

# Managing Capital Outflows with Limited Reserves\*

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## Abstract

We analyze the optimal intervention policy for an emerging market central bank that wishes to stabilize the exchange rate during a capital outflow episode, but possesses limited reserves. Using a linear-quadratic framework, we show that the zero lower bound on reserves generates a time inconsistency problem. A central bank with full commitment achieves a gradual depreciation to the pure-float level by promising sustained future intervention, such that reserves are exhausted after particularly adverse shocks. A central bank without commitment intervenes little, wishing to preserve some reserves forever, and suffers a larger immediate exchange rate depreciation and associated welfare cost. For more persistent shocks, the time inconsistency problem is greater, and simple intervention rules can achieve welfare gains relative to discretion.

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# 1. Introduction

How should central banks in emerging market economies (EMEs) intervene in the foreign exchange (FX) market when faced with capital outflows? As capital flows to EMEs have begun to retrench and reverse after the post-crisis inflow surge, and as new risks to the global economy have surfaced, many countries are grappling with this question.

The principle that EME central banks may have reason to undertake sterilized FX intervention in response to inflow shocks has become increasingly accepted. There is growing recognition that owing to financial market imperfections, exchange rates may become disconnected from traditional macroeconomic fundamentals and instead turn into a source of shocks (*e.g.*, Jeanne and Rose, 2002; Gabaix and Maggiori, 2015). Moreover, several papers have found that sterilized intervention has had traction on the exchange rate in EMEs, at least under some circumstances (*e.g.*, Blanchard, Adler and Filho, 2015; Chamon, Garcia and Souza, 2015). As a result, some policymakers and academics have endorsed the use of FX intervention alongside monetary policy in the face of capital inflows (in particular, see Ghosh, Ostry, and Chamon, 2016, and Blanchard, Ostry, Ghosh, and Chamon, 2015). Such research has provided intellectual backing for the growing popularity among EMEs of managed float regimes, as documented by Ghosh, Ostry, and Qureshi (2015).

However, the optimal FX intervention policy for a managed float regime facing outflow shocks is not well understood. Inflow and outflow shocks are conceptually different, because the latter may result in the central bank depleting its entire stock of reserves, leaving it no scope to intervene further. In addition, the persistence of the shock may be different according to the direction of capital flows. In the absence of a clear policy framework taking these considerations into account, the conventional wisdom has been that the central bank should refrain from intervening in the face of outflows except to counter severe market dysfunction. Indeed, in cases where the central bank has intervened to counteract capital outflows, but has ultimately allowed the exchange rate to be devalued or to depreciate, it is common for the financial press to talk of reserves being “wasted.”<sup>1</sup>

In practice, EME central banks with managed floats have behaved in a heterogeneous manner when faced with capital outflows. To gain some appreciation of the judgments and trade-offs that central banks need to make, we highlight in this paper some notable cases of EME outflow episodes where sterilized FX intervention was used.<sup>2</sup> Several salient features stand out. First, central banks in managed float regimes typically find significant value in

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<sup>1</sup>Wildau and Mitchell (2016) document that “Critics say PBoC [People’s Bank of China] spending on intervention has been a waste because it has only delayed further weakness in the renminbi.” Subramanian (2013), when assessing the effectiveness of India’s FX intervention during the taper tantrum, states by way of background his opinion that “international experience suggests that sterilized intervention to defend a currency, especially during crises, tends to be ineffective or counterproductive.”

<sup>2</sup>The specific outflow episodes we highlight are: Russia 2008Q2, Korea 2008Q2, Brazil 2013Q1, India 2013Q2, Russia 2013Q4, and China 2014Q1. See Section 2 for more details.

delaying the depreciation of the exchange rate to the pure-float level—for example, such a delay may help cushion the domestic economy by providing time for private sector agents to unwind their FX positions. Second, central banks behave differently depending on how large their initial reserve stock is relative to the shock, and on the probability of the shock continuing for many periods.

In this paper, we characterize the optimal FX intervention policy in response to capital outflows in a managed float regime. We take explicit account of the zero lower bound (ZLB) on reserves, which is a distinguishing feature of the outflows case. We also show how the optimal policy depends on the nature of the shock. To preserve the tractability necessary to solve the model under different degrees of commitment, we explore these issues by building on a stylized theoretical framework: a linear-quadratic model where the central bank has an exchange rate target subject to an exchange rate equation. The objective function includes a discount factor that reflects the desire to delay depreciation, while the form of the exchange rate equation captures various forms of limited capital mobility.<sup>3</sup> We abstract from alternative policy tools such as interest rates in order to focus on the FX intervention policies; we thus consider *sterilized* intervention, which is how central banks typically intervene in the FX market.<sup>4</sup>

We derive three key insights, which we believe to be qualitatively robust across a range of models that combine the ZLB on reserves with imperfect arbitrage on the FX market.

Our first insight is that at the start of an outflow episode, a central bank with full commitment and limited reserves optimally promises to intervene in the future, and may not intervene at all today. The exchange rate is a forward-looking asset price: therefore, any promised FX intervention causes the exchange rate to appreciate both in the period of the intervention and also in all previous periods through changes to investors’ expectations. The further in the future the intervention is promised, the larger the number of periods prior to intervention in which the “expectations channel” can be exploited to stabilize exchange rates, implying a larger “bang per buck” from the use of the central bank’s scarce reserves. At the same time, intervention too far in the future is not desirable because of the discounting of future welfare gains. The trade-off between the expectations channel and discounting yields the set of future dates at which FX intervention is optimally promised.

The optimal full-commitment policy is for the central bank to promise a path of sustained intervention in the future, which is aggressive enough that the entire reserves stock eventually becomes depleted if the shock persists. This policy achieves a gradual depreciation to the pure-float level during the outflow episode. Notice that unlike the bipolar regimes of free

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<sup>3</sup>Limited capital mobility encompasses imperfect asset substitutability (*e.g.*, Kouri, 1976, and Blanchard, Giavazzi, and Sa, 2005) and imperfect arbitrage owing to balance sheet constraints on international financial intermediaries (*e.g.*, Gabaix and Maggiori, 2015).

<sup>4</sup>We do not consider capital outflow controls, which may both reduce the effective magnitude of outflow shocks and worsen the financial intermediaries’ ability to arbitrage returns. The first effect reduces the need for intervention to defend the exchange rate, while the second effect strengthens the traction of intervention.

floats and hard pegs, FX intervention and depreciation are jointly optimal under a managed float, even if reserves eventually run out.

Our second insight is that because of limited reserves, the full-commitment solution is not time consistent. We therefore solve for the time-consistent solution, in which the central bank re-optimizes at every date, ignoring past promises.<sup>5</sup> FX intervention turns out to be low, because the central bank recognizes that in the absence of credible promises, a high level of reserves remaining in the vault today is necessary to bolster investors' expectations regarding intervention by "future" central banks, which in turn helps to stabilize the current exchange rate through the "expectations channel." As a result of intervention being low in every period, reserves never run out. Relative to the full-commitment solution, the time-consistent solution involves a larger exchange rate depreciation as soon as the outflow episode begins, with a correspondingly higher welfare cost.

Simple intervention rules, such as a temporary peg or a rule to offset a fraction of the outflow shock, improve welfare above the time-consistent level by avoiding the large immediate depreciation. A central bank with partial commitment power—*i.e.*, one that can commit to simple rules but not to the possibly complicated full-commitment intervention policy—should announce its commitment to such rules at the start of an outflow episode.

Our third insight is that the optimal policy is affected by the persistence of the shock. The more persistent the shock is expected to be, the more delayed is the timing of the full-commitment FX intervention, and the lower is the level of the time-consistent FX intervention.<sup>6</sup> The time consistency problem is more severe for persistent shocks: the longer the outflow episode is expected to last, the more important are investors' expectations of future interventions for determining the exchange rate today, and so the more costly in welfare terms is the absence of credible promises to intervene in the future. Therefore, a simple FX intervention rule is more likely to achieve welfare gains above the time-consistent solution when the shock is persistent than when it is temporary.

A roadmap of our paper is as follows. For the remainder of the introduction, we provide a summary of the related literature. Section 2 highlights some cases where EME central banks have intervened in response to outflow shocks. Section 3 presents our baseline model. Section 4 solves the model for the deterministic case, with subsections on full commitment, time consistency, and simple rules. Section 5 solves the model for the stochastic case, highlighting the role of shock persistence. Section 6 concludes.

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<sup>5</sup>The time-consistent solution must be solved using numerical fixed-point methods. The stylized nature of our model makes the problem tractable enough to solve under a variety of parameter choices.

<sup>6</sup>There is a time consistency problem as long as there is a non-zero probability of reserves being exhausted in the full-commitment solution.

*Related Literature.* Our exchange rate equation assumes the existence of imperfections in the FX market that give rise to two properties: first, finite capital flows in every period even if expected returns are not equalized across bonds denominated in different currencies; and second, a role for sterilized FX intervention. On the first property, the early portfolio balance literature, initiated by Kouri (1976, 1983), established that imperfect substitutability between domestic and foreign assets can indeed generate capital flows that are always finite in size, which in turn means that the uncovered interest parity (UIP) condition central to Dornbusch (1976) is generally broken. Kouri’s work immediately inspired an array of portfolio demand models, for different country configurations and with varied emphases on valuation effects.<sup>7</sup> More recently, Obstfeld (2004) calls for renewed attention to international portfolio positions, and Blanchard, Giavazzi and Sa (2005) build a theoretical model designed to capture valuation effects on gross asset positions.

On the second property, Backus and Kehoe (1989) establish that sterilized FX intervention has no effect in a model with micro-founded welfare and free trade in bonds of different currencies (a weak arbitrage condition). Gabaix and Maggiori (2015) restore a role for intervention by combining the portfolio balance literature with a financial friction that limits the ability of international financial intermediaries to arbitrage excess returns in the FX market. With such a friction, changes in the currency composition of assets cannot be instantaneously undone by participants on FX markets, and instead the attempts by these actors to undo the changes generate real effects. This central role for imperfect arbitrage builds on the literature on the segmentation of asset markets owing to financial frictions.<sup>8</sup>

The growing emphasis on frictions in the asset market in exchange rate models<sup>9</sup> naturally leads to the result that the exchange rate can be driven by shocks to financial intermediaries themselves, as argued by Jeanne and Rose (2002) and Bruno and Shin (2014).<sup>10</sup> As Kouri (1976) had earlier conjectured: “The view of the exchange rate as a relative asset price suggests that ... there is no reason to expect the exchange rate to be stable. In fact, the behavior of the exchange rate is likely to resemble the behavior of asset prices in other speculative markets, such as the stock market.” The associated idea that the exchange rate

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<sup>7</sup>See, among others, Calvo and Rodriguez (1977), Kouri and de Macedo (1978), Tobin and de Macedo (1979), Dornbusch and Fischer (1980), and Henderson and Rogoff (1982). Driskill and McCafferty (1980) assume a portfolio demand specification similar to ours. Branson and Henderson (1985) provide an overview of this literature.

<sup>8</sup>Models of asset market segmentation include Bacchetta and Van Wincoop (2010), Alvarez, Atkeson, and Kehoe (2002, 2009), and Maggiori (2016).

<sup>9</sup>Backus and Smith (1993) document the consumption-real exchange rate anomaly: unlike what a model without financial imperfections would predict, there is little relation between relative consumption and real exchange rates in the data. Chari, Kehoe, and McGrattan (2002), Hau and Rey (2006), Corsetti, Dedola, and Leduc (2008) and Pavlova and Rigobon (2012) add financial market imperfections and market incompleteness to better explain the stochastic properties of observed exchange rates.

<sup>10</sup>Jeanne and Rose (2002) show that the existence of noise traders can cause exchange rates to be volatile even when fundamentals are unchanged. Bruno and Shin (2014) argue that the leverage cycle of global banks is the main determinant of global liquidity conditions and cross-border capital flows.

may become disconnected from macroeconomic fundamentals, and may instead transmit financial shocks to the macroeconomy, rationalizes an exchange rate stabilization motive for EME central banks.<sup>11</sup> We capture this motive in our model’s objective function.

Several recent papers have considered optimal FX intervention policy in models where the free float of the exchange rate may be undesirable. Ghosh, Ostry, and Chamon (2016) solve for optimal FX intervention and monetary policies in a reduced-form model, while Devereux and Yetman (2014) and Benes, Berg, Portillo, and Vavra (2015) work within a simple New Keynesian framework. Recent fully micro-founded approaches to optimal policy, based on the financial imperfections in Gabaix and Maggiori (2015), include Cavallino (2015) and Fanelli and Straub (2016). Relative to this literature, our paper sticks to a reduced-form framework in order to be able to tractably characterize and solve what is, to our knowledge, a novel time consistency problem arising from the ZLB on reserves.

Finally, a growing empirical literature appears to support our model’s assumption that sterilized FX interventions have some traction on exchange rates in EMEs.<sup>12</sup> Papers that summarize country case studies include Disyatat and Galati (2005), who cover an array of different economies, and Chamon, Garcia and Souza (2015), who focus on the recent use of an FX intervention rule by Brazil. Empirical support for the effectiveness of intervention has also been provided by cross-country panel analyses, including Adler and Tovar (2011), Adler, Lisack, and Mano (2015), and Blanchard, Adler and Filho (2015).

