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Modeling Sterilized Interventions and Balance Sheet Effects of Monetary Policy in a New-Keynesian Framework

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Abstract

We study a wide range of hybrid inflation-targeting (IT) and managed exchange rate regimes, analyzing their implications for inflation, output and the exchange rate in the presence of various domestic and external shocks. To this end, we develop an open economy new-Keynesian model featuring sterilized interventions in the foreign exchange (FX) market as an additional central bank instrument operating alongside the Taylor rule, and affecting the economy through portfolio balance sheet effects in the financial sector. We find that there can be advantages to combining IT with some degree of exchange rate management via FX interventions. Unlike "pure" IT or exchange rate management via interest rates, FX interventions can help insulate the economy against certain shocks, especially shocks to international financial conditions. However, managing the exchange rate through FX interventions may also hinder necessary exchange rate adjustments, e.g., in the presence of terms of trade shocks.

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Contents

I. INTRODUCTION

We present a strategy for modeling foreign exchange (FX) interventions in an otherwise standard Inflation Targeting (IT) New–Keynesian dynamic general equilibrium model. The strategy is useful for modeling hybrid IT regimes involving informal exchange rate corridors, pegged or crawling exchange rates, and managed floats. Our strategy differs from other approaches that combine IT with a partial control over the exchange rate in that it uses the exchange rate (and interventions) as an instrument alongside the interest rate. The general equilibrium setting incorporates the analysis of stocks and flows that is needed to capture the balance sheet effects of intervention policies. Our strategy can easily be extended to more complicated monetary policy frameworks with multiple instruments and objectives.

Foreign exchange (FX) interventions have always been an important monetary policy instrument in emerging and developing economies. Central banks operate in the FX market for many different reasons, including to achieve a desired level of FX reserves or to act as a market maker of last resort in case of a market disorder (e.g., as described in Gersl and Holub, 2006). However, several surveys covering a large number of emerging markets (EM) countries also document a wide recourse to sterilized interventions for monetary policy purposes (BIS (2005) and IMF (2011a), among others). Such interventions are the focus of this paper.

Since the financial crisis of 2008/9 the use of FX interventions as a monetary policy instrument has further increased. Central banks in emerging markets employed massive interventions to dampen currency appreciation arising from carry trade flows during 2007–mid 2008 (Adler and Tovar (2011)). Later, when emerging currencies came under selling pressure, many central banks sold FX to control the speed of depreciation. At the same time, central banks in several developed countries (including Switzerland, Australia, and Israel, among others) embarked on regular interventions as a part of their efforts to stabilize domestic financial conditions.[2] In 2010—with a gradual return of capital inflows to emerging markets—central banks once again started accumulating FX reserves to limit currency strengthening and protect competitiveness (among other reasons).

The standard modeling approach does not capture such intervention practices. Rather, the literature addresses them, if at all, in the context of a standard new–Keynesian inflation targeting model that has only one instrument—the interest rate—to affect both inflation and the exchange rate, e.g., as in Monacelli (2004).

However, intervention practices in emerging markets operate through different channels than the interest rate policy of the central bank. In some cases, such as the Czech Republic in 2002 (Gersl and Holub (2006)), the interventions are used as an additional instrument in achieving the central bank's intermediate objectives—such as inflation—supporting the interest rates as the main instrument. There are also cases where interventions are used independently from the main instrument, and aim at different intermediate objectives (such as

[2]On Australia, see Reserve Bank of Australia (2008); On Israel, see Bank of Israel (2009); on Switzerland, see Swiss National Bank (2008).

competitiveness) than interest rate policy. Israel in 2008/9 is an example.[3] Standard modeling approaches featuring only a Taylor-type rule are too stylized to model the interactions between the two instruments and their separate transmission channels.

The main contribution of this paper is the extension of a standard inflation targeting New-Keynesian small–open–economy (SOE) model to include FX interventions as an independent central bank instrument. Our framework adds to the standard New Keynesian model: (i) FX interventions operating alongside interest rate policy; (ii) coexistence of interest–rate–based inflation targeting with a managed float or a fixed exchange rate; and (iii) financial sector balance sheets and portfolio balance sheet effects of intervention policies.

The key new mechanisms here are the interactions of two policy rules with two financial sector spreads (premia) that close the model. The two rules describe the central bank's use of its two instruments: a key policy rate and FX reserve accumulation. By default the former is used to target inflation, while the latter the exchange rate, but both rules can feature multiple targets. The intervention mechanism works through a financial sector whose holdings of financial assets are subject to endogenous interest rate spreads.

Our model features various portfolio balance sheet effects. They result from constraints on the optimization of the financial sector and of households in the model. These constraints lead to wedges (premia) between the interest rates for different assets, which depend on the relative supply of the financial assets themselves. The premia allow sterilized interventions—which change the relative supply of central bank paper available to the financial system—to influence the exchange rate.

Finally, our analysis allows to compare the performance of a full range of hybrid exchange rate regimes in a common framework and look at some of the trade-offs. Earlier analyses—constrained by inadequate modeling approaches—failed to highlight the advantages that active exchange rate management can have under certain circumstances, and the associated risks. We thus believe our paper offers a good starting point for a fuller welfare analysis. For instance, we illustrate the contrasting performance of exchange rate pegs maintained by interest rates and by interventions. In the former case, monetary policy has to follow foreign interest rates in order to keep the exchange rate unchanged, which has implications for the rest of the economy. In the latter, FX interventions may potentially insulate the domestic interest rates from such pressures, by acting instead on the interest rate wedge in the financial system.

While we believe our paper is the first to formalize the use of FX intervention alongside standard monetary policy rules in a new-Keynesian framework, it coincides with recent work by Ostry et al (2012). These authors also argue that monetary policy in emerging markets is best characterized as having two targets (inflation and exchange rates) and two instruments (short–term interest rates and sterilized FX interventions), and that such regimes are preferable when deviations of exchange rates from medium–run values are costly. Our paper is also related to recent work on the use of unconventional monetary policy tools in advanced

[3] See Bank of Israel (2008)

economies during the crisis (Curdia and Woodford (2011) and Gertler and Karadi (2011), among others). These papers also present a quantitative tool—credit policy—related to the size of the central bank balance sheet and that operates alongside traditional instruments. In their case, the unconventional tool is used to help minimize the impact of financial disruptions, especially when the policy rate hits the zero lower bound. We differ from these papers in that our focus is on a different quantitative instrument—sterilized interventions—operating on a different transmission channel—the supply of central bank paper/FX funding available to the banking system. In addition we view interventions as a regular policy tool rather than one used only during episodes of extreme financial distress.

The rest of the paper is organized as follows. The next section describes the pitfalls of standard approaches to modeling exchange rate targeting by central banks. After defining some key concepts, we introduce our modeling strategy and discuss its implications. We then illustrate and contrast various exchange rate/monetary policy regimes using model simulations and discuss the limits of intervention policy. The final section concludes. The appendix contains an extension of the analysis to quantity–based policy transmission and provides foundations for the key equations of the paper. It also presents the model equations and the calibration of the model.

II. Exchange Rate Targeting and Exchange Rate Intervention: Two Unrelated Literatures

The Exchange Rate targeting Literature

Most of the macroeconomic literature dealing with the role of the exchange rate in monetary policy has very limited applicability for emerging market and developing economies. Authors typically assume the central bank has only one instrument—the interest rate—that is used to target both inflation and potentially the exchange rate, and leave aside direct FX market interventions and the different channels through which they may operate. As we will see, this “Exchange rate targeting” literature therefore has limited applicability for many important questions.

Much of this literature is concerned with investigating implicit or ’dirty’ inflation targeting—a combination of inflation targeting and some exchange rate objective. Most authors investigate the conditions under which it makes sense for the central bank to include the exchange rate in the reaction function for its policy rate (Taylor, 2001, Natalucci and Ravenna, 2002, and Roger et al., 2009, which contains a good summary).

While there is little theoretical role for the exchange rate in interest rate rules in models of developed economies, the situation is more complicated for emerging markets. Many authors have analyzed the exchange rate in the reaction function in the context of financially vulnerable or dollarized economies (e.g. Moron and Winkleried, 2005, Batini at al., 2007). Leitemo and Soderstrom (2005) explore the effects of policy transmission uncertainty as a common feature in emerging economies. Roger et al. (2009) also look at policy credibility and expectations formation. Structural features of emerging market economies, such as high productivity growth or limited recourse to intertemporal substitution, are investigated by Natalucci and Ravenna (2008) and Roger et al. (2009).

The literature finds only limited support for including the exchange rate in reaction functions in emerging markets and points at significant risks, despite all the distortions and EM–specific features analyzed in these models. For instance, Roger et al. (2009) conclude that having an exchange rate term in the interest rate rule may help to reduce volatility of the exchange rate, interest rate, and trade balance, but that this may come at a cost in terms of inflation and output volatility, especially if the economy is exposed to demand and cost-push shocks. They also note that any benefits tend to disappear with high degrees of exchange rate targeting.

The main drawback of this literature is that it ignores exchange rate interventions and their transmission channel. The authors typically use an otherwise standard New–Keynesian monetary policy model with interest rates as the only monetary policy instrument. "Dirty" inflation targeting practices are explored by including an explicit exchange rate term into the interest rate reaction function of the central bank. In general:

$$i^T = \bar{i} + \alpha\left(\pi - \pi^T\right) + \delta\hat{y} + \chi\Upsilon, \tag{1}$$

where i denotes the policy rate, π is the rate of inflation and $\hat{y}$ is the output gap. The superscript T denotes a target level of the variable.

The term Υ specifies exchange rate targeting behavior. It can have a number of functional forms. For instance, Roger et al. (2009) cast it in real terms as:

$$\begin{aligned} \Upsilon &= \hat{q} - \eta\hat{q}_{-1} \\ &= \triangle s - \pi + \pi^* + (1-\eta)\,\hat{q}_{-1}, \end{aligned}$$

where q and s are the natural logarithms of real and nominal exchange rates, respectively.[4] This modification of the Taylor rule encompasses a wide array of possible exchange rate policy objectives, such as a concern for real exchange rate "misalignment" ($\eta = 0$) or real exchange rate fluctuations ($\eta = 1$).

By the same token, the Taylor rate rule can also be modified for explicit targeting of a nominal exchange rate level. In this case the Taylor rule contains nominal target levels for both inflation and the exchange rate:[5]

$$\Upsilon = \eta\triangle s + (1-\eta)\left(s - s^T\right). \tag{2}$$

[4] A small Latin letter denotes a log of a variable and a 'hat' a deviation from the steady state.

