Cov}(e_t,\varepsilon_t)\right),$$

where $\mathrm{Cov}(e_t,\zeta_t) = a_6\sigma_\zeta^2$. Note that $\mathrm{V}(CA_t)$, $\mathrm{Cov}(e_t,\varepsilon_t)$ and $\mathrm{Cov}(e_t,\delta_t)$ remain unchanged.

Appendix 3

For a case that intervention is not fully transparent, speculators face uncertainty as to the strength of the central bank intervention. The uncertainty depends on the variance of the independent shock factor, ψ_t. The exchange rate then takes the form:

$$e_t = a_1\varepsilon_t + a_2\varepsilon_{t-1} + a_3\delta_t + a_4\delta_{t-1} + a_5 e_{t-1} + a_6\psi_t,$$

$$E_t(e_{t+1}) = (a_1\rho_\varepsilon + a_2)\varepsilon_t + (a_3\rho_\delta + a_4\delta_t) + a_5 e_t.$$

The reaction function of the central bank is:

- Leaning against the wind:

$$\Delta FR_t = \phi(e_{t-1} - e_t) + \psi_t.$$

Equating coefficients: $a_1, \ldots, a_5$ remain unchanged,

$$a_6 = \frac{1}{\phi + S - \alpha(a_5 - 1)},$$

and the variance of the change in foreign exchange reserves is:

$$\mathrm{V}(\Delta FR_t) = \phi^2\left(2\mathrm{V}(e_t) - 2\mathrm{Cov}(e_t, e_{t-1})\right) + \sigma_\psi^2.$$

- Leaning against exchange rate misalignment:

$$\Delta FR_t = \varphi\left(\frac{\varepsilon_t}{S} - e_t\right) + \psi_t.$$

Equating coefficients: $a_1, \ldots, a_5$ remain unchanged,

$$a_6 = \frac{1}{\varphi + S - \alpha(a_5 - 1)},$$

and the variance of the change in foreign exchange reserves is:

$$\mathrm{V}(\Delta FR_t) = \varphi^2\left(\frac{\mathrm{V}(\varepsilon_t)}{S^2} + \mathrm{V}(e_t) - \frac{2}{S}\mathrm{Cov}(e_t, \varepsilon_t)\right) + \sigma_\psi^2.$$

- Average cost to central banks of holding reserves when central bank:
  - Leans against exchange rate misalignment: opaque intervention policy

$$C_t = -\varphi\left(V(e_t) - \frac{\mathrm{Cov}(e_t, \varepsilon_t)}{S} - \frac{\mathrm{Cov}(e_t, \delta_t)}{1 - \rho_\delta}\right) + a_6\sigma_\psi^2.$$

  - Leans against the wind: opaque intervention policy

$$C_t = \phi\left(\mathrm{Cov}(e_t, e_{t+1}) - \mathrm{V}(e_t) + \mathrm{Cov}(e_t, \delta_t)\right) + a_6\sigma_\psi^2,$$

where:

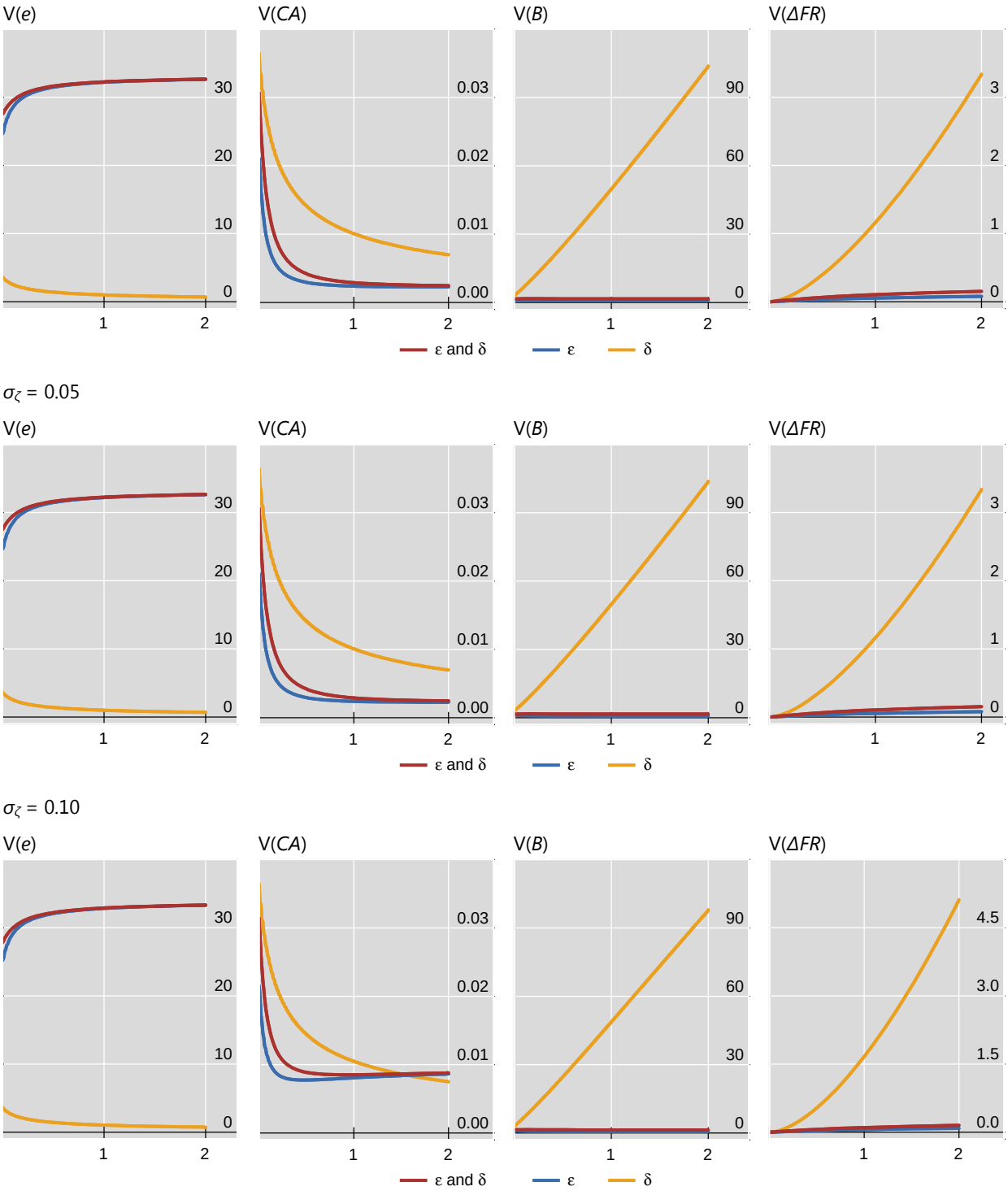
$$\mathrm{V}(\varepsilon_t)=\frac{\sigma_\varepsilon^2}{1-\rho_\varepsilon^2},\ \mathrm{V}(\delta_t)=\frac{\sigma_\delta^2}{1-\rho_\delta^2},\ \mathrm{Cov}(e_t,\varepsilon_t)=\left[\frac{a_1}{1-\rho_\varepsilon^2}+\frac{(a_2+a_1a_5)\rho_\varepsilon}{(1-\rho_\varepsilon^2)(1-\rho_\varepsilon a_5)}\right]\sigma_\varepsilon^2,$$

$$\mathrm{Cov}(e_t,\delta_t)=\left[\frac{a_3}{1-\rho_\delta^2}+\frac{(a_4+a_3a_5)\rho_\delta}{(1-\rho_\delta^2)(1-\rho_\delta a_5)}\right]\sigma_\delta^2,$$

$$\mathrm{Cov}(e_t,e_{t-1})=\left[\frac{a_1^2\rho_\varepsilon}{1-\rho_\varepsilon^2}+\frac{a_1(1+\rho_\varepsilon^2)(a_2+a_1a_5)}{(1-\rho_\varepsilon^2)(1-\rho_\varepsilon a_5)}+\frac{(a_2+a_1a_5)^2(a_5(1-\rho_\varepsilon^2)+\rho_\varepsilon(1-a_5^2))}{(1-\rho_\varepsilon^2)(1-a_5^2)(1-\rho_\varepsilon a_5)^2}\right]\sigma_\eta^2$$
$$+\left[\frac{a_3^2\rho_\delta}{1-\rho_\delta^2}+\frac{a_3(1+\rho_\delta^2)(a_4+a_3a_5)}{(1-\rho_\delta^2)(1-\rho_\delta a_5)}+\frac{(a_4+a_3a_5)^2(a_5(1-\rho_\delta^2)+\rho_\delta(1-a_5^2))}{(1-\rho_\delta^2)(1-a_5^2)(1-\rho_\delta a_5)^2}\right]\sigma_\xi^2.$$