## 2. Heterogeneous Responses to Outflow Shocks

Several EME central banks have undertaken sterilized FX intervention to support their currencies in response to capital outflows and/or a sudden decline in inflows. Here we describe some recent cases of outflow episodes. We observe that central bank behavior is highly heterogeneous across episodes, and we use a narrative approach to briefly outline the judgments and trade-offs that central banks need to make. We attempt later to capture these judgments and trade-offs using our simple model.

The following six capital outflow episodes help illustrate the policies deployed by central bank EMEs:

- I. **Russia 2008Q3.** The Central Bank of Russia (CBR) started with a large level of reserves (USD 556bn, or 119 percent of GDP). Faced with a large temporary shock, as the global financial crisis caused a collapse in oil prices and export revenues, the CBR heavily intervened in order to “slow the pace of the rouble’s depreciation” and thereby

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<sup>11</sup>Such financial shocks may be especially disruptive when domestic agents borrow in foreign currency (Krugman, 1999; Aghion, Bacchetta, and Banerjee, 2001; Mendoza, 2002).

<sup>12</sup>Sarno and Taylor (2001) provide an early survey of the literature. A more recent review of empirical studies is provided in table 1 of Ghosh, Ostry, and Chamon (2016).

mitigate the “heavy strain on the balance sheets of banks, firms and households via the significant level of foreign-currency-denominated debt that these agents had taken on” (CBR-authored section in BIS, 2013). Reserves fell by USD 187bn over three quarters, while the exchange rate depreciated by 31 percent. Conscious of the possibility that a contraction in banks’ external borrowing might cause further depreciation, the CBR also mitigated outflows by offering unsecured lending to banks.

II. **Korea 2008Q3.** The Bank of Korea (BOK) also started with a large level of reserves (USD 258bn, or 95 percent of GDP) and intervened heavily during the global financial crisis in order to achieve its twin goals: to “contain excessive exchange rate volatility” and to “alleviate the FX funding shortages of banks” (BOK-authored section in BIS, 2013).<sup>13</sup> The BOK also provided liquidity directly to banks with FX borrowing. Reserves fell by USD 57bn before recovering, while the exchange rate depreciated by 24 percent.

III. **Brazil 2013Q2.** The Brazilian Central Bank (BCB) faced a moderate decline in inflows rather than an outright outflow in 2013, which started at the beginning of the year and was exacerbated by the “taper tantrum” in May. The BCB started with reserves of USD 374bn, or 60 percent of GDP. Following a period of discretionary FX intervention, the BCB decided to announce an intervention rule of daily sales of USD 500m in currency forwards, insuring investors against a domestic currency depreciation, which was reduced in size at the end of the year.<sup>14</sup> Reserves fell by USD 18bn and the exchange rate depreciated by 14 percent.

IV. **India 2013Q3.** India suffered from a reversal in capital flows during the time of the “taper tantrum,” which turned out to be moderate and short-lived, but which was seen by some at the time as a harbinger of future trends as advanced economies began to normalize monetary policies. The Reserve Bank of India’s (RBI) moderate reserves were large relative to the immediate shock (USD 264bn, or 58 percent of GDP), although not to a sustained continuation of outflows. The RBI intervened by lending in USD to state-owned oil companies (Subramanian, 2013), and later allowing FX losses by the companies to be repaid in rupees instead of USD (Indian Express, 2014). The intervention was small, and reserves fell by just USD 5bn; the exchange rate depreciated by 5 percent.

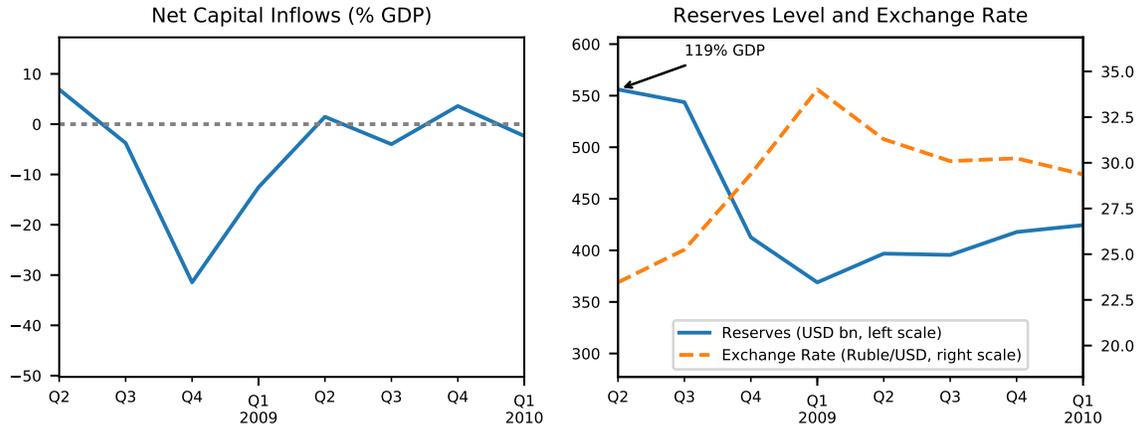
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<sup>13</sup>Despite Korea’s current account surpluses, Korean banks have significant FX borrowing because they are intermediaries for the FX hedging motives of the Korean private sector. For more details, see BIS (2013).

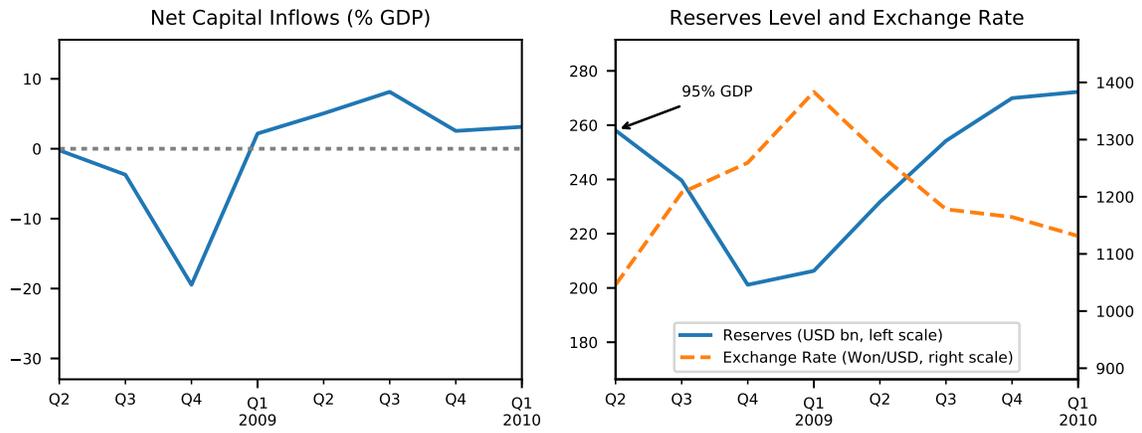
<sup>14</sup>Using a variety of approaches, Chamon, Garcia and Souza (2015) argue that the announcement of the new intervention rule was effective in mitigating the depreciation of the Brazilian real.

Figure 1. Selected Capital Outflow Episodes in EMEs

I. Russia 2008Q2-2010Q1



II. Korea 2008Q2-2010Q1



III. Brazil 2013Q1-2014Q4

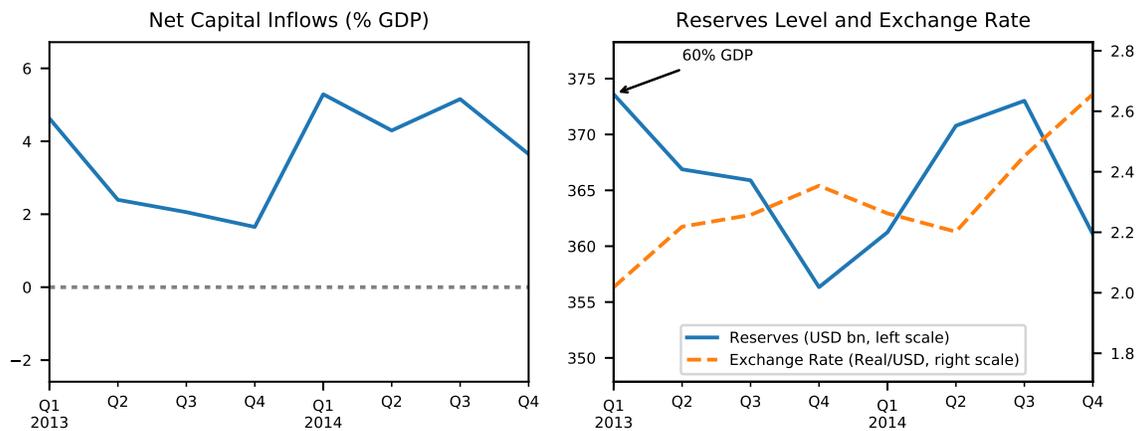
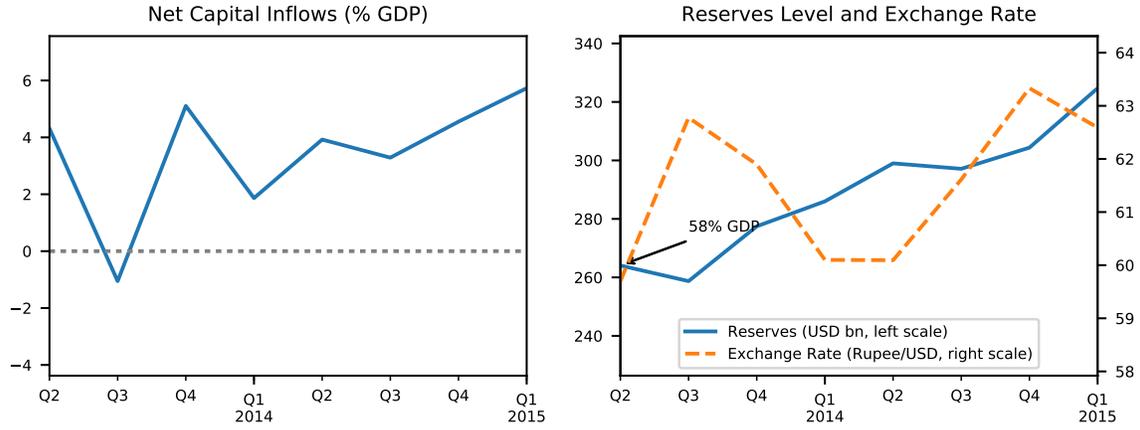
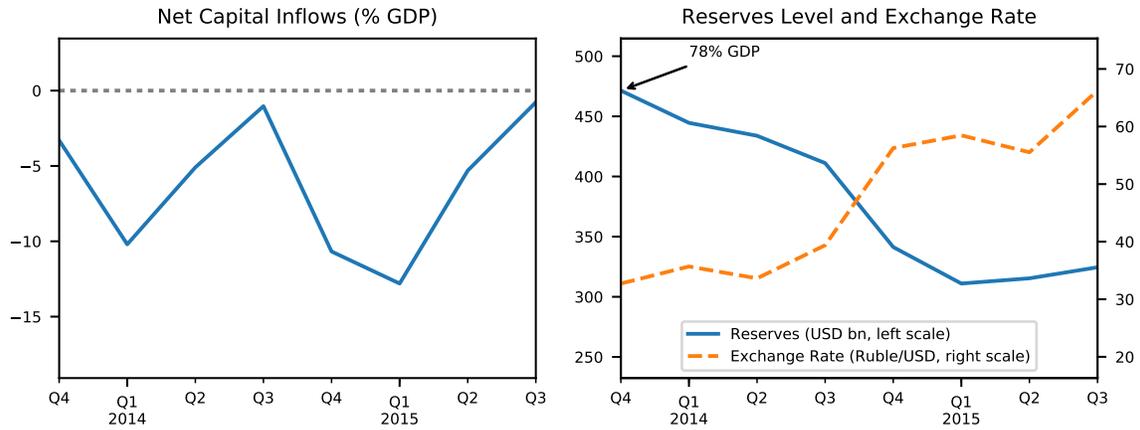


Figure 1 (Continued)

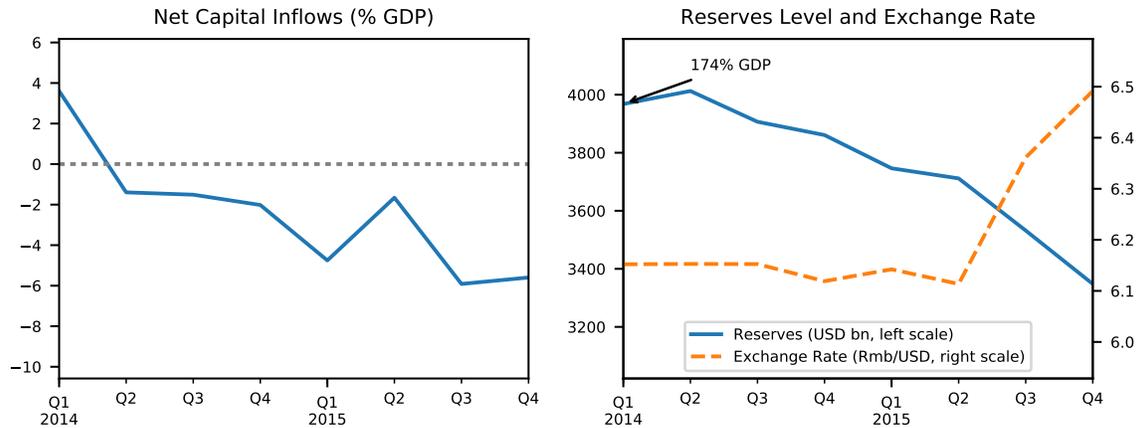
IV. India 2013Q2-2015Q1



V. Russia 2013Q4-2015Q3



VI. China 2014Q1-2015Q4



V. **Russia 2014Q1 and Q4.** Russia was hit by a sequence of two outflow shocks in 2014, the first as a result of the beginning of the military intervention in Ukraine, and the second later in the year owing to Western sanctions and the collapse in oil prices. Relative to the 2008 crisis, the CBR started with a lower level of reserves (USD 471bn, or 78 percent of GDP), and the shock was smaller (albeit still large) and more permanent. Reserves fell by USD 160bn over five quarters (so intervention was smaller but more sustained than in the 2008 crisis), while the exchange rate depreciated by 44 percent over five quarters and continued depreciating after the intervention had been stopped. The CBR also provided capital support to banks to ease their FX deleveraging process (IMF, 2015).