[5] In order for the the steady state to be properly defined, the two targets much be consistent with each other and cannot be chosen independently. In particular, in the absence of a trend in the real exchange rate, they are tied together by the $\triangle s^T = \pi^T - \pi^*$.

Less flexible exchange rate regimes are represented by a high weight on the deviation of the exchange rate from the target (high χ and small η), as in Parrado (2004a) or Natalucci and Ravenna (2002).

However, these approaches are unsatisfactory for several reasons:

- Sterilized interventions are the main instrument used by many emerging market and developing country central banks to affect the exchange rate. While some central banks may have explicit exchange rate objectives in mind when setting interest rates, that is not their main instrument for influencing the exchange rate.
- In these models, including the exchange rate in the Taylor rule reduces the central bank autonomy in setting the interest rate, which contradicts actual practices. In the extreme case, fixing the exchange rate through the Taylor rule implies the interest rate becomes totally exogenous to domestic monetary policy and its shocks.[6] For instance, setting χ in (1) to infinity makes the Taylor rule collapse to $S = S^T$, and the interest rate becomes determined through the uncovered interest rate parity (UIP) condition. By contrast, in practice many central banks manage exchange rates precisely to increase their autonomy and room for policy maneuvering.
- It is clear that central banks resorting to exchange rate management hope to engage different transmission channels working through balance sheet effects and FX liquidity, and potentially also to target several objectives simultaneously (BIS, 2005). Even as they operate de facto pegs, many central banks consider that they face a separate policy decision on interest rates. Yet in the standard models, the interest rates affect the economy, as usual, by influencing the nominal exchange rate (through UIP) and the consumption/investment behavior of the private sector (through Euler conditions). There is no separate transmission channel involved in exchange rate targeting.
- The issue of sterilization cannot be studied with a single central bank instrument. Sterilized interventions require two instruments: purchases and sales of FX, and open–market operations to neutralize effects on the policy interest rate.

A few authors introduce a separate explicit rule for the exchange rate directly into their models. However, they do not provide an alternative channel through which such a rule could operate. For instance, Parrado (2004b)—in his analysis of monetary policy in Singapore—and Roger et al. (2009)— in their literature survey—suggest replacing the interest rate rule by a rule specified in terms of the exchange rate directly, such as

$$s^T = \rho s^T_{-1} + (1-\rho)\left(\alpha\hat{\pi} + \delta\hat{y}\right).$$

[6] The interest rate reflects domestic shocks only to the extent that the risk premium does (e.g. by being sensitive to NFL or CA movements).

As before, the main shortcoming of this approach is that it leaves the determination of interest rates to external elements through the UIP condition. Benes et al. (2008) provides for the coexistence of both the exchange rate and interest rate rules, but their mechanism is ad hoc.

The FX Intervention Literature

The literature on sterilized exchange rate interventions is large and rich, mostly predating the new–Keynesian models used to analyze inflation targeting in recent years. The portfolio–balance approach to the balance of payments and exchange rate determination (Kouri (1983), Branson and Henderson (1985)) embraced a potentially important role for sterilized intervention to affect the exchange rate, by allow changes in the asset composition of portfolios to influence risk premia. This strand of work in open economy macroeconomics generally lost out to the assumption of perfect asset substitutability, a line of work going back to Dornbusch (1976).[7]

One reason why the portfolio balance approach fell out of favor was the difficulty in micro–founding the link between risk premia and the gross supply of public sector assets, from a general–equilibrium perspective. The strongest critique of sterilized foreign exchange interventions along this line is by Backus and Kehoe (1989): with the help of a general–equilibrium monetary model, they demonstrate that certain types of sterilized interventions—those that hold the time paths of fiscal and standard monetary policy constant—have no effect on private sector decisions (and hence on premia). Moreover, interventions that are associated with changes in fiscal and monetary policy do have real effects but not because of the intervention itself. However, Kumhof (2010) shows that it is theoretically possible to generate imperfect substitutability between various kinds of public sector assets in a general equilibrium setting. He does so by introducing government spending shocks, which in his setup require adjustments to the nominal exchange rate. The risk associated with these shocks is sufficient to make sterilized interventions work, because they affect the private sector's exposure to exchange rate risk.

More generally, and especially for developing countries, the existence of country–specific default risk and in some cases various forms of partial capital controls, along with incomplete asset markets, make plausible the assumption of partial asset substitutability. This in turn opens up the (at least theoretical) possibility that sterilized intervention will matter for real and nominal outcomes. For these reasons, in our model we will assume the existence of reduced–form financial frictions that result in gross–debt sensitive risk premia.

Empirical tests of the effectiveness of sterilized intervention also have a long and varied history, continuing up to the present. Almost all of the focus has been on developed countries, where enthusiasm for the notion that sterilized interventions "work"—in the sense of mattering for the exchange rate—has ebbed and flowed. Efforts to directly test the portfolio balance model are hampered by difficulties in defining and measuring the relevant asset supplies. Earlier tests were generally negative. However, Dominguez and Frankel

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[7]Blanchard et al. (2005)) propose a revival of the portfolio approach, however.

(1993) find that deviations from uncovered interest parity between the dollar and the Swiss Franc or the German mark depend significantly on intervention variables.

Most recent work has focussed directly on whether sterilized interventions seem to affect the exchange rate (and in some cases other variables). A constant theme is the fundamental identification problems challenging empirical analyses of sterilized intervention: the interventions presumably are motivated by events in the exchange rate market, confounding efforts to measure the effects of the interventions per se. Finding good instruments (ie variables correlated with the propensity to intervene but not with the exchange rate itself) is a serious challenge. One frequent approach has been to rely on very high frequency data, on the assumption that the intervention then does not depend on contemporaneous exchange rate developments.

Event studies have in many cases found significant if often small effects. A more recent survey (Cavusoglu, 2010) concludes that a major consistent finding is that interventions have a significant but short-lasting effect on exchange rates, with only a few studies looking at the effects on longer movements and few clear results. Among notable papers, Fatum and Hutchison (2003) in a careful event study analysis of German and the U.S. find that interventions do indeed affect the exchange rate. However, for Japan, the same authors find that only sporadic and relatively infrequent intervention is effective (Fatum and Hutchison 2010). More recent studies have began to look at emerging markets. Papers such as Domac and Mendoza (2004) (Mexico and Turkey), Guimaraes and Karacadag (2004) (Mexico), Gersl and Holub (2006) (Czech Republic), Egert (2007) (several central and Eastern European countries), Kamil (2008) (Colombia), find some evidence that sterilized interventions affect the level of the exchange rate; others e.g. Tuna (2011) Turkey) find negative results. In an interesting recent paper focussed on emerging markets, Adler and Tovar (2011) attempt to address the endogeneity problem by examining episodes identified ex ante as those where global shocks may push exchange rates towards appreciation, then testing whether intervention was successful in "leaning against the wind," using deviations in the exchange rate from estimated equilibrium values as well lagged exchange rate terms as instruments. They find some evidence that interventions can affect the pace of appreciation, particularly in countries that have a relatively closed capital account according to the Chinn and Ito (2008) index. The usual questions about identification are nonetheless hard to fully put to rest.

Beyond this evidence, and particularly in the face of the econometric difficulties, we give some weight to the views of many practitioners, particularly in emerging markets and developing countries, that FX interventions can be effective (Neely, 2008 and BIS, 2005; see also Canales-Kirilenko (2003)). Particularly for emerging and frontier markets, and a fortiori low–income countries that are just beginning to enter global capital markets, it seems plausible that assets are imperfect substitutes and that markets are relatively "thin", in that changes in supplies can have substantial effects on relative prices. In what follows we examine the implications of these assumptions.

III. Key concepts

Exchange rate targeting versus exchange rate interventions

We now define a few concepts involving common but often confusing terminology. Let us start by considering price stability as the final policy *objective*. Furthermore, let us restrict our attention to two *intermediate targets* consistent with the price stability objective: an exchange rate and a rate of inflation. If both intermediate targets co-exist, they must be set consistently.

By *operational targets* we understand the levels of interbank interest and exchange rates aimed at by central bank operations, which are transactions with the market that change the central bank's balance sheet, such as open market operations in domestic liquidity/T-bills and foreign exchange operations. In common central bank parlance both the operational targets as well as the operations themselves are often referred to as instruments. The instruments are set so as to achieve the intermediate targets directly associated with price stability, but in addition can follow other intermediate targets, such as certain values for the real exchange rate or output growth. In accordance with standard practice we will also use *instruments* interchangeably referring to both operations and operational targets.

It is now useful to distinguish between two types of central bank actions with respect to the exchange rate. By *exchange rate targeting* we mean that the central bank adjusts its policy interest rate as an instrument so as to achieve a particular level/path of the exchange rate set as an intermediate target. By contrast, by *exchange rate interventions* we understand central bank operations in the FX market whose aim is to affect the behavior of the exchange rate as an operational target/instrument. As a result, the exchange rate can function both as an intermediate as well as operational target. For instance, a central bank's intermediate target maybe a dollar parity, while in the short term it might be willing to allow for temporary deviations owing to market conditions or the business cycle.

While most of the model–based literature studying the role of the exchange rate in monetary policy focuses on exchange rate targeting, our paper focusses on exchange rate interventions, because they introduce the exchange rate as a central bank instrument (in addition to the interest rate).[8] However, we analyze and compare both cases.

In reality, both exchange rate targeting and exchange rate interventions are common and often concurrent. For instance, the setting of policy interest rates in Hungary before 2008 took into account that the exchange rate must not escape the official bands.[9] At the same time, the central bank also intervened in the FX market to defend the exchange rate bands. In many cases exchange rate interventions are supported by dramatic changes in interest rates to preserve exchange rate bands as an intermediate target, as it happened, for instance, during the speculative attacks on the ERM in 1992 or most recently during the financial crisis (e.g.

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[8]Note that central banks use FX market operations also for other reasons than to affect the exchange rate behavior, e.g. to accumulate FX reserves and to preserve market stability.

[9]See Ersek (2005).

in Hungary or Serbia).[10] On the other hand, exchange rate interventions alone can be enough for targeting inflation, especially for very small and open economies with a strong exchange rate pass-through. For instance, the regime in Singapore closely resembles such behavior (Parrado, 2004b).