Effect of leaning against exchange rate misalignment when fundamental value is measured with error

N = 10 Graph A1

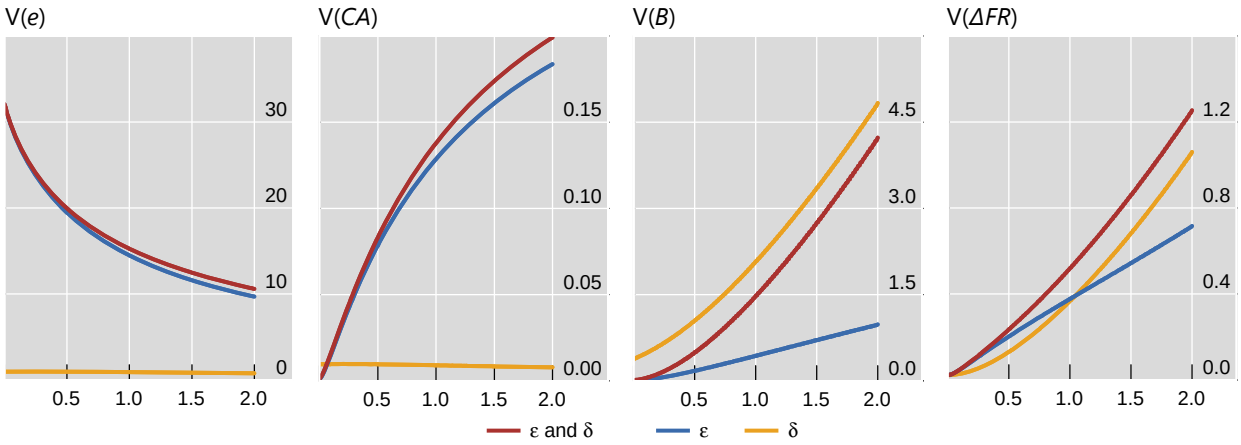


Horizontal axis: φ (strength of intervention against exchange rate misalignment)

Source: Authors' calculations

Effect of leaning against the wind (responding to exchange rate change) with opaqueness

$N = 1 / \sigma_\psi = 0.15$ Graph A2

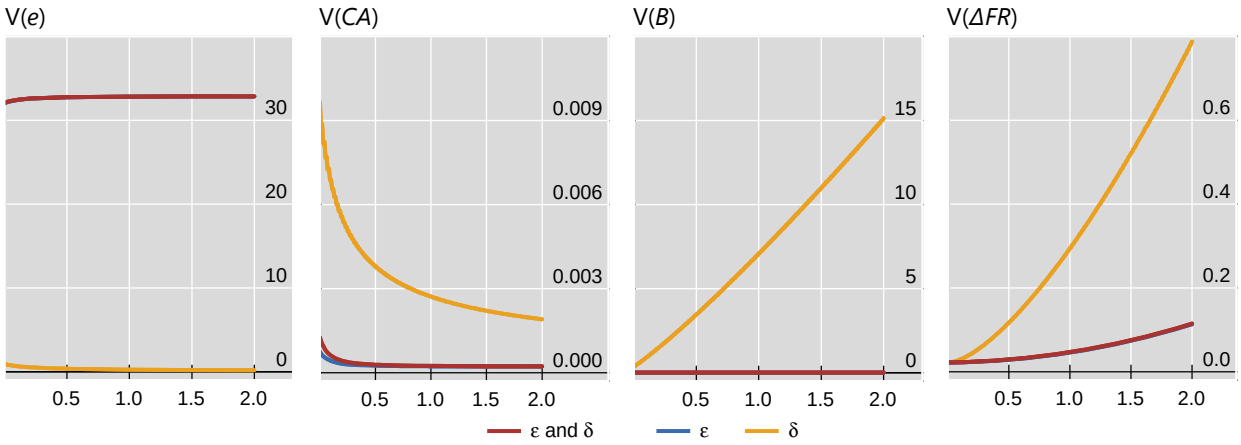


Horizontal axis: ϕ (strength of intervention against change in the exchange rate)

Source: Authors' calculations.

Effect of leaning against exchange rate misalignment on variances with opaqueness

$N = 1 / \sigma_\psi = 0.15$ Graph A3



Horizontal axis: φ (strength of intervention against exchange rate misalignment)

Source: Authors' calculations.