VI. **China 2014Q2.** The People’s Bank of China (PBC) started with the largest level of reserves of all the EME examples considered here (USD 3.97tn, or 174 percent of GDP). Capital outflows picked up as the Chinese economy weakened in 2014, and then worsened in mid-2015. The persistence of the shock remained unclear. During this period, China was moving to a managed float regime from a peg. The PBC used its warchest of reserves to keep the exchange rate almost unchanged for five quarters before allowing some depreciation. While some observers deemed reserves to have been “wasted” because the exchange rate eventually moved, at least one PBC official was reportedly cautiously pleased that some of the depreciation pressures had been contained, because a sharp depreciation carried the risk of generating a larger panic: “once confidence is lost, it can’t easily be restored” (Wildau and Mitchell, 2016).<sup>15</sup>

These case studies underline that the responses of EME central banks to outflow shocks are very heterogeneous, with a multitude of factors affecting their decisions. In this paper, we will focus our analysis on a couple of themes that appear to be common across the outflow episodes. First, in some episodes, central banks do view an immediate depreciation as hurting domestic welfare—*e.g.*, by generating excessively rapid deleveraging of FX positions by domestic agents—and in response, they choose to intervene and delay the depreciation. In section 3, we turn to building a simple model capturing in reduced form the incentive to delay depreciation. Second, it appears that central bank behavior is connected both to the level of reserves relative to the shock’s magnitude (which we explore in section 4) and to the assessed persistence of the shock (which we explore in section 5).

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<sup>15</sup>Wildau and Mitchell (2016) document the official’s comments as follows: “The cost of intervention in terms of reserves has been high but this policy can’t be evaluated just in terms of numbers. Once confidence is lost, it can’t easily be restored. Then a lot of bad things can happen.”

### 3. Stylized Model

We consider a capital outflows episode where financial shocks are generating volatility in the exchange rate independently of shifts in underlying macroeconomic fundamentals, and the EME central bank is attempting to manage the exchange rate in order to limit the transmission of these shocks to the wider economy. However, it possesses limited reserves with which to accomplish this objective.

Our baseline framework comprises a linear-quadratic optimization problem amended with a zero lower bound (ZLB) constraint on reserves. The simplicity of the model yields two advantages. First, it helps clarify the exposition regarding the motive to postpone intervention in the full-commitment solution. Second, it keeps the model tractable enough for the time-consistent solution to be numerically solvable.

The central bank's objective is to minimize a quadratic loss function:

$$W(R_0) = -E_0 \left[ \sum_{t=0}^{\infty} \beta^t \frac{(e_t - e^*)^2}{2} \right]. \quad (1)$$

where the outflow episode begins at  $t = 0$  and potentially continues into the indefinite future,  $\beta \in (0, 1)$  is the central bank's discount factor,  $e_t$  is the exchange rate in period  $t$  (defined so that an increase means a depreciation), and  $e^*$  is the exchange rate target relevant for the episode.<sup>16</sup> This welfare function captures the notion described in the literature review that financially-driven exchange rate deviations can be destabilizing to the macroeconomy, particularly when domestic agents are leveraged in foreign currency; and as a result, the central bank may wish to delay any depreciation.<sup>17</sup>

The feasible set is described by a stylized equilibrium model of exchange rate determination. The capital flow equation is as follows:

$$k_t = a(E_t e_{t+1} - e_t) + z_t, \quad (2)$$

where  $k_t$  represents capital outflows,  $z_t$  denotes a capital outflow shock, and  $E_t e_{t+1}$  is the expected exchange rate for the next period  $t + 1$ . We assume that the domestic and for-

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<sup>16</sup>Since our model is intended for managed float regimes,  $e^*$  does not represent a strict peg: there is no obligation that the exchange rate be maintained at that level as long as possible.

<sup>17</sup>In a standard New Keynesian (NK) model with imperfect financial markets, monopolistic competition, and home bias, a squared quadratic term for the exchange rate around its steady state level will naturally be a part of the central bank's objective function after portfolio balance shocks, when the policy rate is not included as an instrument in the policymaker's toolkit (see, for example, Cavallino, 2015). More broadly, our objective function is intended to also capture in reduced form a range of costs stemming from balance sheet effects (*e.g.*, Krugman, 1999; Aghion, Bacchetta, and Banerjee, 2001; Mendoza, 2002) that have not yet been fully captured in standard NK treatments, but which are a key worry for EME policymakers. For example, by limiting and delaying the depreciation of the currency, the central bank can allow unhedged borrowers (*e.g.*, households, firms and financial institutions) more time to reduce their FX exposure.

ign interest rates are identical or that the wedge between them is constant (and therefore absorbed into the shock  $z_t$ ), so that the policy rate is not a separate item in the toolkit.<sup>18</sup>

Our specification is conceptually related to the framework in Gabaix and Maggiori (2015). The shock  $z_t$  captures in reduced form portfolio balance shocks to international financial intermediaries which move the exchange rate but are unrelated to traditional macroeconomic fundamentals.<sup>19</sup> A finite value for  $a$  in our model reflects a limit to arbitrage by the private sector, which means that FX intervention can have traction on the exchange rate; as  $a \rightarrow \infty$ , we obtain instead the standard perfect-arbitrage uncovered interest parity (UIP) condition.<sup>20</sup>

We assume a simple linear formulation for the current account surplus  $x_t$ , which is normalized so that the current account is in balance when  $e_t = 0$ :

$$x_t = ce_t. \tag{3}$$

The central bank's policy variable is the level of sterilized FX intervention  $f_t$ :

$$f_t \equiv R_t - R_{t+1} \in [0, R_t], \tag{4}$$

where  $R_t$  is the stock of reserves at the beginning of period  $t$  and is determined by the intervention policies up to time  $t - 1$ , and  $R_0$  is the exogenous initial level of reserves. The upper bound on  $f_t$  represents the zero lower bound on reserves, which is the source of the new insights in this paper. Since we are focused on an outflow episode, we additionally impose for analytical convenience that  $f_t$  is weakly greater than zero, *i.e.*, reserve accumulation is not possible. Our key insights are robust to the relaxation of this second constraint. Finally, the balance of payments identity is as follows:

$$k_t \equiv x_t + f_t. \tag{5}$$

The exchange rate equation is derived by combining equations (2), (3), and (5):

$$e_t = \frac{1}{a + c} (z_t - f_t + aE_t e_{t+1}). \tag{6}$$

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<sup>18</sup>Ghosh, Ostry and Chamon (2016) show in a model without a lower bound on reserves that if the policy rate is available, it should be used alongside FX intervention so as to stabilize the exchange rate (*i.e.*, higher interest rate after outflow shocks). We abstract from such considerations in this paper and focus instead on the simplest model with a zero lower bound on reserves.

<sup>19</sup>This feature is also characteristic of the broader portfolio balance literature (*e.g.*, Kouri, 1976; Blanchard, Giavazzi, and Sa, 2005).

<sup>20</sup>In Gabaix and Maggiori (2015), there is a limit to the arbitrage between domestic and foreign assets because the financial intermediaries who must conduct such arbitrage face constraints on the size of their balance sheets. Our parameter  $a$  can be loosely compared with their variable  $\frac{1}{\Gamma}$ , where  $\Gamma$  is related to the portion of shareholders' funds that financial intermediaries are able to steal, and therefore measures the strength of financial frictions for investors. Under this interpretation, as  $a \rightarrow \infty$ ,  $\Gamma \rightarrow 0$  and financial frictions disappear, so perfect arbitrage becomes possible.

Iterating this equation forward:

$$e_t = \frac{1}{a+c} E_t \sum_{i=0}^{\infty} \left( \frac{a}{a+c} \right)^i [z_{t+i} - f_{t+i}]. \quad (7)$$

Therefore, in our model, FX intervention appreciates the exchange rate, which is consistent with the empirical evidence for EMEs and the theoretical findings of recent micro-founded models (*e.g.*, Gabaix and Maggiori, 2015; Cavallino, 2015; Fanelli and Straub, 2016). Our model includes an “expectations channel”: FX intervention to support the exchange rate in future periods supports the exchange rate today as well. One unit of FX intervention today appreciates the exchange rate by  $\frac{1}{a+c}$  today, while one unit of FX intervention tomorrow appreciates the exchange rate today by the lower amount  $\frac{a}{(a+c)^2}$ .

Equations (4) and (6), together with the value of  $R_0$ , summarize the central bank’s constraints. We denote the pure-float exchange rates  $\{\bar{e}_t\}_{t=0}^{\infty}$  as the exchange rate path in the absence of intervention, *i.e.*,  $f_t = 0$  for all  $t$ . The central bank’s problem is interesting when the shock  $z_t$  causes  $\bar{e}_t$  to deviate from  $e^*$  in at least some periods.

In this paper, we focus on an outflow shock that begins at  $z_0 = \bar{z} > 0$ , and then in each period has a probability  $p$  of persisting at the same level into the next period, and a probability  $1 - p$  of falling to zero (the absorbing state) and remaining there forever.<sup>21</sup> The Markov transition matrix is:

$$\begin{array}{l} z_{t+1} = 0 \\ z_{t+1} = \bar{z} \end{array} \quad \begin{array}{cc} z_t = 0 & z_t = \bar{z} \\ \left[ \begin{array}{cc} 1 & 0 \\ 1-p & p \end{array} \right] \end{array} \quad (8)$$

We first solve in section 4 the special case of constant outflows given by  $p = 1$ , because it is easy to understand and clearly demonstrates most of our key insights. However, the pure-float exchange rate and the target remain permanently apart in this case. In section 5, we solve the general stochastic case  $p \in (0, 1)$ . This specification allows us to examine the effect of the shock persistence  $p$  on the optimal policy, and it also ensures that in the long run, the pure-float exchange rate always reverts to the target  $e^*$ , so the central bank is not forever trying to keep the exchange rate away from its pure-float level.

Clearly, the precise form of our optimal solutions for intervention and the exchange rate path will depend on the assumed functional forms for welfare and the exchange rate equation. Nevertheless, the qualitative effect of the ZLB on the time consistency of the solution, and on the comparative levels of FX intervention and welfare across different degrees of central bank commitment, should apply across a wide range of models, as long as a policy of stabilizing

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<sup>21</sup>When  $p \in (0, 1)$ , this simple shock specification captures one key feature that is operational over a variety of more general stochastic processes: the central bank knows that it faces an outflow shock today, but it is uncertain whether or not it will face outflow shocks in the future.

the exchange rate at  $e^*$  forever causes reserves to become exhausted with probability greater than zero. This condition is satisfied provided that  $p > 0$ .

## 4. Optimal Intervention with the ZLB

In this section, we characterize the optimal FX intervention policy for the constant outflows case:  $p = 1$ , which implies that  $z_t = \bar{z} > 0$  for all  $t$ .

We prove that the ZLB on reserves, combined with imperfect capital mobility, generates a time consistency problem. In practical terms, the implications are as follows. For very large levels of reserves, the optimal intervention policy does not depend much on the degree of commitment of the central bank, and involves fully offsetting the outflow shock and keeping the exchange rate at  $e^*$ . For low-to-moderate levels of reserves, however, the optimal intervention policy does depend on commitment power. If the central bank has full commitment, it achieves a gradual depreciation to the pure-float level by promising at the beginning of the outflow episode to intervene aggressively, but at later dates rather than immediately. In the absence of commitment power, the central bank undertakes only a small level of intervention in all periods, and lets the exchange rate depreciate. A central bank with intermediate commitment power finds it optimal to announce a simple intervention rule. Finally, in the limiting case where the central bank starts with no reserves, intervention becomes trivially identical at zero for all degrees of commitment power.