Sterilized versus non-sterilized exchange rate interventions

We define sterilized interventions as such exchange rate interventions *that keep market interest rates unchanged.* All exchange rate interventions of central banks using interest rates as the main instrument (such as IT central banks) are automatically sterilized in this sense. For instance, an IT central bank buying FX creates reserve money that is automatically absorbed using open market operations that target the policy rate. Indeed, if a central bank with an interest based policy wants to imitate the results of an *unsterilized* intervention, it must simultaneously alter the level of its key policy rate. For instance, it must lower the key policy rate when buying the FX.

An alternative definition would be that sterilized interventions *do not change the level of reserve (base) money*. Central banks that targeted reserve money would automatically sterilize FX interventions according in this alternative sense. The definitions are very close, because if interventions change the levels of free reserves held by the commercial banks with the central bank, then market interest rates change as well.

This paper's main focus is on sterilized interventions that work alongside interest rates as the other central bank instrument. To simplify the exposition, the main body of the paper works with a stylized IT central bank operating an interest-rate based monetary policy. This allows us to abstract from free reserves in the balance sheets of the central and commercial banks, because the central bank will always absorb all the reserves at its key policy rate. Any intervention is therefore automatically sterilized. Nevertheless, the appendix extends the analysis to the case of non-interest based monetary policy where free reserves are important. That extension is important for analyzing policy options in many money-targeting low–income economies.

The stochastic behavior of the exchange rate

A strength of our approach is that it covers traditional pegs (including crawling arrangements), managed floats of various sorts, and IT in a common framework. This will facilitate direct comparisons that are not possible when pegs are not modeled with intervention. In this context, an important technical issue for modeling of interventions is the stochastic behavior of the exchange rate. In standard flexible–exchange–rate SOE models the exchange rate has a stochastic trend; its long-term trajectory is path–dependent and the steady–state/balanced–growth–path value cannot be determined ex–ante. In such models

[10] On the ERM see Buiter, Corsetti and Pesenti (1997). On Hungary, see IMF (2011b). On Serbia, see IMF (2008b).

inflationary shocks result in permanently weaker exchange rates. The cause is the UIP condition that gives the exchange rate a unit root.

A stochastic trend in the exchange rate level may be an undesirable feature when modeling certain exchange rate regimes. For the exchange rate level to be a nominal anchor, its behavior should not have a stochastic trend. No matter what the shocks, the long–term exchange rate trajectory should be known ex ante. For instance, while a shock may cause a temporary deviation of the exchange rate from this long–term trajectory, eventually the exchange rate will return to its target value.[11] As a consequence, in order to provide for a general treatment of exchange rate regimes our intervention design should be able to remove the stochastic trend (unit root) from the exchange rate.[12]

IV. MODEL

We modify an otherwise standard new–Keynesian small–open economy model (such as in Gali and Monacelli (2005), or Benes et al., (2007)) by adding:

- FX interventions as a central bank instrument, independent of the interest rate instrument and capable of stabilizing the exchange rate fluctuations within a given stochastic band;
- Balance sheet (liquidity) effects of interventions as a new channel of monetary policy transmission working through endogenous spreads derived from an optimal behavior of the financial sector.

In this section we describe the key equations of the model, the rest of which is presented in appendix C.

A. Balance sheets

The balance sheets of households, the financial sector and the central bank have the following simple structure:

Central Bank		Financial Sector		Households	
F	O	O	B		L
		L			NW

[11]This long–term trajectory need not be constant, such as in crawling pegs.

[12]Models with exchange rate targeting (i.e. exchange rate terms in the interest rate reaction function) typically have a stochastic trend in the exchange rate, unless the interest rate rule includes a target exchange rate level (not just a rate of change) or a target price level (when modeling price targeting regimes).

The central bank keeps a stock of FX reserves, *F,* and issues its own securities, *O*, held by the financial sector. In addition, the commercial banks provide loans to households, *L*, and are refinanced from abroad, *B*. *NW* stands for Households net worth. All items are expressed in the domestic currency. In the simple setup we exclude financial dollarization: *F* and *B* are denominated in foreign currency, while all the other assets are denominated in domestic currency. The economy is cashless and a net debtor, because the country's net foreign liabilities (NFL) are equal to the household debt *L*, which is positive.[13]

B. Central bank behavior

Every period the central bank receives interest on its FX stock at an exogenously determined—and constant—rate of i^*. It pays interest i (which we assume is compounded over the period) on the stock of its own securities held by the financial sector (O_{-1}, issued last period) and transfers its cash-flow (CF^{CB}) to households:

$$CF^{CB} = \frac{S}{S_{-1}} F_{-1} \exp(i^*) - O_{-1} \exp(i) - FX + O.$$

The central bank decides on the level of foreign exchange and on the interest rate it pays to the banks. The central bank adjusts the stock of FX reserves in order to achieve a particular operational target for the nominal exchange rate as follows:

$$\log\left(\frac{F}{L}\right) = \log\left(\overline{\frac{F}{L}}\right) - \omega \log\left(\frac{S^T}{S}\right) - \vartheta \log\left(\frac{S_{-1}}{S}\right), \tag{3}$$

where $\overline{\frac{F}{L}}$ is the steady state ratio of FX reserves to the stock of credit (NFL) in the economy and S^T is the level of the operational exchange rate target.

At one extreme the central bank can keep the exchange rate on its target level at all times ($\omega \to \infty$) by instantly adjusting the level of reserves; at the other, it will ignore exchange rate movements ($\omega = 0$) and keep FX reserves at some desired level (relative to NFL). We chose

[13] We chose to use as simplistic balance sheets as allowed by the requirements of our analysis. In doing so, we disregarded many sometimes-important practical aspects, sacrificing realism. For instance, our financial sector runs an unhedged short position in FX, which would not be allowed by prudential regulation. Our households are net borrowers, rather than savers. And we assume an economy with a 'structural liquidity surplus' of the banking sector: the central bank on average issues its own securities to permanently withdraw excess reserves from the banking system. This is the more likely situation in the developing and emerging world, often reflecting a history of central bank purchases of private capital inflows from the market or of aid and natural resource export revenues from the government. The situation in much of the developed world is rather one in which the banking system is in a "structural liquidity deficit': central banks are permanently engaged in providing liquidity to the market. However, our exposition can easily be generalized. For instance, firms borrowing from the financial sector can be added to make households net savers. The financial sector can run separate balance sheets in FX and local currencies, thus assuming partial financial dollarization. And allowing for negative O enables switching between structural liquidity surplus and deficit. For the purposes of our exposition these are unnecessary complications, though. The appendix shows how reserve money can be added.

to express the rule in terms of credit (NFL), because it captures the central bank's primary motive for permanently holding large stocks of FX reserves.[14] Finally, the last term $\vartheta log\left(\frac{S_{-1}}{S}\right)$ captures exchange smoothing behavior—so called 'leaning–against–the–wind' interventions. This will allow us to model managed floats later on.

An important assumption we make is to ignore the lower bound on reserves. We implicitly assume the volume of reserves implied by rule (3) is always positive, or if it entails a negative number, we assume the country can receive external financing, e.g., from official sources like the IMF, for this purpose. We return to the lower bound on reserves in our discussion of limits to sterilized interventions.

As the central bank adjusts FX reserves it also adjusts the level of unremunerated reserves (not modeled) so as to keep the inter-bank interest rate i at the desired level:

$$i = i_t^T. \tag{4}$$

The central bank thus has two operational targets: S^T and i^T. The levels of these operational targets are set by the exchange rate and interest rate rules that can both take—in principle—the general form of a Taylor–type rule (1):

$$\begin{aligned} i^T &= \rho i_{-1}^T + (1-\rho)\left(\bar{i} + \alpha\left(\pi - \pi^T\right) + \delta\hat{y} + \chi\Upsilon\right). \\ s^T &= \rho_s s_{-1}^T + (1-\rho_s)\left(\bar{s} - \alpha_s(\pi - \pi^T) - \delta_s\hat{y}\right), \end{aligned} \tag{5}$$

where Υ is defined as in (2). For simplicity, we will set $\rho_s = \alpha_s = \delta_s = 0$.

The central bank tracks the exchange rate operational target by adjusting the quantity of FX reserves in (3), but unless ω is very large the tracking is not perfect. By contrast, the interest rate operational target is assumed to be met at all times.

Note that our treatment of central bank instruments is not symmetric: for the exchange rate we track movements in the central bank balance sheet, while for interest rates we do not.[15] While this is a good description of policy implementation in central banks that run "lite"

[14] See Obstfeld, Shambaugh and Taylor (2009).

[15] This asymmetry reflects central bank practices as well as some underlying economics. Exchange rate targets are analogous to targets on long-term interest rates, in that both imply setting prices for assets that yield capital gains or losses if prices change and hence that are more subject to speculative attacks than overnight rates (see Woodford (2005) for the case of long rates). This implies that achieving these targets exactly, as represented by an infinite ω in (3) may strain central bank balance sheets and be difficult to achieve. We return to this point later. For current purposes, however, the implication is that many central banks conduct quantity–based operations aimed at achieving targets for the exchange rate without necessarily hitting the targets exactly. Similarly, recent efforts at "quantitative easing' in developed countries aim to influence but not precisely target long interest rates.

inflation targeting regimes, it does not fit the central banks that make decisions about monetary aggregates rather than policy interest rates.[16] We take up this issue in appendix A.

C. Financial sector behavior

The behavior of perfectly competitive financial sector firms (owned by households) is described by the following arbitrage relationships:

$$\exp(i) = \exp(i^*)\frac{S_{+1}}{S} + \Omega_O(\frac{F}{P}),\ \Omega_O'(F/P) > 0 \tag{6}$$

$$\begin{aligned} \exp(j) &= \exp(i^*)\frac{S_{+1}}{S} + \Omega_L \\ &= \exp(i) + \Omega_L - \Omega_O(\frac{F}{P}) \end{aligned} \tag{7}$$

Condition (6) postulates the uncovered interest parity (UIP) condition as an arbitrage between the interest rate on central bank bills and an exchange–rate–adjusted foreign rate, augmented with a spread $\Omega_O(.)$ that is increasing in the stock of FX reserves (deflated by the price level P). As the rate *i* is defined by the Taylor rule, (6) defines the exchange rate expectations (for a given spread). Condition (7) defines a credit supply curve, which introduces a spread Ω_L between the interest rate on credit (*j*) and the UIP term. The spread between the policy rate *i* and the credit rate *j* is given by $\Omega_L - \Omega_O$.