### 4.1. Full-commitment solution

**Definition 1 (Full-commitment optimization problem)** *The central bank chooses in period  $t = 0$  a sequence of FX interventions  $\{f_t\}_{t=0}^{\infty}$  to maximize the expression (1) subject to the constraints (4) and (6) and given the value of  $R_0$ .*

A central bank with full commitment optimally combines intervention with market communication. It is able to credibly commit at the start of the outflow episode,  $t = 0$ , to the entire future FX intervention path  $\{f_t\}_{t=0}^{\infty}$ , provided that the path is feasible, *i.e.*, it satisfies equation (4) given the value of  $R_0$ . These promises regarding future FX interventions are correctly regarded as unbreakable by foreign investors, and pin down the path of exchange rates  $\{e_t\}_{t=0}^{\infty}$  via equation (6).

Of course, full commitment may not be a realistic assumption, but it establishes the optimal policy benchmark as well as an upper bound for the welfare level. EME central banks with an extensive history of prior FX interventions and a reputation for fulfilling their commitments may be able to implement policies close to the full-commitment solution.

By taking the first order condition of the optimization problem with respect to the exchange rate and backing out the value of the multiplier  $\Gamma_t$  on the exchange rate equation,

we can show that the marginal value of intervention in period  $t$  on welfare in period 0 is:

$$\Gamma_t = \sum_{u=0}^t \beta^u \left( \frac{a}{a+c} \right)^{t-u} (e_u - e^*). \quad (9)$$

A unit of intervention that is promised for a future period  $t$  appreciates exchange rates in all prior periods  $u \in \{0, \dots, t\}$  through the “expectations channel.” The effect on the loss function within each period  $u$  is valued according to the marginal utility of the central bank in those periods,  $(e_u - e^*)$ . The multiplicative factor  $\left(\frac{a}{a+c}\right)^{t-u}$  reflects the dampening of the magnitude of the appreciation as we consider periods further and further before the date of the intervention. The multiplicative factor  $\beta^u$  captures the discounting of welfare gains as we consider periods further and further after the beginning of the outflow episode. The total effect of promised intervention in period  $t$  on period-0 welfare is the sum of all the weighted changes in the loss function over the periods from 0 to  $t$ .

We normalize  $e^* = 0$ , so in the absence of any outflow shocks, the pure-float exchange rate is at the target,  $\bar{e}_t = \bar{e} = 0$ , and there is no rationale for intervention. When there is a constant outflow shock  $z_t = \bar{z}$  but zero intervention, the pure-float exchange rate is constant over time at  $\bar{e}_t = \bar{e} = \frac{\bar{z}}{c} > e^* = 0$ . FX intervention may be desirable in this case to bring the exchange rate closer to the target.

Figure 2. Marginal value of intervention in pure-float equilibrium

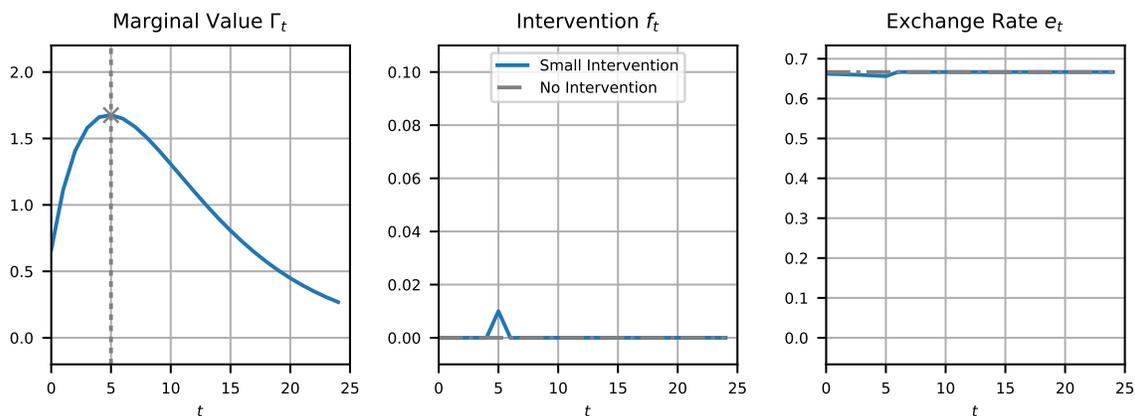


Figure 2 shows the constant-outflows case using the baseline parameters  $e^* = 0$ ,  $\bar{z} = 0.1$ ,  $a = 0.8$ ,  $c = 0.15$ , and  $\beta$  set such that  $\frac{1}{\beta} = \frac{a+c}{c}$  (we discuss this equality condition in more detail below). The schedule for  $\Gamma_t$ , the marginal value of intervention in period  $t$  on welfare in period 0, is hump-shaped. The cumulative effect of the expectations channel dominates for dates close to the beginning of the outflow episode:  $\Gamma_t$  increases when the promised intervention is further in the future, because there is a larger number of periods prior to intervention during which the expectations channel can operate. Discounting is the dominant effect for dates of intervention that are far after the beginning of the outflows

episode, and  $\Gamma_t$  decreases.<sup>22</sup>

If the central bank has only a small amount of initial reserves  $R_0$ , it should promise in period  $t = 0$  to spend all of it not immediately, but rather in some future period  $t^* > 0$  when  $\Gamma_t$  reaches its peak—in other words, in the period when the central bank will get the highest “bang per buck” from the use of its scarce reserves. As figure 2 illustrates, the promised future intervention causes all prior exchange rates to appreciate slightly below the pure-float level  $\bar{e}$ .

Suppose next that the central bank has non-negligible initial reserves  $R_0$ . These reserves are optimally used in periods when the marginal value of intervention is the highest; and during the periods of intervention, the marginal value of intervention must be equalized. Therefore, it must be that  $\Gamma_{t \in \{\text{Intervention dates}\}} = \bar{\Gamma} > \Gamma_{t \notin \{\text{Intervention dates}\}}$  for some constant  $\bar{\Gamma}$ . The following Euler condition, equating the discounted marginal utilities across periods, is derived by combining the first order conditions of the optimization problem with respect to reserves and the exchange rate, and it holds during the periods of intervention:

$$e_t = \beta e_{t+1}. \quad (10)$$

Given the shape of the  $\Gamma_t$  function in figure 2, it is apparent that intervention is optimally promised for some interval of periods around  $t^*$ . The next proposition formalizes this result.

**Proposition 1 (Full-commitment solution)** *The optimal FX intervention policy is to promise positive intervention for a subset of consecutive periods  $[t_1, t_2]$ . There is zero intervention before  $t_1$  and reserves are fully depleted in period  $t_2$ . The exchange rate path follows:*

$$e_t = \begin{cases} \left(1 - \left(\frac{a}{a+c}\right)^{t_1-t}\right) \bar{e} + \left(\frac{a}{a+c}\right)^{t_1-t} e_{t_1} & \text{for } t \in \{0, \dots, t_1 - 1\} \\ \beta^{t_2-t} e_{t_2} & \text{for } t \in \{t_1, \dots, t_2 - 1\} \\ \bar{e} - \frac{1}{a+c} R_t \quad (\geq \beta \bar{e}) & \text{for } t = t_2 \\ \bar{e} & \text{for } t \in \{t_2 + 1, \dots, \infty\}, \end{cases} \quad (11)$$

where the formula for  $e_{t_2}$  has a slight complication because of the discrete time setup. Within  $[t_1, t_2]$ , intervention satisfies:

$$f_t = \begin{cases} \left[\frac{1}{\beta} - \frac{a+c}{a}\right] a e_t + \bar{z} & \text{for } t \in \{t_1, \dots, t_2 - 1\} \\ R_t & \text{for } t = t_2. \end{cases} \quad (12)$$

---

<sup>22</sup>The hump-shaped schedule for  $\Gamma_t$  is not dependent on  $e^*$  being forever away from  $\bar{e}$ . In appendix A.1, we show a similar graph for the case where  $e^*$  gradually adjusts to  $\bar{e}$  (this case is intended to capture in reduced form an environment where the long-run desire of the central bank is to adjust the exchange rate to accommodate the permanent shock, but where adjusting immediately to the pure-float exchange rate generates short-run costs, *e.g.*, private sector FX borrowers are forced to deleverage too rapidly). In section 5, we show a similar graph for the specification  $p < 1$ .

which is flat during  $\{t_1, \dots, t_2 - 1\}$  iff  $\frac{1}{\beta} = \frac{a+c}{a}$ , upward-sloping iff  $\frac{1}{\beta} > \frac{a+c}{a}$ , and downward-sloping iff  $\frac{1}{\beta} < \frac{a+c}{a}$ .  $t_1$  and  $t_2$  satisfy the feasibility condition  $\sum_{t=t_1}^{t_2} f_t = R_0$  such that  $e_{t_2} \geq \beta \bar{e}$  and  $\Gamma_{t \in \{t_1, \dots, t_2 - 1\}} = \bar{\Gamma} > \Gamma_{t \notin \{t_1, \dots, t_2 - 1\}}$  for some constant  $\bar{\Gamma}$ .

**Proof.** Combine the first order conditions of the optimization problem described in definition 1 with equations (4) and (6). ■

Because of the quadratic loss function, the optimal depreciation of the exchange rate during  $\{t_1, \dots, t_2\}$  is pinned down solely by the ratio  $\frac{1}{\beta}$ . By contrast, the optimal path of the intervention depends on the solution of a separate sub-problem which compares the preference parameter  $\frac{1}{\beta}$ , capturing the optimal rate of exchange rate depreciation, against  $\frac{a+c}{a}$ , which captures the rate of depreciation that would be achieved using a constant intervention path. In the knife-edge case when  $\frac{1}{\beta} = \frac{a+c}{a}$ , these two depreciation rates are identical, so it is optimal to set the intervention level at the constant value  $\bar{z}$  during  $\{t_1, \dots, t_2\}$ . In the main text of this paper, we focus solely on the parameter specification described above, which satisfies this equality condition; appendix A.2 contains some comparative static exercises on the parameters.

Figure 3. Full-commitment solution

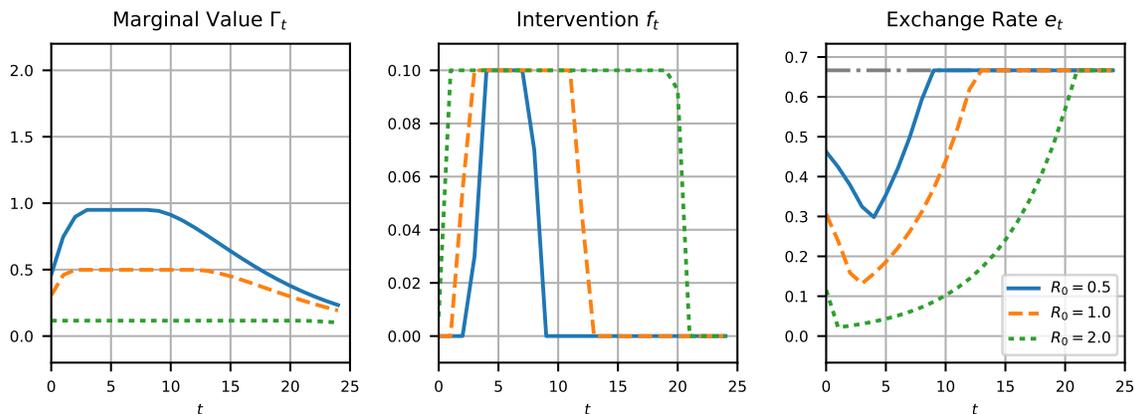


Figure 3 illustrates the solution for various levels of  $R_0$ . For any level of initial reserves, the exchange rate depreciates above  $e^* = 0$  as soon as the outflow episode begins in period  $t = 0$ . During the periods  $\{0, \dots, t_1 - 1\}$ , there is no intervention but nevertheless, the exchange rate appreciates in anticipation of future intervention. During the periods of intervention  $\{t_1, \dots, t_2\}$ , the deviation of the exchange rate from its target  $e^*$  grows by a factor of  $\frac{1}{\beta}$  in every period. The central bank is conducting intervention to hold the exchange rate below  $\bar{e}$ , but the exchange rate is nevertheless depreciating in anticipation that reserves will run out. Notice that the marginal value of intervention is equalized during  $\{t_1, \dots, t_2 - 1\}$ . After reserves are fully depleted in period  $t_2$ , the exchange rate remains at  $\bar{e}$  forever.<sup>23</sup>

<sup>23</sup>The optimal behavior of the exchange rate poses problems for empirical estimation of the effectiveness of

The larger is the level of initial reserves  $R_0$ , the earlier that intervention begins and the later that reserves run out, so the greater the stabilization of the exchange rate. For initial reserves  $R_0$  sufficiently large,  $t_1 = 0$ . As  $R_0 \rightarrow \infty$ ,  $t_2 \rightarrow \infty$ , so the exchange rate is perfectly stabilized at the target  $e^*$ .