The most important feature is that the UIP spread is *increasing* in the level of FX reserves, which is central to the FX intervention mechanism. This may initially sound counter-intuitive, but a UIP premium increasing in FX reserves can arise in a number of contexts. Appendix B shows how such arbitrage conditions can be derived in two different behavioral set-ups: a portfolio allocation problem and the minimization of bank operating costs. Intuitively, when the balance sheets of the financial sector get overloaded with one type of asset (central bank paper O in this case), the premium that is required for banks to hold these bonds increases. Because the stock of central bank paper equals the stock of FX reserves, it follows that increasing the central bank holding of FX reserves increases the UIP spread.

D. Households behavior

The only nonstandard behavior here is that households face adjustment costs when altering the stock of loans taken from banks. In particular, their budget constraint is:

$$PC - L = -\exp(j_{-1})L_{-1} + \Pi - \Psi(L/P),\ \Psi'(L/P) > 0, \Psi''(L/P) > 0. \tag{8}$$

[16]On IT “lite” see Carare and Stone (2003).

where C denotes household consumption, and Π is the total amount of labor income and profits households receive from the firms, the financial sector and the central bank (treated as exogenous by the household). $\Psi(L/P)$ are quadratic adjustment costs. They are private—not social—costs. These costs provide a mechanism for closing our model, i.e. determining the steady state values of real consumption and net foreign assets, similar to other mechanisms in the literature (see Schmitt-Grohe and Uribe (2003)).

The otherwise standard household optimization problem subject to this constraint yields the following FOCs:

$$\begin{aligned} \frac{\lambda}{\lambda_{+1}}\left(1-\varrho\left(L/P\right)\right) &= \beta\exp(j), \\ P\lambda &= U'(C). \end{aligned} \tag{9}$$

where λ is the Lagrange's multiplier associated with the budget constraint and $\varrho\left(L/P\right) \equiv \Psi'\left(L/P\right)$ introduces a credit–sensitive wedge between the interest and discount factors in the Euler condition, with the latter becoming a downward sloping credit demand curve.

E. Rest of the model

The rest of the model has standard features (see Appendix C for a full description and calibration). It has two sectors—exportables and non–tradables—using labor as the only factor of productions and subject to decreasing returns. Both sectors produce differentiated varieties sold in monopolistically competitive markets with staggered pricing, giving rise to standard Phillips curves. Global demand to domestic exports is price–sensitive. Labor can move between the sectors and wages are equalized. In addition to the domestically–produced non–tradable varieties, households also consume foreign goods imported by domestic firms, whose domestic prices are also subject to nominal rigidities.

V. Discussion

Steady state and two spreads

An important feature of the model is that it removes the unit root from the real values of all financial stocks and—depending on the exchange rate regime— from the exchange rate level. Both the country's net foreign liabilities and the FX reserves —which would normally follow a random walk—return to a unique steady state following any domestic or external shock.

This is achieved by the coexistence of two real spreads (premia): $\varrho\left(L/P\right)$ and $\Omega_O(F/P)$. Equation (9) ensures unique steady–state values for real consumption and NFL (as in Schmitt-Grohe and Uribe (2003)) through the $\varrho\left(L/P\right)$ spread. Equation (6) then makes F/P uniquely determined at steady state, through the $\Omega_O(F/P)$ spread. With F/L determined, equation (3) ensures the exchange rate is also equal to its target level at steady state, and hence exhibits no unit root.[17]

The intervention rule (3) has therefore a similar role with respect to the exchange rate than the Taylor rule has with respect to inflation. The Taylor rule in the steady state determines inflation and not the interest rate level. By the same token, the FX rule determines the level of the exchange rate and not the level of FX reserves in the steady state.

The intervention rule has this capacity thanks to the existence of the financial sector in the model. Consider adding the intervention rule (3) to a standard model without the financial sector. In this case, the rule would define movements in foreign exchange reserves as a function of the exchange rate, and hence *F/L* would inherit the stochastic properties of the exchange rate. Because the nominal exchange rate typically has a unit root in the standard model—just like the price level does—so would F/L, and there is no guarantee that *S* would equal its operational target level S^T at steady state.[18]

Intervention mechanism

The second important feature of the model is the exchange rate stabilization mechanism outside the steady state. When the exchange rate rises above the target level (i.e. depreciates), the central bank draws on its reserves (relative to NFL) to defend the currency. This results in falling UIP premium $\Omega_O(F/P)$ in (6), which then works towards currency strengthening (ceteris paribus).[19]

One attractive feature of this intervention mechanism is that it can help control the behavior of the exchange rate, without affecting the stochastic behavior of the policy rate. In particular, it can be calibrated so that the exchange rate fluctuates within a pre-specified probabilistic corridor (given the variance of the model's structural shocks). For instance, for ω large, the exchange rate will be fixed at its target level S^T. This is suitable for modeling hard and crawling pegs. For ω approaching zero, the exchange rate will be fully flexible, as the central bank refrains from intervening against exchange rate deviations. The intermediate cases provide for modeling of 'soft' exchange rate corridors, i.e., corridors without enforceable hard boundaries. On the other hand, parameter ϑ introduces "leaning–against–the–wind" interventions that we will use to model a managed float.

[17]This mechanism also provides room for the traditional "leaning–against–the–wind" interventions under dirty inflation targeting: setting ω to zero and ϑ positive preserves the unit root in the exchange rate, as we will see in simulations later.

[18]Besides, a standard model would have a UIP spread increasing in the country's net foreign liabilities, i.e. falling in *F* (for a given *B*). This implies that buying FX reserves in order to depreciate the currency will work instead towards currency strengthening via the falling spread.

[19]In the baseline calibration, holding expectations and interest rates constant, a one percent increase in reserves—relative to its steady state value—depreciates the exchange rate by one fourth of a percent.

VI. Simulations

Intervention mechanism: illustration

We demonstrate the workings of the intervention channel and the balance sheet effects by simulating the model when it is hit with a foreign interest rate shock.

The foreign interest rate shock is illustrative, for it allows to compare the economy's response when monetary policy fixes the exchange rate by adjusting interest rates and when it does so by intervening in the foreign exchange market. In the former case, monetary policy has to follow foreign interest rates in order to keep the exchange rate unchanged. On the other hand, FX interventions insulate the domestic interest rates from such pressures, by operating on the interest rate premium in the financial sector. As will be shown below however, these interventions will engage other transmission channels.

We compare the model responses under four monetary policy settings: (i) Pure inflation targeting (IT)/flexible exchange rate regime, (ii) fixed exchange rate regime through interest rates, (iii) fixed exchange rate regime through interventions, (iv) managed exchange rate regime (a corridor around a parity), and (v) managed float. The float case (i.e. "pure" IT) serves as a benchmark, while the exchange rate corridor is essentially a weaker version of (iii). For all five regimes, the exchange rate objective Υ is set as in equation (2) with $\eta = 0$. The five regimes then correspond to the following parametrization of the Taylor rule (1) and of the intervention rule (3):

Regime/parameter	χ	ω	ϑ
IT pure float	0	0	0
Fixed via interest rate	Inf	0	0
Fixed via interventions	0	Inf	0
Exchange rate corridor	0	5	0
Managed float	0	0	20

Figure 1 presents the results. The IT case shows the basic challenges such a shock presents to the authorities: a rise in foreign rates pushes the exchange rate to depreciate, inducing inflation through import prices, but at the same time supporting the export sector. Under "pure" IT, monetary policy will seek to tame inflation by raising nominal rates, somewhat offsetting the impact of the shock on the exchange rate and putting downward pressures on domestic consumption. Net exports improve, as real exports are up and real imports decline following real exchange rate depreciation. Despite the increase in net exports, the country's net foreign liabilities worsen because of the higher interest rate burden.

Note that the nominal exchange does not return to its initial level in the IT case. The rising price level resulting from this shock leads the exchange rate to settle at a weaker level. The same is true for the managed float specification, in which the central banks uses interventions only to smooth the speed of the exchange rate adjustment, but does not control the exchange rate level. By contrast, in the other regimes the exchange rate returns to the original level—which serves as an intermediate target.

Fixing the exchange rate via the interest rate rule leads to lower inflation but at the cost of a sharper economic decline than in the float case. The reason is that monetary policy has to raise interest rates to match the foreign interest rate increase. In addition, unlike the float case, the export sector does not get a boost from a nominal exchange rate depreciation as in the float case. This greater impact of external shocks on the real economy is a well known weakness of fixed exchange rate regimes, going back to Friedman (1953).

On the other hand, fixing the exchange rate through interventions allows interest rates to fall, thus limiting the extent of the economic contraction. The economy still contracts, but by less and for different reasons than in the previous case. The positive shock to foreign rates increases the debt repayment burden for households. As a result, the country's net foreign liabilities rise, increasing the effective interest rates faced by households in the Euler equation (9). The resulting economic contraction brings inflation down, allowing policy interest rates to decrease in response.[20]

Both the exchange rate corridor and the managed float show the advantages of active exchange rate management. In both cases interventions allow the interest rates to stay lower than in the pure float or exchange rate targeting, thus helping consumption recover faster. Both also allow for some exchange rate depreciation (at least temporarily), thus providing a short–term impulse to the export sector that is otherwise not available in the fixed regimes.

The simulations nicely illustrate the practical problems with implementing the fixed exchange rate regime through interest rates. In the float case the rates increase *in order* to fight inflation pressures, while when fixing through interest rates the rates increase *despite* a fall in inflation and in economic activity. Interventions, by contrast, give the policy rates room for maneuvering in response to the contraction of the economy. As a result, the economic impact is smaller when fixing through interventions than when fixing through interest rates.

Stochastic properties of policy regimes

We now study macroeconomic volatility under various regimes faced with a variety of structural shocks. Because we do not have any particular economy in mind, we characterize the economies by a "prevailing structural shock." For that purpose, we set the standard error of the 'prevailing' shock to unity and standard errors of all other shocks to zero. We then compute unconditional moments of the model variables in each 'shock-economy' under the five regimes considered above.

The structural shocks we choose are: shocks to the foreign interest rate, to non-tradable consumption, to non-tradable inflation, and to the terms of trade. These are probably the most

[20] The NFL effect on household borrowing costs that is causing the economy to contract in the intervention case is also present in the other simulations, but is overshadowed by other channels there.

important shocks that occur in small open economies. In some economies, monetary policy is constantly responding to changes in foreign interest rates, in others government shocks are prevalent, some have bouts of seasonal food price changes, while in others the terms of trade are the main source of macroeconomic volatility.

Table 1 shows unconditional standard errors for key variables in each economy type and for each FX regime. For purposes of comparison, standard errors are normalized with respect to the pure IT regime.

The main observations are the following:

- When shocks to foreign interest rates are the dominant source of fluctuations, regimes with interventions outperform “pure IT” and the fixed exchange rate regime via interest rates in terms of the volatility of almost all key variables, with the obvious exception of FX reserves. As we saw earlier when discussing Figure 1, interventions give the central bank partial autonomy in using its interest rate to respond to domestic economy rather than ’blindly’ following the foreign rates.
- With the notable exception of the terms of trade shock, fixing or managing the exchange rate is a powerful tool in smoothing the volatility of exports. In the case of terms of trade shocks however, these shocks require fluctuations in the real exchange rate as part of the macroeconomic adjustment. These real exchange rate movements are costly under pegs—regardless of the instrument used. In this case, greater exchange rate volatility helps reduce the volatility of inflation, consumption and other real variables.
- Consumption volatility is never higher in regimes with interventions than in the free floating/IT regime. This is because interventions help reduce the volatility of real interest rates (not shown) more effectively than when the exchange rate is fully flexible or fixed through nominal interest rates.
- With the exception of foreign interest rate shocks, inflation is always least volatile in floating regimes.
- The most intensive use of reserves (i.e. the highest volatility of reserves) is found in economies dominated by domestic inflation and foreign interest rate shocks.

As this exercise shows, there are trade-offs among the policy regimes regimes—almost regardless of the predominant shock, at least as long as the shocks are relatively small.[21] Against this backdrop, the choice of policy will depend on the structure of the economy, the expected composition of structural shocks, and policymakers preferences. Nonetheless, some policy lessons emerge. For instance, in small economies dominated by foreign interest rate shocks fixing the exchange rate through interest rates looks to be uniformly worse (in terms

[21] For instance, if the reaction to shocks involve a large drop in FX reserves, this may lead to non–linear reactions of other variables—otherwise assumed constant—that drive the risk premiums in the UIP, and may thus invalidate the results and mechanisms presented there.

of volatility) than other regimes. When output/consumption stability is of primary concern, some kind of exchange rate management through interventions will help achieve this objective across several shock types. On the other hand, if inflation is the main objective, then the free float is a robust policy response. We leave the general validation of these lessons, and the analysis of how they depend on the calibration to specific economies, to further research.

Limits of interventions

Our analysis suggests that interventions are a viable policy instrument that could be used in a systematic way to improve monetary policy performance. However, two broad sets of arguments qualify that conclusion.

First, our analysis abstracts from practical consequences of markets knowing the central bank's intervention reaction function. Market knowledge of such a function for interest rates is commonly assumed and often desirable, but intervention and exchange rate rules are more problematic. Suck an awareness by the markets may help the central bank to achieve its objectives more easily, but it could also lead to lethal speculative attacks. As a result, most intervening central banks prefer to keep their intervention tactics (i.e. the reaction function) hidden, if possible, to preserve credibility.

Such concerns are less acute for the interest rate rule, because the central bank is the ultimate market maker in the money market and because capital gains and losses are very limited for short-duration securities—unlike in the FX market. As Woodford (2005) argues though, in the case of interest rate rules practical considerations tend to favor short–term, as opposed to long–term, rates as the operating target. Otherwise, the predictability of the rule is likely to create distortions and unnecessary volatility in the money markets—essentially speculative attacks on long bonds—especially before dates when monetary policy measures are taken.

The threat of an attack arises especially when the markets believe that the central bank does not understand the nature of the exchange rate movements. While our analysis assumes the central bank always knows perfectly what kind of shock it deals with, in reality this perfect knowledge is difficult to achieve and markets often have a different opinion, leading them to probe the central bank's resolve.

A typical example is when markets and central banks disagree whether the exchange rate movement is driven by permanent or temporary shocks. Permanent shocks, i.e. shocks changing the steady state level of real variables, require a different response than temporary shocks. Figures 2 and 3 show model reactions to temporary and permanent terms-of-trade shocks. The initial size of the shock is same in both cases, but while the shock gradually dissipates in Figure 2, the terms-of-trade remain at a permanently lower level in Figure 3.

The permanently worse terms-of-trade require permanent real adjustments, such as a permanently weaker real exchange rate (not shown) and a permanently lower consumption level. The new weaker real exchange rate level can be achieved either via a weaker nominal exchange rate or a permanently lower price level. The former is the outcome under the floating regimes, while fixed exchange rate regimes tend to experience deflation. At the same time the fixed regimes kept by interventions require a larger spending of reserves to keep the exchange rate at the parity.

As the comparison with the temporary shock in Figure 2 reveals, the amount of reserves required to keep the peg—as well as the extent of deflation—are much larger when the shock is permanent. Such cases therefore typically lead for a parity adjustment—something which is beyond the scope of this paper. However, the initial symptoms of the permanent shocks are similar to temporary ones and can easily mislead the central banks into believing that the peg is easily defendable, which can then spark a market attack.

Another example of a practical difficulty in using intervention and exchange rate targets is the consistency of exchange rate and inflation intermediate targets. While in our analysis we assume this consistency, it can be very difficult to achieve in practice, because it requires a good assessment of the equilibrium real exchange rate movements that link them together.

The second set of arguments on why interventions may not be viable as a systematic policy instrument involves the so called "impossible trinity'.[22] This asserts that independent monetary policy cannot function with a fixed exchange rate and a free capital account, because the financial flows unleashed by any interest rate differential would make the peg short-lived. For instance, an attempt to keep interest rates lower (say, to stimulate the economy) than foreign rates adjusted for a risk premium would trigger an outflow, eventually bringing down the peg, as FX reserves run out.

Our analysis does not contradict the impossible trinity. The impossible trinity is about long-term sustainability: a fixed exchange rate requires the sacrifice of either independent monetary policy or capital account openness. The former goes in the case of exchange rate targeting via interest rates. To keep the exchange rate fixed coefficient χ in the interest rate rule is infinite, collapsing the rule into $S = S_T$. Monetary policy loses its independence, as the domestic interest rates become determined by the foreign rates through the UIP in (6).

On the other hand, keeping the exchange rate fixed via interventions has ω infinite, collapsing the intervention rule into $S = S_T$, while the interest rate rule (4) stays unchanged, preserving monetary policy autonomy. Note however, that a large $\Omega_O'(F/P)$ reduces sensitivity of the UIP condition (6) to domestic interest rates, in effect partly insulating the exchange rate from interest rate arbitrage. In other words, FX interventions act as if they were constraining capital account openness, as required by the impossible trinity. This partial capital account closure does not take place through administrative measures, but by adjusting market balance sheet positions. The key for this mechanism to work is an interior solution for optimal balance sheet holdings. In other words, while the adjustments in the balance sheets are instantaneous, they are finite, because we assume that extreme accumulations (or decumulations) are progressively costlier and/or riskier. The peg is therefore sustainable as long as the CB has enough reserves. In Figure 4, we study what happens when the economy

[22]The literature on the impossible trinity is time-honored and extensively large. See Obstfeld, Shambaugh and Taylor (2004) for a historical perspective.

is hit with the same shock to foreign interest rates but with a premium that is twenty times less sensitive to sterilized interventions (compared to the baseline case). In this case a one percent increase in foreign interest rates results in a loss of one fourth of the country reserves. This simulation underscores the risks to intervention when interest premia are not very sensitive to balance sheet operations.[23]

A corollary is that managed floating regimes can be more robust to uncertainty about the effectiveness of interventions. Because the rule is specified in terms of volumes of intervention, a low sensitivity of the premium to interventions implies that the intervention will not make much difference, but there is also little risk of running out of reserves.[24] On the other hand, when a peg is enforced by intervention, a low sensitivity of the premium creates great risks of running out reserves, as in Figure 4.

VII. Conclusions

The modeling of regimes that combine IT with various degrees of exchange rate management—and of the mechanisms that make such combinations possible—is an important issue for many central banks and institutions. Unlike for "pure" IT, an analytical framework for these hybrid regimes has not yet been established, and standard analytical approaches appear unfit for the policy reality in emerging and developing countries.

In general, the coexistence of some form of IT with some kind of exchange rate management is a common phenomenon in many countries, at least informally. For instance, there are countries with a fixed or strongly managed exchange rate that are in transition towards a more flexible exchange rate regime and implement elements of inflation targeting by controlling short-term interest rates. Others attempt to control excessive exchange rate fluctuations by interventions of various forms (e.g., sterilization of inflows). Some even recognize two explicit intermediate targets in terms of the exchange rate and inflation bands.

Our paper provides a framework for modeling monetary policy in such economies. The framework is useful for modeling hybrid IT regimes of informal exchange rate corridors, pegged or crawling exchange rates, and comparing them to pure floats. It features an FX intervention rule operating as an independent instrument alongside the standard interest rate rule. Balance sheet effects are needed in order to make both rules functional, and in our framework they are introduced through a simple financial sector and endogenous interest rate premiums (spreads).

We believe our paper sets the stage for useful extensions in several directions. First, more work can be done in mapping the intervention mechanism to micro-foundations and thus strengthening the academic rigor of the analysis. Our appendices show two such avenues that

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[23] A third objection to the use of sterilized interventions is that they may raise the domestic real interest rate (Calvo, Reinhart and Vegh (1995). Depending on the stock of outstanding public domestic debt, the intervention may have a sizeable fiscal impact.

[24] This result is available upon request.

we think deserve attention. For instance, using the portfolio choice theory in making interest rate premiums a function of portfolio allocations is a particularly attractive way of introducing portfolio effects in a wide range of applications. In the other avenue, the empirical literature on the micro behavior of banks could substantiate the role of banking production/cost functions in creating endogenous interest rate premiums, especially when banks are the sole or main participants in the FX market.

Second, a formal welfare analysis could be applied to study the use of intervention and interest rate rules. The simulations in Section 6 of our paper show an attempt in this direction by quantifying the second moments of the main variables implied by a particular combination of policy and shocks. A formal study of welfare effects could also recast the analysis in terms of target rather than instrument rules. Finally, an advantage of our approach is that it can be used to study the behavior of central banks empirically. Our approach encompasses as special cases most common exchange rate regimes, including crawling pegs, soft (i.e. unenforceable) exchange rate corridors as well as a managed float with leaning-against-the-wind interventions. By calibrating the model to specific country data one can study the effects of different policies as well as to gauge the strength of each instrument needed to combat a particular shock.