**Remark 1 (Time consistency)** *The full-commitment solution is not time consistent.*

A full-commitment central bank with low-to-moderate reserves promises at the beginning of the outflow episode not to intervene today but to do so in the future, because intervention in the future affects exchange rates over a long time period. If the full commitment assumption were broken and the central bank were allowed to re-optimize tomorrow, it would again follow the same logic and postpone all intervention to the future. Therefore, the full-commitment solution is not time consistent. A central bank without full commitment faces some limits on the promises that it can credibly make regarding future intervention.

## 4.2. Time-consistent solution

**Definition 2 (Time-consistent optimization problem)** *A time-consistent solution comprises an FX intervention policy  $f(R)$  and an exchange rate relation  $e(R)$  which are infinitely-differentiable fixed points of the Bellman operator:<sup>24</sup>*

$$v^{TC}(R) = \max_{e, R'} \left\{ -\frac{(e(R) - e^*)^2}{2} + \beta v^{TC}(R') \right\} \quad (13)$$

*subject to modified versions of equations (4) and (6) and the set of feasible exchange rates:<sup>25</sup>*

$$f(R) = R - R' \in [0, R] \quad (14)$$

$$e(R) = \frac{1}{a+c} (\bar{z} - f(R) + ae(R')) \quad (15)$$

$$e(R) \geq \bar{e} - \frac{1}{a+c} R. \quad (16)$$

---

intervention: although intervention is assumed to have traction in our model, the exchange rate nevertheless appreciates in the periods of zero intervention and depreciates during the intervention periods. This behavior is motivated by investors' expectations regarding future interventions, which is difficult to capture empirically.

<sup>24</sup>Infinite differentiability is a necessary condition for the policy functions  $f(R)$  and  $e(R)$  to be defined over all  $R$  (any kinks in the function  $e(R)$  will cause problems in applying the generalized Euler condition that will be derived below).

<sup>25</sup>Following Kydland and Prescott (1980), the set of feasible exchange rates  $M(R)$  is constructed recursively:  $M(R) = \left\{ \mu : \mu = \frac{1}{a+c} (\bar{z} - f + a\mu') \text{ for some } \mu' \in M(R') \text{ and } f = R - R' \in [0, R] \right\}$ .

When the central bank has no commitment power, the solution must be time consistent, *i.e.*, it must take into account that the central bank re-optimizes in every period, ignoring the promises of the past. Therefore, both the optimal policy and investors' exchange rate expectations depend not on any explicit promises, but instead on the only state variable of the problem: the level of reserves at the beginning of each period. The two fixed-point functions  $f(R)$  and  $e(R)$  fully characterize the solution.<sup>26</sup> In economic terms, instead of being free to make any promise that satisfies feasibility, the central bank must take as given the function  $e(R')$  describing investors' expectations about next period's exchange rate, where those investor expectations come from knowing that the central bank will again face the same Bellman problem at every date in the future.

The time-consistent solution necessarily achieves lower welfare than does the full-commitment solution, because commitment power is valuable in this model. In practice, every central bank has an intermediate degree of commitment power, lying somewhere between the two extremes of zero and full commitment.

Again normalizing  $e^* = 0$ , the full-commitment Euler condition (10) is replaced by the time-consistent Euler condition:

$$e(R) [1 + ae_R(R - f(R))] \geq \beta e(R - f(R)) \quad (17)$$

which holds with equality when reserves are not optimally exhausted in the current period. To gain intuition for this condition, let us re-write it as follows:

$$\frac{1}{a+c}e(R) \geq \frac{1}{a+c}\beta e(R - f(R)) - \frac{a}{a+c}e_R(R - f(R))e(R) \quad (18)$$

The left-hand side captures the marginal benefit of spending an extra unit of reserves today: the effect of intervention on today's exchange rate,  $\frac{1}{a+c}$ , multiplied by the marginal reduction in the loss function today, which turns out to be  $e(R)$ . The right-hand side has two terms capturing the marginal benefit of leaving an extra unit of reserves for tomorrow. The first term assumes that the extra unit is entirely spent tomorrow, and is the effect of intervention on tomorrow's exchange rate,  $\frac{1}{a+c}$ , multiplied by the discounted marginal reduction in the loss function tomorrow,  $\beta e(R - f(R))$ . The second term draws on equation (15) and is the effect of having an extra unit of reserves tomorrow on today's exchange rate: the strength of the expectations channel,  $\frac{a}{a+c}$ , multiplied by the change in expectations when the level of reserves left for tomorrow is higher,  $e_R(R - f(R))$ , multiplied by the marginal reduction in the loss function today,  $e(R)$ .<sup>27</sup> The solution will involve  $e_R < 0$ , with higher reserves

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<sup>26</sup>The functions  $f(R)$  and  $e(R)$  do not vary with time. The level of reserves  $R_t$  does change over time, but we have suppressed the time subscript on reserves for the fixed-point analysis.

<sup>27</sup>It might appear odd that the first term assumes that the extra reserves are entirely spent tomorrow while the second term assumes that they are not (as long as  $e_R(R - f(R)) > -\frac{1}{a+c}$ ). However, there is no paradox here: the extra reserves are not entirely spent tomorrow, but from the envelope condition (which

causing an appreciation in exchange rate expectations.

Our stylized linear-quadratic model with a ZLB on reserves is tractable enough for us to be able to solve the time-consistent case numerically.<sup>28</sup> Figure 4 illustrates our solutions for  $f(R)$  and  $e(R)$  for the same baseline parameters as in the previous subsection. The time consistency problem is related to the level of reserves, which in turn reflects the proximity of the ZLB constraint on reserves. FX intervention is low near  $R = 0$  and converges to the outflow-shock level  $\bar{z}$  as  $R \rightarrow \infty$ . The exchange rate is at the pure-float level  $\bar{e}$  at  $R = 0$ , and converges to the exchange rate target  $e^* = 0$  as  $R \rightarrow \infty$ .

Notice that  $f(R) \in (0, R)$  for all  $R$ . In practical terms, positive intervention occurs in every period regardless of the level of reserves, and importantly, reserves never run out. In addition,  $f(R)$  and  $e(R)$  close to  $R = 0$  satisfy the conditions  $\lim_{R \rightarrow 0} e_R(R) = \frac{\beta-1}{a}$  and  $\lim_{R \rightarrow 0} f_R(R) = \frac{1-\beta}{\beta} \frac{c}{a}$ , which can be derived from the Euler condition (17) and exchange rate equation (15). In other words, when reserves are low, intervention and the exchange rate depend on discounting and the degree of imperfect arbitrage on FX markets, but not on the distance between  $\bar{e}$  and  $e^*$ .

Figure 4. Time-consistent fixed-point functions

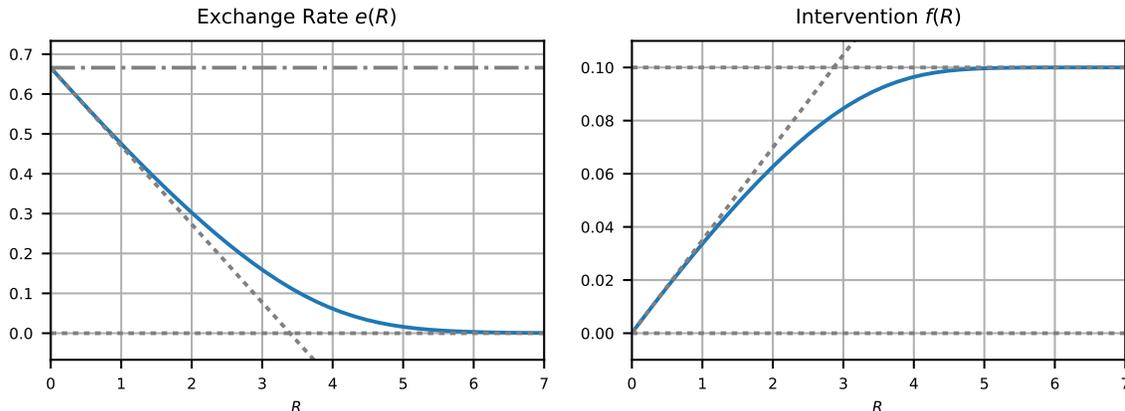


Figure 5 illustrates the solution for various levels of  $R_0$  (some comparative static exercises on the parameters are presented in appendix A.3). Intervention begins as soon as the outflow episode begins at  $t = 0$ , but is lower than the outflow-shock level  $\bar{z}$  in all periods and diminishes over time. Crucially, the exchange rate depreciates more in the first period than it does in the full-commitment case. At low reserve levels, intervention is roughly equal to a constant fraction of the remaining reserves, so the central bank always retains some reserves

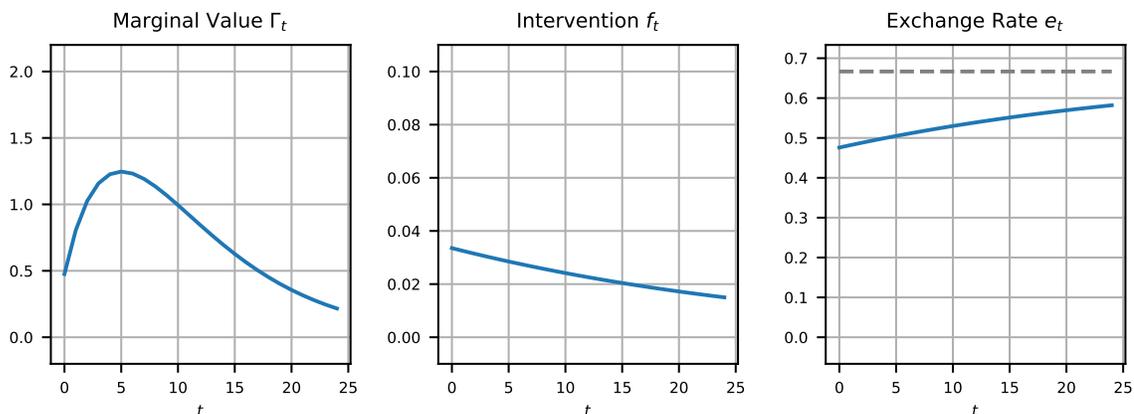
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assumes optimization of the path from tomorrow onward), we can treat them as if they are, for the purpose of calculating the first term.

<sup>28</sup>Our numerical procedure consists of two steps. Firstly, we construct a guess for the policy functions  $f(R)$  and  $e(R)$  which satisfies the feasibility conditions (14) and (16). Secondly, we put this guess for the shape of the policy functions into a simultaneous equation solver for equations (15) and (17), the latter equation holding with equality. We use the Levenberg-Marquardt method and cubic splines to interpolate and calculate the derivatives  $e_R(R)$ .

in its vaults.

Figure 5. Time-consistent solution



Combining the analytical and numerical findings above, for a central bank with low-to-moderate levels of reserves, the intuition for low FX intervention and poor exchange rate stabilization is as follows.

Just as in the full-commitment case, the central bank knows that it benefits from being able to make credible promises of future intervention. However, in the time-consistent case, the central bank is never under any obligation in the future to fulfil any past promises. In fact, the only way that the central bank can today make a credible “promise” to intervene in the future is to leave reserves in its vault today, so that in the future the central bank finds itself with plentiful reserves and *optimally* wishes to intervene as a result. This logic explains why investors’ expectations regarding the future exchange rate depend on the level of reserves left at the end of each period.

Unfortunately for the central bank, this argument applies not only today, encouraging the central bank to intervene little and to leave reserves for the future, but in every period. Therefore, even if the central bank leaves all its reserves in its vault today, the expected future intervention levels are still rather low, as the central bank is expected to keep its vault well-stocked in future periods too. Therefore, while the “expectations channel” is operational, it is too weak in the time-consistent case to be the sole stabilization mechanism for the exchange rate at any date. It is optimally complemented by some up-front intervention occurring in every period.

The end result is positive but low intervention at all dates. In practice, central banks with low levels of commitment hesitate to use any of their previously-accumulated reserves.

As a result, the central bank must live with a large immediate exchange rate depreciation at the beginning of the outflow episode. Therefore, relative to the full-commitment case, central banks experience a reduction in welfare when they lack the power to commit to future interventions. In light of this, we turn next to possible remedies.

### 4.3. Simple intervention rules

In this section, we consider an EME central bank with a partial degree of commitment power: it remains unable to commit to the full-commitment FX intervention path, but it does have the ability to commit to simple intervention rules which are easy to communicate to investors (one reason why these simple rules may be more credible is that they are more easily verified by market participants). We show that for some parameter conditions, the central bank can raise its welfare above the time-consistent level.