APPENDIX A STERILIZED INTERVENTIONS IN QUANTITY BASED MONETARY POLICY

This appendix extends the analysis of the main text to the case where the central bank makes decisions about sterilized quantities rather than the interest rate. The main text assumes the central bank controls the money market rates perfectly at all times by adjusting its sterilizing operations (O) so that the inter-bank rate i is always at the desired (operational target) level i^T.[25] However, these operations are not explicitly present in the model.

This extension is useful for describing the behavior of central banks that do not control market interest rates perfectly, such as money targeting central banks or banks that use 'unconventional' monetary practices, such as affecting the exchange rate behavior through additional supply of free liquidity (as attempted by Switzerland in 2011).

Modifying the central bank balance sheet

The extension introduces a downward sloping sterilization demand curve of the central bank. While the supply curve is given by the commercial bank behavior in (6), the main text makes the sterilized amount O a residual item determined from the central bank balance sheet by the central bank's choice of F in (3). However, this is a simplifying short-cut.

In order for the decisions over F and O to be independent as central bank instruments, the central bank balance sheet needs to include another residual term - free reserves held by the commercial banks at the central bank (R):

Central Bank		Financial Sector		Households	
F	O	O	B		L
	R	L			NW
		R			

The central bank now has one extra choice variable - the sterilized amount O, which we assume evolves according to a rule similar to (3):

$$\frac{O}{L} = \frac{\overline{O}}{L} - \tau(i - i^T), \tag{10}$$

where $\frac{\overline{O}}{L}$ is the parametrized steady state ratio of the sterilized stock and credits (NFL).

The sterilization rule (10) assumes the central bank adjusts its sterilizing operations according to deviations of the sterilization (and also market) interest rates i from the

[25]Because in our model the interbank liquidity market always clears, the sterilization rate is the marginal return on bank's assets and hence equals the money market rate. Therefore, the perfect control over sterilization rate also implies perfect control over money market rates.

operational target level i^T.[26] If the rate achieved in sterilizing operations exceeds the target, the sterilized amount will decline, pressing down the sterilization rate through the upward sloping supply curve of commercial banks (6). The results in the main body of the paper occur, when τ is infinite. On the other hand, the central bank completely resigns to using interest rates as operational targets, when $\tau = 0$.

Finally, the central bank has to decide on the rate at which to remunerate the free reserves that are not sterilized using its main operations—i^R. For simplicity, we assume the reserves are remunerated at the sterilized rate, i.e. $i^R = i^T$, which is the best practice.[27]

Modifying the financial sector

We introduce an upward sloping supply curve of reserves from the perspective of the financial sector firms, as follows:

$$\exp(i^R) = \exp(i^*)\frac{S_{+1}}{S} + \Omega_R(R/P),\ \Omega_R'(.) > 0 \tag{11}$$

while the other conditions (6) and (7) remain unchanged.[28]

The central bank demand for reserves is horizontal at the given remuneration rate. This is important, because as long as the central bank does not sterilize the entire liquidity of the financial system through *O*, then the marginal return to domestic currency is defined by the remuneration rate i^R, which affects the effectiveness of monetary policy transmission as well as the exchange rate dynamics.

The analysis can further be extended to the situation, when there are both sterilizing and refinancing operations at the same time. While uninteresting for most developed and emerging economies, the case is relevant for many developing countries that rely on liquidity targeting as their operational target through both sterilizing and refinancing operations.

APPENDIX B

This appendix presents two ways of rationalizing a UIP spread increasing in the stock of the central bank's FX reserves (interventions): portfolio allocation and the bank cost function.

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[26] Other potential operational target variables, such as reserve money targets can easily be added. However, for compactness we keep the economy cash-less.

[27] The most common alternative is remunerating free reserves at a zero rate. This is also possible in our framework, but would necessitate modifications to steady state assumptions.

[28] The new condition can be easily derived in both the portfolio balance or cost minimization approaches.

Portfolio allocation approach

Assume that instead of being risk neutral the financial sector firms are risk averse and compose their portfolio so as to maximize a risk adjusted expected real revenue from the asset portfolio:

$$\max_{L,O,B}\left\{E\left(\widetilde{RR}_{+1}\right)-\frac{c}{2}var(\widetilde{RR}_{+1})\right\} s.t.\, L+O=B$$

where c is a risk aversion parameter and tilde denotes the actual random variable (so that $E(\widetilde{x}_{+1})=x_{+1}$, and $E(.)$ and $var(.)$ are the expected real revenue from the asset portfolio and its variance expressed in domestic currency:

$$\begin{aligned}
E\left(\widetilde{RR}_{+1}\right) &= \frac{\exp(j)L}{P_{+1}}+\frac{\exp(i)O}{P_{+1}}-\frac{\exp(i^*)B}{P_{+1}}\frac{S_{+1}}{S} \\
var(\widetilde{RR}_{+1}) &= \frac{\exp(j)^2L^2\sigma_P^2}{P^2}+\frac{\exp(i)^2O^2\sigma_P^2}{P^2}+\frac{\exp(i^*)^2\, B^2(\sigma_S^2+\sigma_P^2)}{P^2}
\end{aligned}$$

where σ_S^2 denotes the model implied variance of exchange rate depreciation $\frac{\widetilde{S}_{+1}}{S}$ and σ_P^2 the model implied variance of the inverse of inflation rate $\frac{P}{\widetilde{P}_{+1}}$ and where we assume (inconsistently, for the sake of simplicity) that inflation does not correlate with the exchange rate.
The FOCs are:

$$\begin{aligned}
\exp(i) &= \exp(i^*)\frac{S_{+1}}{S}+c\frac{P_{+1}}{P}\left(\exp(i)^2\sigma_P^2\frac{O}{P}+\exp(i^*)^2(\sigma_S^2+\sigma_P^2)\frac{O+L}{P}\right) \\
\exp(j) &= \exp(i).
\end{aligned}$$

The first condition derives the UIP equation with a spread that is linear in the stock of FX reserves expressed in real terms ($O=F$). The other merely states that in the absence of a risk differentiation between central bank papers and loans, the banks are indifferent and hence both the loans and the papers need to carry the same interest rates in the optimum.

The spread (risk premium) in the UIP is also proportional to the size of the foreign exposure $(O+L)$, because the banks care about the absolute size of the risk and we assume the banks' balance sheet is fully exposed to the exchange rate risk. If the central bank accumulates FX (say to prevent appreciation following a capital inflow), it increases the risk premium that weakens the exchange rate.

The cost function approach

The perfectly competitive commercial banks (owned by households) maximize their cash flow subject to a technological constraint expressed by a cost function $\Omega(O,L)$ that is assumed to be properly behaved and linearly homogeneous, such as in Edwards and Vegh (1997):

$$\Omega(O,L),\ \Omega_i(.)>0,\ \Omega_{ii}(.)>0,\ \Omega_{ij}(.)<0,\ i,j\epsilon\{O,L\}$$

The function stipulates that loans and OMOs are not perfect substitutes on the asset side of the balance sheet, and hence can carry different interest rates. A specific example is Diewert's cost function (as in Benes et al, 2008):

$$\Omega(O,L)=\theta_O O+\theta_L L-2\theta\sqrt{OL}.$$

Two features of the cost function are worth mentioning:

- the choice of arguments in which the cost function is increasing and concave, i.e. $\Omega_i(.)>0,\ \Omega_{ii}(.)>0$, and
- the cost complementarity, i.e. negative cross terms between the arguments $\Omega_{ij}(.)<0$.

The first feature is related to the absence of product specific economies of scale in the banking industry, while the other to the existence of economies of scope.[29]

Out of the two, only the former is crucial for our main results. It guarantees that the supply curves of loans and sterilized liquidity are upward sloping, and hence the financial variables are properly determined. It is also this feature that makes the FX intervention mechanism to work.

On the other hand, the complementarity of arguments in the cost function makes the spreads functions of the ratio of the FX reserves to NFL. The linear homogeneity paves way for introducing deterministic trends in the financial sector variables. As long as the ratio of the financial sector variables is stationary, the linear homogeneity allows the spreads to be stationary even in the presence of trends.

The banks maximize the net present value of the cash flow stream given by the following recursive cash flow formula over the balance sheet items *L*, *O* and *B* subject to the cost function and the balance sheet restriction, and taking interest rates as given:

[29] Assuming product specific scale economies are defined as declining marginal costs. There are numerous other definitions, though (see e.g. Clark, 1988). The economies of scope are defined as lower costs of producing a combined set of products than the sum of costs producing them individually.

$$\Pi = \exp(j_{-1})L_{-1} - L + \exp(i_{-1})O_{-1} - O + B - \exp(i^*_{-1})B_{-1}\frac{S}{S_{-1}} - \Omega(O_{-1}, L_{-1}),$$

where j is the interest rate banks charge on loans to households. Imposing the balance sheet identity and iterating one period forward turns this problem into a static one:

$$\max_{\{O,L\}} \Pi_{+1} = \exp(j)L + \exp(i)O - O + \exp(i^*)\left(O + L\right)\frac{S_{+1}}{S} - \Omega(O, L).$$

The FOCs for this problem are:

$$\begin{aligned}
\exp(i) &= \exp(i^*)\frac{S_{+1}}{S} + \Omega_O(.) = \exp(i^*)\frac{S_{+1}}{S} + \theta_O - \theta\sqrt{\frac{L}{O}} && (12)\\
\exp(j) &= \exp(i^*)\frac{S_{+1}}{S} + \Omega_L(.) = \exp(i^*)\frac{S_{+1}}{S} + \theta_L - \theta\sqrt{\frac{O}{L}} && (13)\\
&= \exp(i) - \Omega_O(.) + \Omega_L(.)\\
&= \exp(i) + \theta_L - \theta_O - \theta\sqrt{\frac{O}{L}}\left(1 - \frac{L}{O}\right)
\end{aligned}$$

Condition (12) derives the UIP condition with a spread (premium) equal to $\Theta = \theta_O - \theta\sqrt{\frac{L}{F}}$. As *i* is defined by the Taylor rule, the UIP condition defines the exchange rate expectations (for a given spread). The important observation is that the spread is *increasing* in the ratio of FX reserves to NFL.

Condition (13) defines an upward sloping credit supply curve. The condition also introduces an interest rate spread between policy and credit rates of $\theta_L - \theta_O - \theta\sqrt{\frac{O}{L}}\left(1 - \frac{L}{O}\right)$. Note that because of linear homogeneity of the cost function this spread is falling in the FX to loan (NFL) ratio.