We consider two rules to help stabilize the exchange rate around its normalized  $e^* = 0$ . The first rule is an exchange rate peg until reserves run out:

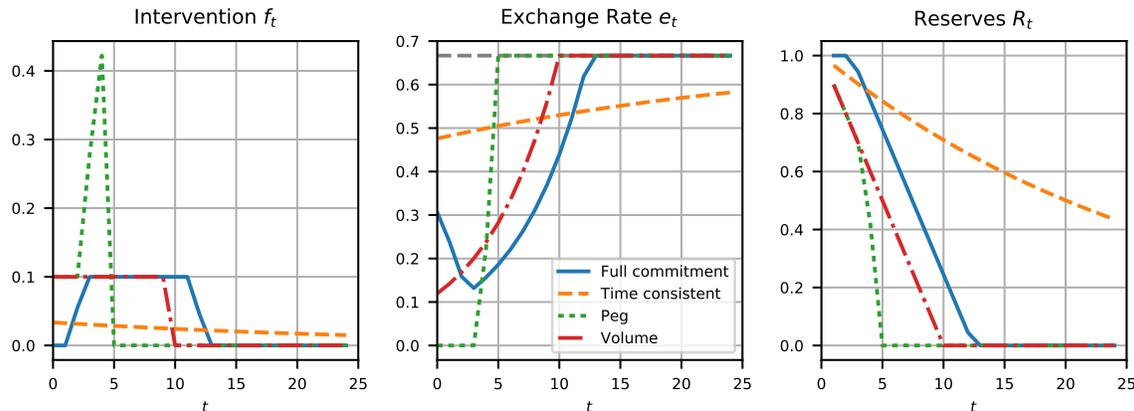
$$e_t = (1 - \kappa) \bar{e}, \quad (19)$$

where  $\kappa \in [0, 1]$  represents the position of the peg between the target  $e^*$  and the pure-float exchange rate  $\bar{e}$  (the higher is  $\kappa$ , the closer is the peg to the target). When reserves are exhausted, the peg breaks and the exchange rate jumps to  $\bar{e}$  forever. The second rule is a volume intervention rule until reserves run out:

$$f_t = \kappa \bar{z}, \quad (20)$$

where  $\kappa \in [0, 1]$  represents the fraction of the outflow shock that is offset by intervention. Once reserves are exhausted, the exchange rate stays at  $\bar{e}$  forever.

Figure 6. Solutions under full, zero, and partial commitment



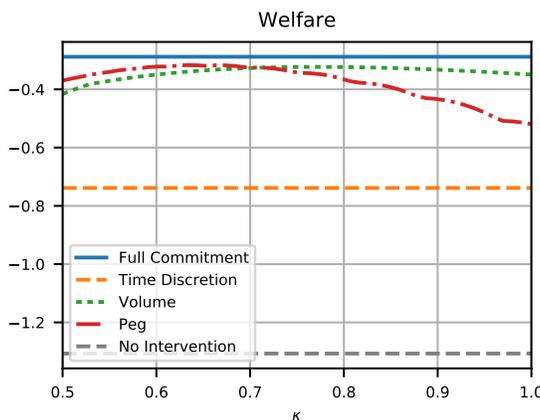
To begin, we focus on the case  $\kappa = 1$ , and using the same baseline parameters as in the previous subsections, we plot the solutions for full commitment, time consistency, and simple intervention rules in figure 6. The peg keeps the exchange rate at the target  $e^*$  for some time by setting intervention to fully offset the outflow shock  $\bar{z}$ , but intervention spikes in the period before the peg breaks, when investors sell the domestic currency in anticipation of the break of the peg, following Krugman (1979). This spike in intervention curtails the

duration of the peg. The volume intervention rule fully offsets the outflow shock  $\bar{z}$  in all periods, and the exchange rate depreciates smoothly, such that the deviation of the exchange rate from its target  $e^*$  grows by a factor of  $\frac{a+c}{a}$  in every period. For our baseline parameters, this rate coincides with the full-commitment rate  $\frac{1}{\beta}$ . However, the rule is different from the full-commitment solution: it directs intervention to begin immediately in period  $t = 0$ , rather than to be postponed in the optimal fashion to future periods.

By definition, both rules achieve lower welfare than does the full-commitment solution. Relative to the time-consistent solution, both rules increase the FX intervention, and reduce the depreciation, in the initial period  $t = 0$ . The avoidance of a large immediate depreciation at the beginning of the outflow episode means that welfare may be higher under the rules than in the time-consistent solution.

Next, in figure 7 we show the welfare levels which are achieved by varying the value of  $\kappa$  in the intervention rules between 0.5 and 1. Both rules can achieve welfare gains over the time-consistent case. Therefore, a central bank with partial commitment power should commit to a simple intervention rule rather than pursuing purely discretionary policies.

Figure 7. Welfare comparison



## 5. The Persistence of the Shock

Next, we turn to the general stochastic case, and we characterize the optimal FX intervention policy as a function of the shock persistence parameter  $p \in (0, 1)$ . Notice that for this parameter range, the pure-float exchange rate reverts to the target  $e^*$  at some future date with probability 1, so the central bank is not forever trying to keep the exchange rate away from its pure-float level. To simplify the algebra in this section, we consider solutions such that as soon as the shock ends, intervention goes to zero.

We show that the time consistency problem is more severe for persistent shocks. For very temporary shocks, the optimal intervention policy does not depend much on the degree of

commitment of the central bank, and involves fully offsetting the outflow shock and keeping the exchange rate at  $e^*$ . For more persistent shocks, the optimal intervention policy does depend on commitment power: a central bank with full commitment delays the timing of the intervention, but a central bank without commitment power diverges from this benchmark and just reduces the level of intervention in all periods, which results in a large immediate depreciation. Simple rules are especially welfare-improving following persistent shocks, even if the magnitude of the outflows within each period is small.

## 5.1. The incentive to postpone intervention

The full-commitment optimization problem continues to follow definition 1, subject to the additional constraint that intervention is zero once the shock ends. In the stochastic case, the central bank credibly commits at the start of the outflow episode to the level of intervention after every possible sequence of shocks. Such time- and state-contingent commitments place a higher burden on the central bank's communication capacity than did the solely time-contingent commitments in the constant-outflow case.

The marginal value of intervention in period  $t$ , in the circumstance that the outflow shock has continued up to period  $t$ , on welfare in period 0 follows the amended formula:

$$\Gamma_t^{\bar{z}} = \sum_{u=0}^t (\beta p)^u \left( \frac{a}{a+c} p \right)^{t-u} (e_u^{\bar{z}} - e^*) \quad (21)$$

$$= p^t \sum_{u=0}^t \beta^u \left( \frac{a}{a+c} \right)^{t-u} (e_u^{\bar{z}} - e^*) = p^t \Gamma_t, \quad (22)$$

where  $e_u^{\bar{z}}$  is the exchange rate in period  $u$  subject to the shock having continued up to that period. Relative to the constant-outflows formula for  $\Gamma_t$  in equation (9), the expression for  $\Gamma_t^{\bar{z}}$  in equation (21) is modified along two dimensions. First, the effective discount factor  $\beta p$  is lower in the stochastic case, because the welfare effect of future intervention is only evaluated along time paths where the shock has continued occurring. Second, the expectations channel  $\frac{a}{a+c} p$  is also weaker, because future intervention only occurs if the shock continues, so it only appreciates exchange rates in previous periods to the extent that in those previous periods, the shock is expected to persist.

Equation (22) establishes that  $\Gamma_t^{\bar{z}}$  is identical to the marginal value of intervention in the constant-outflows case, where the shock definitely continues up to period  $t$ , multiplied by the probability  $p^t$  that the shock does in fact continue to period  $t$  in the stochastic case.<sup>29</sup>

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<sup>29</sup> Although intervention does not occur once the shock ends, the marginal value of intervention after the shock has already ended can still be calculated. The marginal value of intervention in period  $t$ , in the circumstance that the outflow shock continued up to period  $s < t$ , is given by  $\Gamma_t^{0,s} = (1-p) \left( \frac{a}{a+c} \right)^{t-s} \Gamma_s^{\bar{z}}$ .

We again normalize  $e^* = 0$ . When the shock is occurring  $z_t = \bar{z}$  but there is zero intervention, the pure-float exchange rate is constant over time at  $\bar{e}_t = \bar{e}^z = \frac{\bar{z}}{a(1-p)+c} > e^* = 0$ . FX intervention may be desirable in this case to bring the exchange rate closer to the target. Once the shock has ended and there is zero intervention, the exchange rate is forever at the target:  $\bar{e}_t = \bar{e}^0 = 0$ .

Figure 8. Marginal value of intervention in pure-float equilibrium,  $p \leq 1$

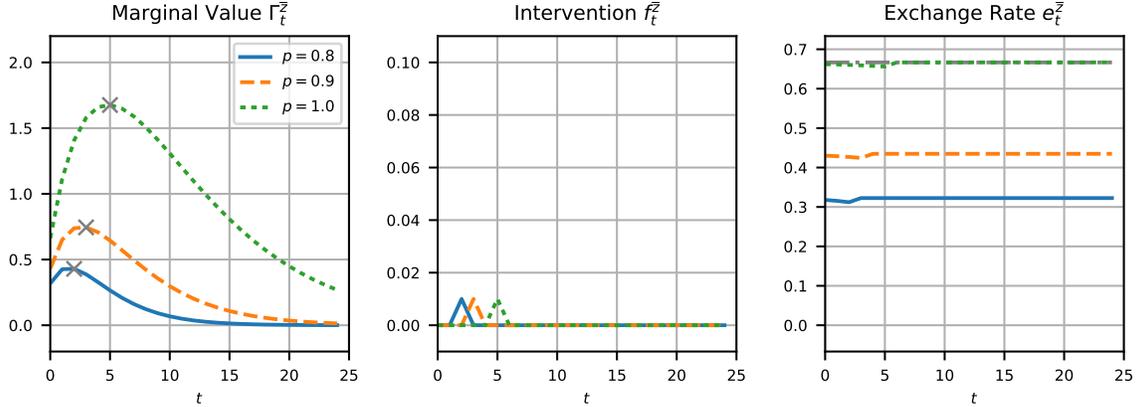


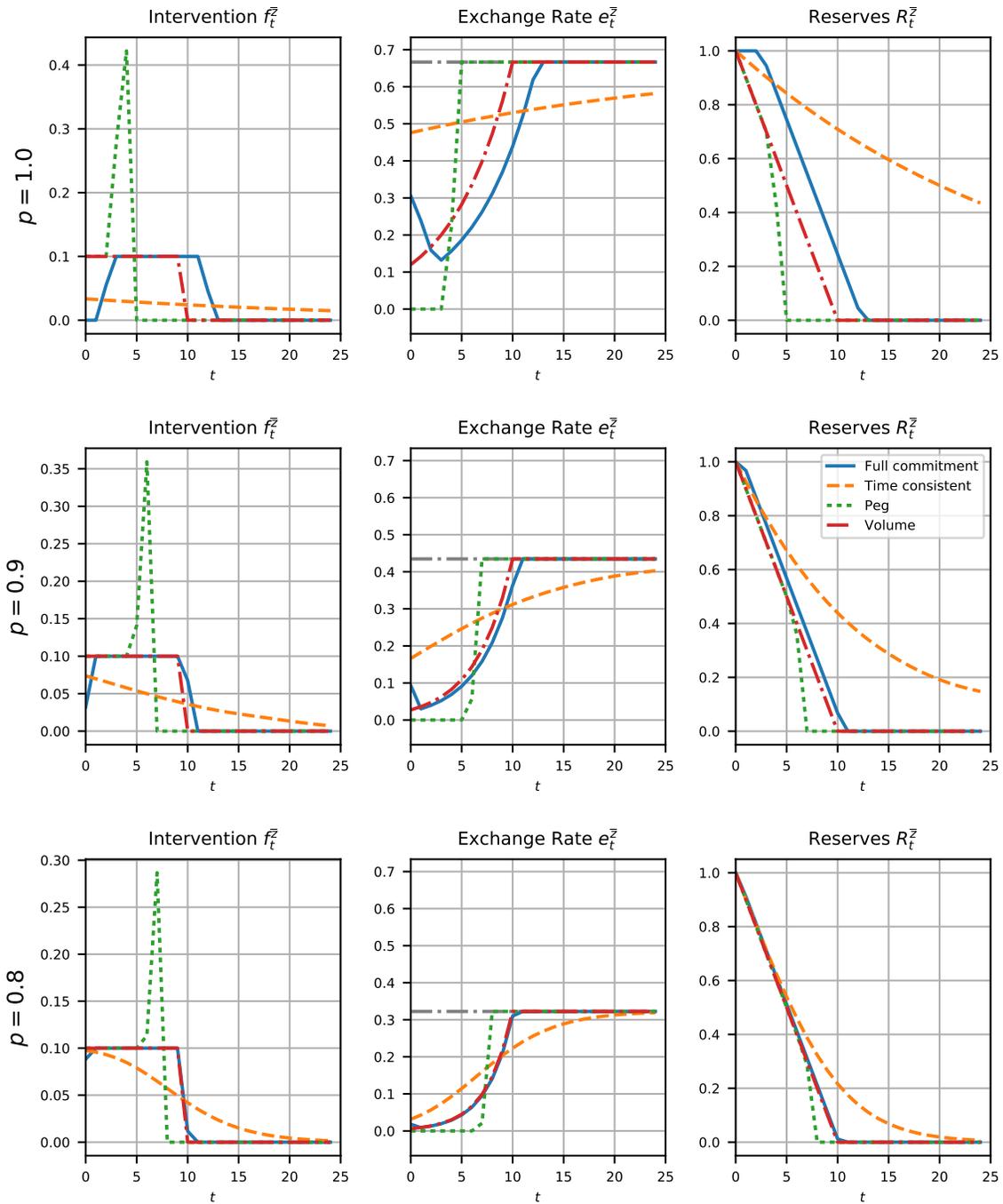
Figure 8 shows the marginal value of intervention using the same baseline parameters as in figure 2, except that we consider probabilities of persistence  $p$  that are smaller than 1. We set intervention conditional on the shock continuing,  $f_t^z$ , equal to zero, and we plot the exchange rate conditional on the shock continuing,  $e_t^z$ .  $\Gamma_t^z$  is hump-shaped like  $\Gamma_t$  was, but the lower the persistence, the earlier the period  $t_p^*$  in which  $\Gamma_t^z$  reaches its peak. In other words, intervention should be promised for earlier periods: since it is more likely that the shock is still occurring in earlier rather than later periods, these earlier periods are weighted more in welfare terms, and intervention in earlier periods has a stronger effect on the period-0 exchange rate.

Therefore, for more temporary shocks, there should be less postponement of intervention in both the full-commitment and time-consistent solutions. We turn to those solutions next.

## 5.2. Solutions under full, zero, and partial commitment

Figure 9 compares the full-commitment solution, the time-consistent solution, and simple FX intervention rules in the stochastic case (we have plotted the implied FX interventions, exchange rates, and remaining stocks of reserves in the circumstance that the outflow shock continues occurring). To see how the solutions change as  $p$  declines below 1, this figure should be compared to figure 7 in the previous section. We explain these solutions one by one and in relation to each other for the remainder of section 5.

Figure 9. Solutions under full, zero, and partial commitment,  $p \leq 1$



In the full-commitment case, reserves are now optimally used such that the marginal value of intervention is equalized across periods and states where reserves are actually useful, *i.e.*, in those circumstances where the shock continues. In other words,  $\Gamma_{t \in \{\text{Intervention dates}\}}^{\bar{z}} = \bar{\Gamma}^{\bar{z}} > \Gamma_{t \notin \{\text{Intervention dates}\}}^{\bar{z}}$  for some constant  $\bar{\Gamma}^{\bar{z}}$ . Combining the first order conditions of the optimization problem with respect to reserves and the exchange rate, we obtain a new Euler condition that holds during the periods of intervention:

$$e_t^{\bar{z}} = \beta p e_{t+1}^{\bar{z}}. \quad (23)$$

The next proposition summarizes the full-commitment solution in the stochastic case.

**Proposition 2 (Full-commitment solution)** *The optimal FX intervention policy is to promise positive intervention for a subset of consecutive periods  $\{t_1, \dots, t_2\}$ , provided that the shock continues occurring. There is zero intervention before  $t_1$  and reserves are fully depleted in period  $t_2$ . The exchange rate path follows the same expressions as in proposition 1, but with  $\beta$  replaced by  $\beta p$ ,  $\bar{e}$  replaced by  $\bar{e}^{\bar{z}}$ , and  $e_u$  replaced by  $e_u^{\bar{z}}$  for all  $u$ . The intervention path follows the same expressions as in proposition 1, but with  $e_u$  replaced by  $e_u^{\bar{z}}$  for all  $u$ .  $t_1$  and  $t_2$  satisfy the feasibility condition  $\sum_{t=t_1}^{t_2} f_t = R_0$  such that  $e_{t_2}^{\bar{z}} \geq \beta p \bar{e}^{\bar{z}}$  and  $\Gamma_{t \in \{t_1, \dots, t_2-1\}}^{\bar{z}} = \bar{\Gamma}^{\bar{z}} > \Gamma_{t \notin \{t_1, \dots, t_2-1\}}^{\bar{z}}$  for some constant  $\bar{\Gamma}^{\bar{z}}$ .*

**Proof.** Same as for proposition 1. ■

Therefore, for our baseline parameter specification which satisfies  $\frac{1}{\beta} = \frac{a+c}{a}$ , the full-commitment intervention level remains unchanged at  $\bar{z}$  irrespective of  $p$ . However, the depreciation of the exchange rate during the period of intervention becomes more rapid as  $p$  decreases, which indicates that investors expect reserves to be used up earlier. The rationale for this expectation is provided in figure 9: intervention is promised for earlier periods as  $p$  decreases. For a very temporary shock, *i.e.*, when  $p$  is small, intervention begins in period 0, right at the beginning of the outflow episode.

The time-consistent problem follows definition 3 below. Relative to definition 2, we have already normalized  $e^* = 0$  and taken into account that intervention only occurs as long as the shock continues.

**Definition 3 (Time-consistent optimization problem)** *A time-consistent solution comprises an FX intervention policy  $f^{\bar{z}}(R)$  and an exchange rate relation  $e^{\bar{z}}(R)$ , both conditional on the outflow shock continuing to occur, which are infinitely-differentiable fixed points of the Bellman operator:*

$$v^{TC, \bar{z}}(R) = \max_{e^{\bar{z}}, R'} \left\{ -\frac{e^{\bar{z}}(R)^2}{2} + \beta p v^{TC, \bar{z}}(R') \right\} \quad (24)$$

subject to modified versions of equations (4) and (6) and the set of feasible exchange rates:

$$f^{\bar{z}}(R) = R - R' \in [0, R] \quad (25)$$

$$e^{\bar{z}}(R) = \frac{1}{a+c} (\bar{z} - f^{\bar{z}}(R) + ape^{\bar{z}}(R')) \quad (26)$$

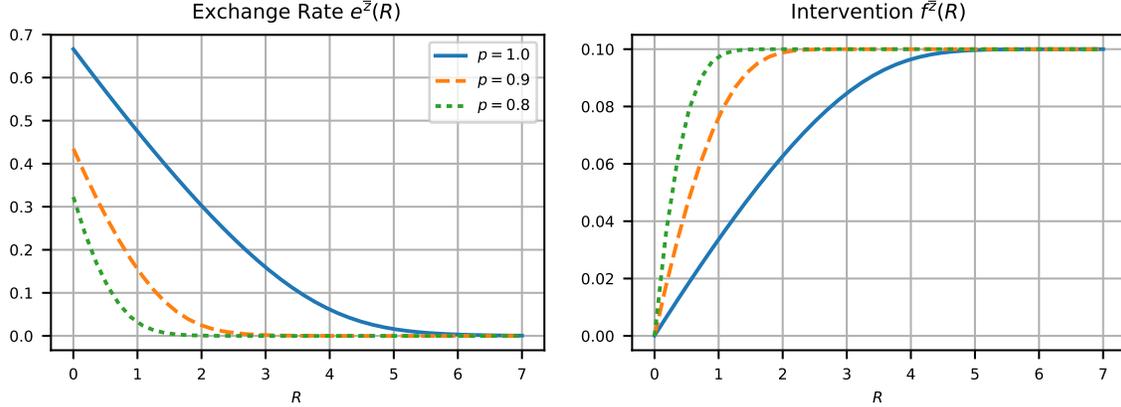
$$e^{\bar{z}}(R) \geq \bar{e}^{\bar{z}} - \frac{1}{a+c} R. \quad (27)$$

The new time-consistent Euler condition takes the following form:

$$e^{\bar{z}}(R) [1 + ape^{\bar{z}}_R (R - f^{\bar{z}}(R))] \geq \beta pe^{\bar{z}} (R - f^{\bar{z}}(R)). \quad (28)$$

Our shock specification is tractable enough that we are able to numerically solve the time-consistent case.<sup>30</sup> Figure 10 illustrates our solutions for  $f^{\bar{z}}(R)$  and  $e^{\bar{z}}(R)$  for the same baseline parameters as in figure 4, but with different values of the shock persistence  $p$ .

Figure 10. Time-consistent fixed-point functions,  $p \leq 1$



As the shock becomes more temporary, *i.e.*,  $p$  decreases, the time-consistent intervention increases towards the higher full-commitment level  $\bar{z}$  for all levels of reserves. There are two reasons for this result, echoing the discussions above about the incentive to postpone intervention. First, the central bank assigns a lower welfare weight to future periods where the shock continues, because temporary shocks are unlikely to continue for long. Second, it is less valuable to bolster investors' expectations regarding future exchange rates by keeping reserves in the central bank's vault, when it is less likely that the shock continues and that those reserves will then be used. Therefore, even if reserves are low today, the central bank may wish to almost fully offset a temporary outflow shock today, and correspondingly keep few reserves for the future.

<sup>30</sup>  $f^{\bar{z}}(R)$  and  $e^{\bar{z}}(R)$  close to  $R = 0$  satisfy  $\lim_{R \rightarrow 0} e^{\bar{z}}_R(R) = \frac{\beta p - 1}{ap}$  and  $\lim_{R \rightarrow 0} f^{\bar{z}}_R(R) = \frac{1 - \beta p}{\beta p} \frac{a(1-p) + c}{ap}$ .

As  $p$  decreases, the exchange rate function becomes closer to the target  $e^*$ , firstly because the pure-float exchange rate is less depreciated relative to the target, and secondly because the central bank's intervention becomes more aggressive.

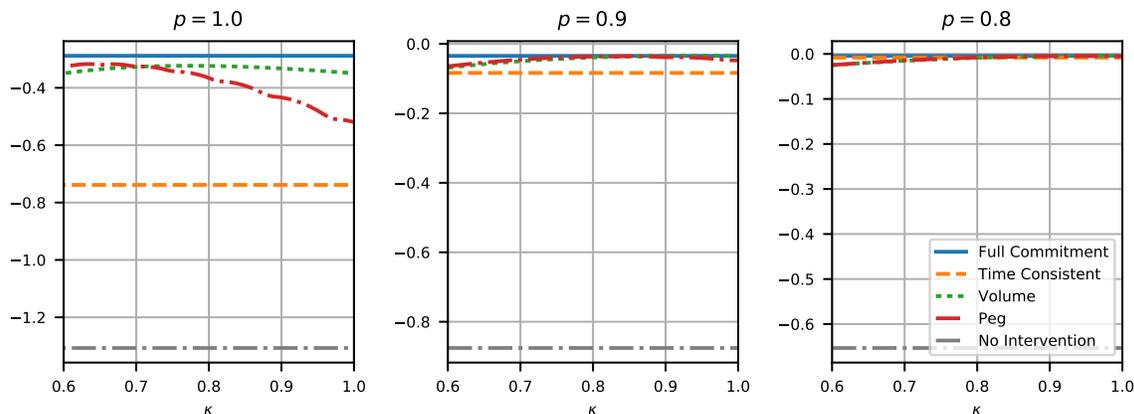
These results are reflected in figure 9. As  $p$  decreases, the time-consistent intervention becomes higher and begins to fully offset the outflow shock  $\bar{z}$  at the beginning of the outflow episode. As a result, the exchange rate becomes stabilized closer to the target  $e^*$ , and the large immediate depreciation that we derived in section 4 is avoided.

Both the full-commitment and time-consistent solutions become closer to each other and to the simple FX intervention rules when the shock becomes more temporary. The full-commitment intervention is brought earlier in time and eventually coincides exactly with the volume intervention rule, while the time-consistent intervention level rises to fully offset the outflow shock  $\bar{z}$  at the beginning of the outflow episode, which happens to be a feature of both of the simple intervention rules.

### 5.3. Welfare comparison

The arguments above suggest that relative to the time-consistent solution, the scope for welfare improvements through the use of rules may diminish as the shock persistence  $p$  decreases. Figure 11, which illustrates the welfare levels under full commitment, time consistency, and simple intervention rules across various levels of  $\kappa$ , shows that this is indeed the case. Moreover, as  $p$  decreases, there is a reduction in the range of values of  $\kappa$  for which the simple intervention rules yield higher welfare than the purely discretionary time-consistent solution.

Figure 11. Welfare comparison,  $p \leq 1$



Taking stock, the time consistency problem is more severe for more persistent shocks.

When the shock is a pure one-off ( $p = 0$ ), the shock is expected to go to zero in all future periods, so no intervention is expected in the future, and investors' expectations about next period's exchange rate are unaffected by the central bank's commitment power. Moreover, the central bank does not expect that reserves will be valuable in future periods. Therefore,

the central bank solves a simple one-period problem today, which yields an identical policy in both the full-commitment and time-consistent cases.

When the shock is very persistent ( $p$  near 1), it is expected to continue for many periods, so investors' expectations regarding the central bank's future interventions become important for the exchange rate today, and the central bank also values the ability to intervene in future periods. In addition, the shock has a higher net present value, so the ZLB on reserves is more likely to become binding. For all these reasons, the central bank wishes to preserve reserves to last throughout a long outflow episode. The central bank with full commitment achieves this by credibly committing to begin an aggressive intervention strategy in future periods, even if reserves thereby run out. But the time-consistent central bank cannot do this in the presence of the ZLB on reserves, because it will choose to preserve reserves rather than spend them when reserves are about to run out. Correspondingly, investors are skeptical of regarding any promises to intervene aggressively in the future. Therefore, in a model with a ZLB on reserves, the larger is the shock persistence parameter  $p$ , the more damaging is a lack of commitment power, and the more likely it is that committing to simple intervention rules can yield welfare gains.<sup>31</sup>

## 6. Conclusion

In this paper, we have used a stylized linear-quadratic framework to analyze optimal FX intervention in the face of outflows in a managed float regime. We have explicitly taken into account the ZLB on reserves, and we have related the optimal policy for an EME central bank to some of the key assessments that it needs to make in every outflow episode—specifically, the level of available reserves and the persistence of the shock. While the precise form of our optimal solutions for the exchange rate and intervention level depend on our functional forms for welfare and the exchange rate equation, the qualitative effect of the ZLB on the time consistency of the solution, and on the comparative levels of intervention and welfare across different degrees of central bank commitment, should apply across a wide range of models.