APPENDIX C THE COMPLETE MODEL

Households

The household's maximization of utility subject to the budget constraint in (8) leads to the following first order conditions:

$$\lambda P = \frac{1}{C},$$

a labor supply condition

$$N^{\phi} = \lambda W,$$

and the Euler equation

$$\lambda \left(1 - \varrho(\frac{L}{P})\right) / \lambda_{+1} = \beta \exp{(j)},$$

where $\varrho(\frac{L}{P})$ has the following functional form

$$\varrho(\frac{L}{P}) = \varrho \left(\frac{L}{P} - \overline{\frac{L}{P}}\right).$$

Consumption is an aggregate of non–traded goods C_n and imports C_m:

$$C = C_n^{\omega_n} C_m^{1-\omega_n},$$

resulting in the following demand functions:

$$P_n \frac{C_n}{\exp(\epsilon_{cn})} = \omega_n PC, \qquad P_m C_m = (1 - \omega_n) P_c C.$$

P_n and P_m denote prices for C_n and C_m, respectively. CPI inflation ($\pi_t = log(P) - log(P_{-1})$) is given by:

$$\pi = \omega_n \left(log(P_n) - log(P_{n-1})\right) + (1 - \omega_n) \left(log(P_m) - log(P_{m-1})\right) = \omega_n \pi_n + (1 - \omega_n) \pi_m$$

The household's outstanding stock of loans—the country's net foreign liabilities—is given by

$$L = L_{-1} \left(\exp(i^*) + \pi_S\right) + \left(P_m C_m - P_x Y_x\right),$$

where $\pi_S = log(S) - log(S_{-1})$.

Banks/Financial Intermediaries

As discussed in the main text, the arbitrage conditions in the financial sector are the following

$$exp(i) = exp(i^* + \pi_{S_{+1}})\Omega_O, \qquad exp(j) = exp(i^* + \pi_{S_{+1}})\Omega_L,$$

where

$$log(\Omega_O) = \Omega_O \left(\frac{F}{P} - \overline{\frac{F}{P}}\right) + \epsilon_{prem},$$

and

$$log(\Omega_L) = 0.$$

Non–traded Producers

There is a continuum of firms in the non–traded sector, each having a monopoly on the production of a variety of the non–traded good. Cost minimization results in the following labor demand condition

$$\gamma_n MC_n C_n = N_n W,$$

where γ_n is labor share in the non–traded sector and MC_n denotes the representaive firm's nominal marginal cost. Firms are subject to nominal rigidities, resulting to the following Phillips curve:

$$\pi_n - \pi_{n_{-1}} = \beta \left(\pi_{n_{+1}} - \pi_n\right) + \xi_n \log\left(\frac{P_n^{flex}}{P_n}\right) + \epsilon_{\pi_n},$$

where P_n^{flex} is a notional flexible price level

$$P_n^{flex} = \mu MC_n.$$

Finally, equilibrium in the non–traded sector requires

$$C_n = N_n^{\gamma_n}.$$

Exporters

Exporters face a similar profit maximization problem, the main difference being that they set prices in foreign currency:

$$\gamma_x MC_x Y_x = N_x W,$$
$$P_x^{flex} = \mu MC_x,$$
$$Y_x = A_x N_x^{\gamma_x},$$

and

$$(\pi_x - \pi_S) - \left(\pi_{x_{-1}} - \pi_{S_{-1}}\right) = \beta\left(\left(\pi_{x_{+1}} - \pi_{S_{+1}}\right) - (\pi_x - \pi_S)\right) + \xi_x \log\left(\frac{P_x^{flex}}{P_x}\right).$$

Importers

Importers profit maximization conditions are the following:

$$P_m^{flex} = \mu MC_m,$$

$$MC_m = SP_M^*,$$

$$\pi_m - \pi_{m_{-1}} = \beta\left(\pi_{m_{+1}} - \pi_m\right) + \xi_m \log\left(\frac{P_m^{flex}}{P_m}\right).$$

Monetary Policy

Monetary policy is as described in the main text.

Rest of the World

Demand for exports is given by

$$P_x Y_x = P_x^* \overline{Y_w} \exp\left(\epsilon_{yw}\right).$$

The country's terms of trade $T = SP_x^*/P_m^*$ follow an autoregressive progress

$$\log(T) = \rho_{tot} \log\left(T_{-1}\right) - \epsilon_{tot}.$$

Finally, foreign interest rates also follow an autoregressive process:

$$i^* = \rho_{i^*} i_{-1}^* + (1 - \rho_{i^*})\bar{i} + \epsilon_{i^*},$$

where $\bar{i} = 1/\beta + \pi^T$.

Calibration

Parameter	Value	Parameter	Value
ρ	0.7	ξ_n	0.01
α	3	ξ_x	0.5
δ	0	ξ_m	0.5
β	0.9975	ρ_{i^*}	0.8
ϱ	0.01	ρ_{tot} (temporary)	0.8
ω_n	0.5	ρ_{tot} (permanent)	1
ϕ	0.5	s^T	0
Ω_o	0.201	π^T	0
γ_n	0.5	$\overline{F/L}$	1.503
γ_x	0.5	$\overline{L/P}$	0.679
μ	1.1		

	Inflation	Δ Ex Rate	Cons	Exports	Int Rate	FX Res.
Foreign Interest Rate Shock						
IT pure float	1	1	1	1	1	0
Fixed via interventions	0.5	0	0.9	0.8	0.5	12.4
Fixed via taylor	0.4	0	1.3	0.8	1.1	0
Ex rate corridor	0.4	0.5	0.9	0.9	0.3	7.1
IT managed float	0.5	0.2	1	0.8	0.5	7.6
NT Consumption Shock						
Fixed via interventions	2.5	0	0.9	0.8	1.6	0.4
Fixed via taylor	2.4	0	1.1	0.9	2.9	0
Ex rate corridor	1.6	0.7	1	0.9	1.2	0.2
IT managed float	1.6	0.2	0.9	0.9	1.3	0.4
NT Inflation Shock						
Fixed via interventions	3.6	0	0.8	0.6	3.6	15.7
Fixed via taylor	3.4	0	0.8	0.5	0.1	0
Ex rate corridor	2.3	0.5	0.7	0.5	2.2	8.3
IT managed float	2.1	0.3	0.8	0.6	2	10.6
Temp ToT Shock						
Fixed via interventions	2.7	0	1	1.2	3.2	2.7
Fixed via taylor	2.4	0	1.1	1.2	0.6	0
Ex rate corridor	1.6	0.5	1	1.1	1.7	1.5
IT managed float	0.9	0.3	1	1.2	1.2	1.5

Table 1: **Macroeconomic volatility under various policy regimes.**
The tables show normalized unconditional standard errors of model variables assuming that the only source of volatility is the shock in the table heading. The normalization of each shock is relative to the IT/pure float case, except for movements in FX reserves whose real value is constant in the fully floating case—absolute variance is used instead.

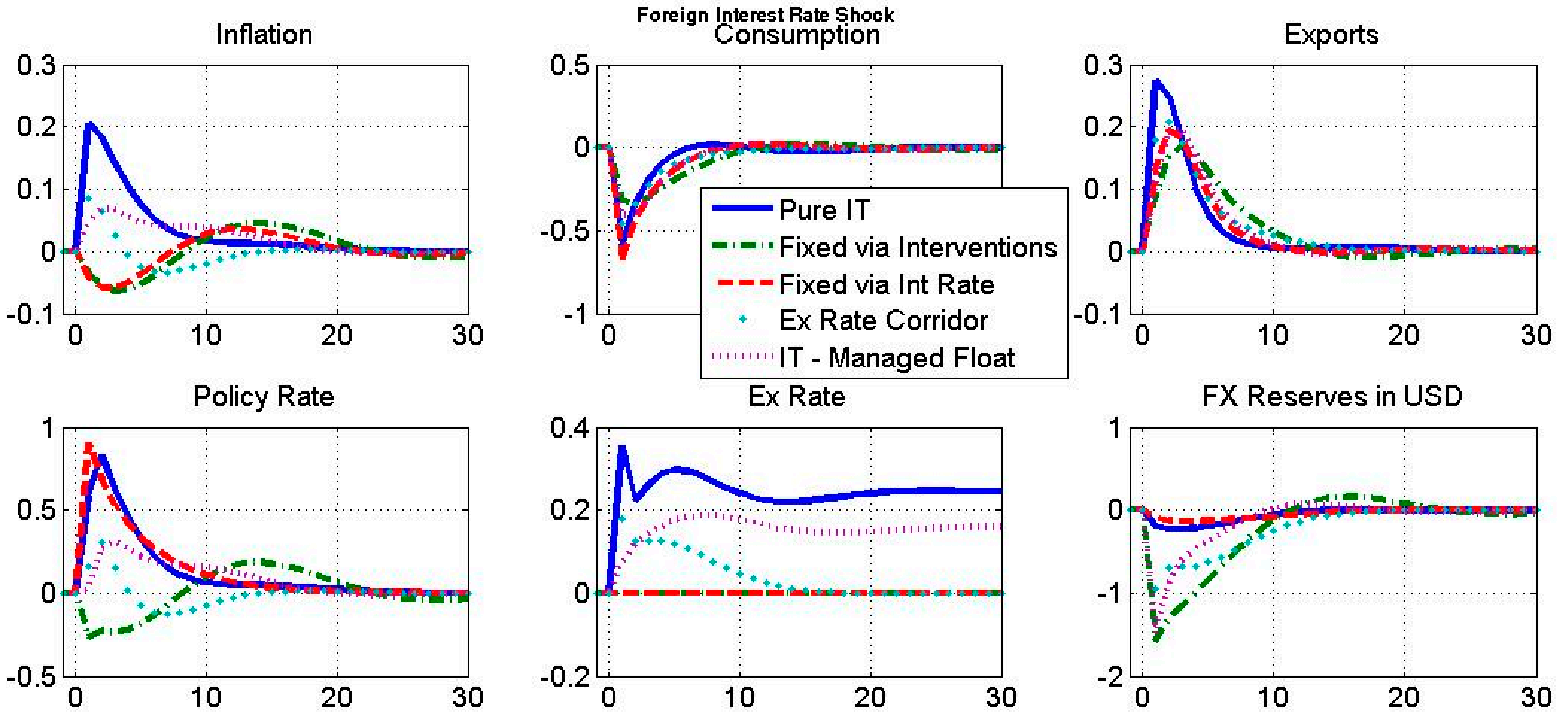

Figure 1: Foreign Interest Rate Shock in Different Exchange Rate Regimes

"Pure" IT Simulation simulation (blue, solid line), fixed via Intervention simulation (green, dashed with dots), fixed via interest rates simulations (red, dashed), exchange rate corridor simulation (light blue, dotted), IT managed float simulation(magenta, dashed) . Units are percentage deviations from steady state.