First, we have shown that a central bank with full commitment and limited reserves optimally uses a combination of intervention and market communication. At the beginning of an outflow episode, the central bank may not intervene at all, but it does promises to intervene aggressively in the future, so that the entire reserves stock eventually becomes depleted if the shock persists. As a result of this commitment, the exchange rate depreciates gradually to the pure-float level.

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<sup>31</sup>This argument applies to other models with different welfare functions and exchange rate equations, provided that the probability of reserves being exhausted is above zero in the full-commitment solution.

Second, we have highlighted a novel time consistency problem when there is a ZLB on reserves and imperfect arbitrage on the FX market. In the absence of commitment power, the central bank undertakes only a small level of intervention in all periods. As a result, there is a large depreciation as soon as the outflow episode begins, which generates a substantial welfare loss. To mitigate this large immediate depreciation, a central bank with intermediate commitment power finds it optimal to announce a simple intervention rule, such as a temporary exchange rate peg or a volume intervention rule.

Third, we have related the optimal FX intervention policy to the persistence of the shock. The more persistent is the shock, the larger the time consistency problem, and the more likely that a simple intervention rule achieves welfare gains above the time-consistent solution. Therefore, in practice, a shock that looks small but is actually potentially persistent may require the central bank to announce an intervention rule in order to affect the exchange rate, even if such a rule is not needed for a larger, but far more temporary, shock.

The general message which emerges from our approach is that the characterization of optimal policy in a managed float regime, away from the bipolar extremes of free floats and hard pegs, is a non-trivial problem. The empirical effectiveness of FX intervention in managing the exchange rate does not immediately imply an obvious intervention modality to be adopted by all EME central banks, but rather opens the door to a host of additional considerations such as time consistency and the connection between the nature of the outflow shocks and the specific financial imperfections present in the FX market. Echoing the literature on inflation targeting regimes, the optimal managed float regime requires investment in communication, reputation, and rules.

# Appendix

## A.1. Constant-outflows case with $e^*$ adjusting to $\bar{e}$

Consider the following time path for the exchange rate target in each period  $t$ :

$$e_t^* = \bar{e} (1 - \lambda^t). \quad (29)$$

For  $\lambda = 1$ , this equation reverts to the normalization  $e^* = 0$  in the main text. For  $\lambda = 0$ ,  $e_t^* = \bar{e}$  for all  $t$ , so it is optimal to let the exchange rate depreciate to the pure-float level immediately. For  $\lambda \in (0, 1)$ , which is the case that we focus on here, the target  $e_t^*$  adjusts smoothly in an exponential fashion to the pure-float level  $\bar{e}$ .

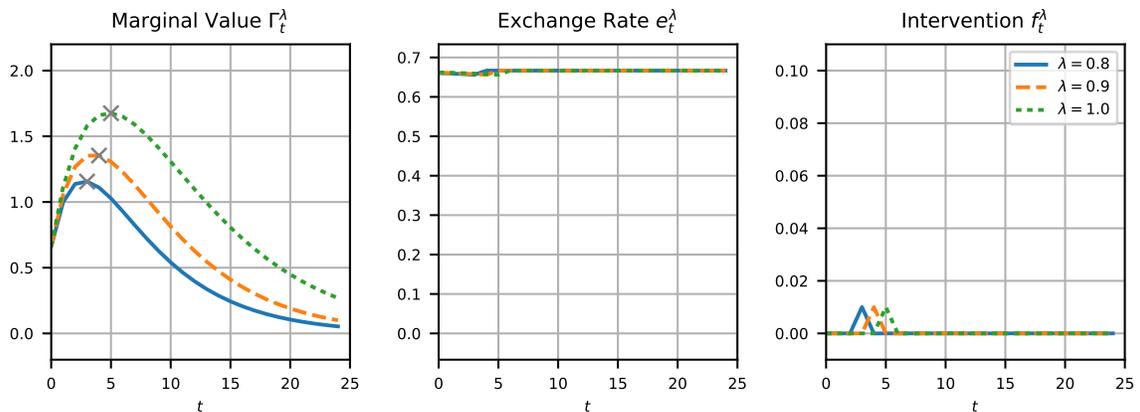
This model is intended to capture in reduced form an environment where the long-run desire of the central bank is to adjust the exchange rate to accommodate the permanent shock (since  $\lim_{t \rightarrow \infty} e_t^* = \bar{e}$ ), but where adjusting immediately to the pure-float level  $\bar{e}$  generates short-run welfare costs (*e.g.*, private sector FX borrowers are forced to deleverage too rapidly), so that  $e_0^* \neq \bar{e}$ .

Substituting equation (29) into definition 1, and taking the first order condition of the optimization problem with respect to the exchange rate, we can back out the amended value of the multiplier  $\Gamma_t^\lambda$  on the exchange rate equation, in the absence of intervention:

$$\Gamma_t^\lambda = \sum_{u=0}^t (\beta\lambda)^u \left( \frac{a}{a+c} \right)^{t-u} \bar{e}. \quad (30)$$

This formula is isomorphic to the one for the model used in subsection 4.1, but with  $\beta$  replaced by  $\beta\lambda$ . In figure A.1, we plot the schedule  $\Gamma_t^\lambda$  using the same baseline parameters as in figure 2.

Figure A.1. Marginal value of intervention in pure-float equilibrium

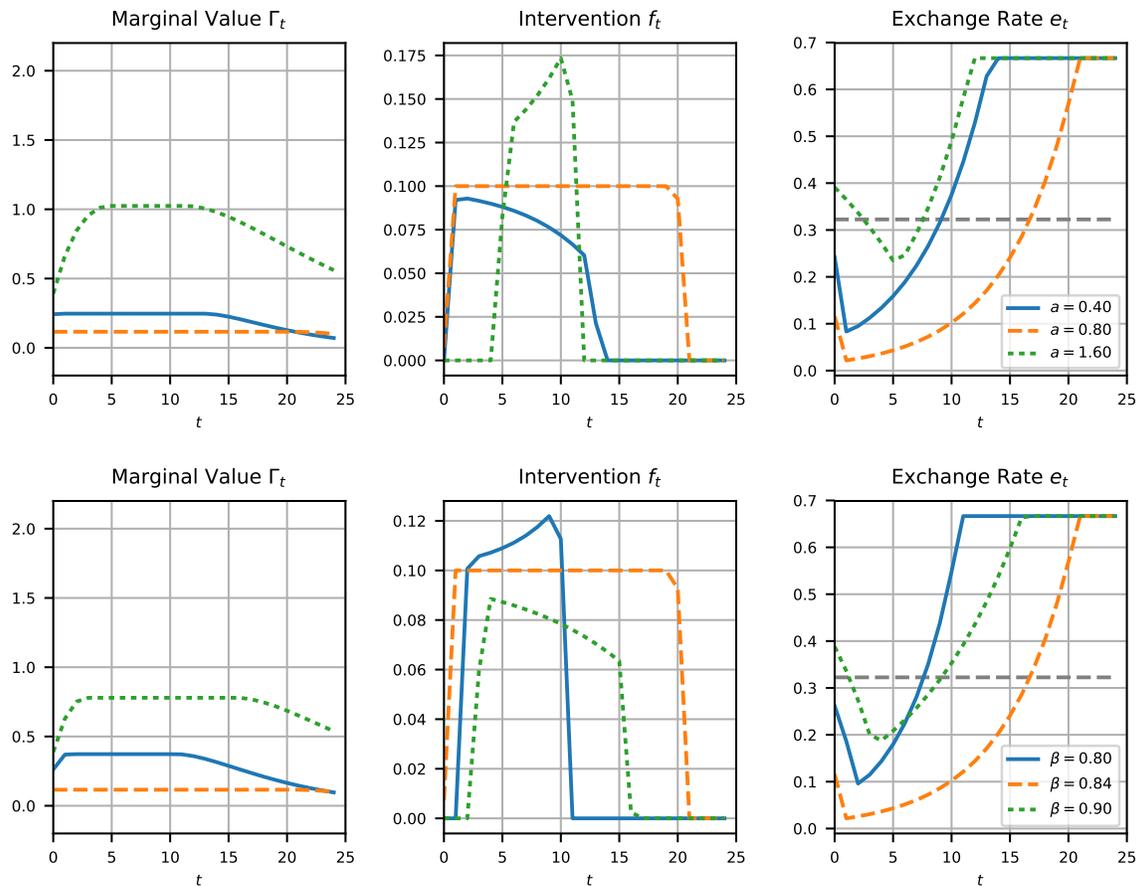


The schedule for  $\Gamma_t^\lambda$  is hump-shaped, so the highest marginal value of intervention is achieved in a period  $t_\lambda^*$  that is greater than zero; in other words, at the beginning of the outflow episode, intervention in the future is more valuable than intervention today (just as in the baseline model in subsection 4.1). As the parameter  $\lambda$  decreases and the exchange rate target  $e_t^*$  adjusts faster to  $\bar{e}$ , the period  $t_\lambda^*$  becomes smaller, *i.e.*, the marginal value of intervention is maximized closer to the beginning of the outflow episode.

## A.2. Comparative statics for the full-commitment case

Figure A.2 shows the full-commitment solutions for various values of  $a$  and  $\beta$ .

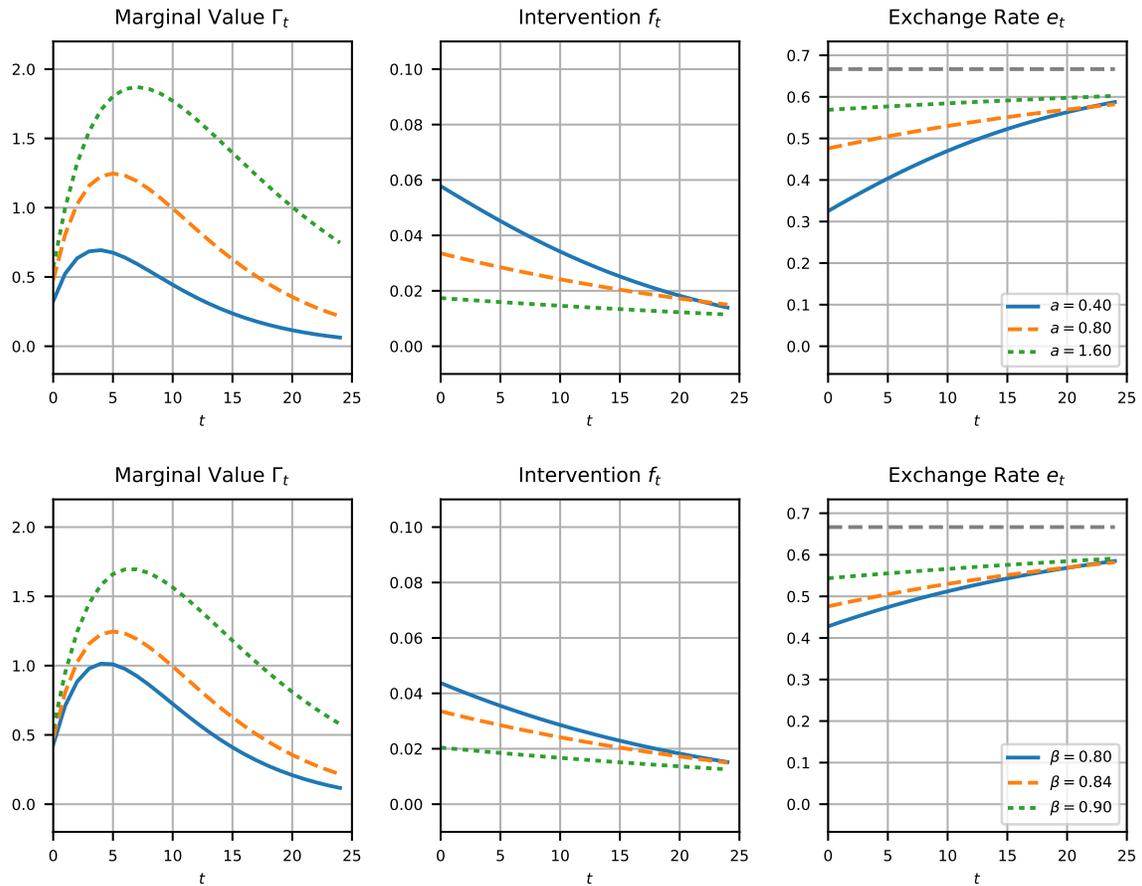
Figure A.2. Full-commitment solution, various  $a$  and  $\beta$



### A.3. Comparative statics for the time-consistent case

Figure A.3 shows the time-consistent solutions for various values of  $a$  and  $\beta$ .

Figure A.3. Time-consistent solution, various  $a$  and  $\beta$



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