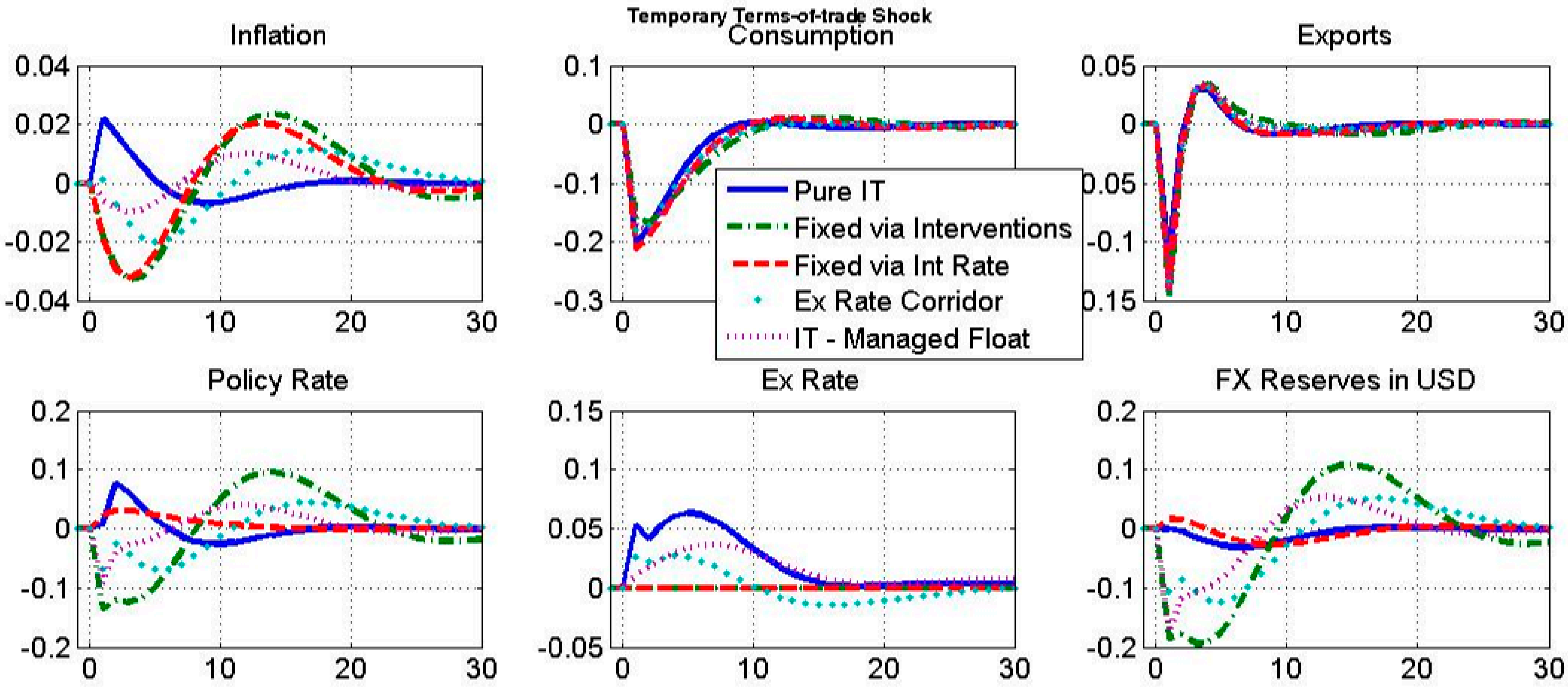

Figure 2: Temporary terms-of-trade shock in different exchange rate regimes

"Pure" IT Simulation simulation (blue, solid line), fixed via Intervention simulation (green, dashed with dots), fixed via interest rates simulations (red, dashed), exchange rate corridor simulation (light blue, dotted), IT managed float simulation(magenta, dashed) . Units are percentage deviations from steady state.

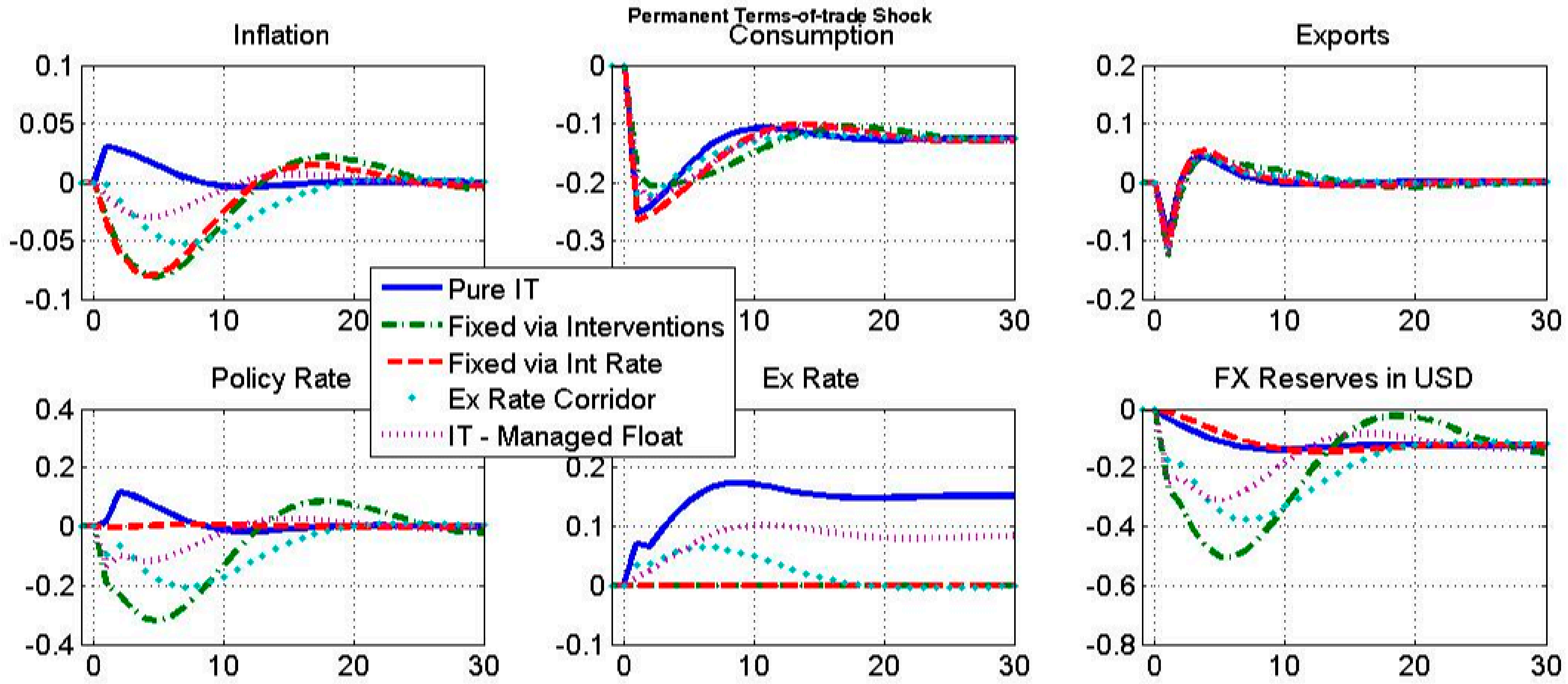

Figure 3: Permanent terms-of-trade shock in different exchange rate regimes

"Pure" IT Simulation simulation (blue, solid line), fixed via Intervention simulation (green, dashed with dots), fixed via interest rates simulations (red, dashed), exchange rate corridor simulation (light blue, dotted), IT managed float simulation(magenta, dashed) . Units are percentage deviations from steady state.

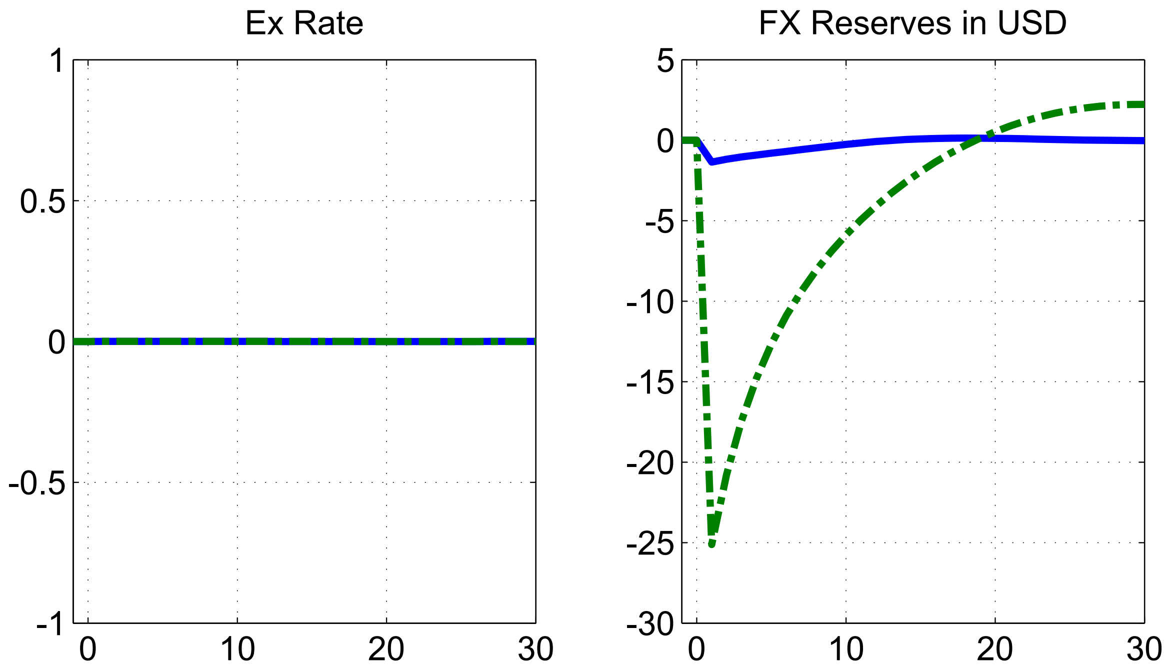

Figure 4: Foreign Interest Rate Shock Under Fixed Exchange Rate Regime Via Interventions
strong sensitivity to sterilized interventions (blue, solid line), weak sensitivity to sterilized interventions (green, dashed with dots).

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