# Incomplete Exchange Rate Pass-Through and Simple Monetary Policy Rules

**Malin Adolfson***

*Research Department, Sveriges Riksbank, SE-103 37 Stockholm, Sweden*

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Abstract

This paper investigates the performance of various monetary rules in an open economy with incomplete exchange rate pass-through. Implementing monetary policy through an exchange rate augmented policy rule does not improve social welfare compared to using an optimized Taylor rule, irrespective of the degree of pass-through. A direct exchange rate response improves welfare only if the other reaction coefficients, on inflation and output, are sub-optimal. However, an indirect exchange rate response, through a policy reaction to Consumer Price Index (CPI) inflation rather than to domestic inflation, is welfare enhancing. This result is independent of whether society values domestic or CPI inflation stabilization.

*Keywords*: Exchange rate pass-through, monetary policy, simple policy rules, small open economy, Taylor rule

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* *Tel.: + 46 8 787 04 96; fax: + 46 8 21 05 31.*
E-*mail address*: malin.adolfson@riksbank.se.

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## 1. Introduction

In a small open economy, where the exchange rate influences inflation and output via import prices and relative prices, the exchange rate will transmit monetary policy in addition to the traditional (i.e., closed economy) interest rate channel. If the exchange rate contains information about, for example, inflationary impulses, the policy maker might improve social welfare by extending her simple monetary policy rule to include a direct reaction to the exchange rate. The reason for this is multifaceted; first, augmenting the policy rule with an exchange rate term does, to some extent, internalize the 'total' effects interest rate adjustments have on the economy, since movements in the interest rate (i.e., the policy instrument) also influence the exchange rate. Hence, there might be an informational advantage to such a policy rule, measuring the overall position of the policy (see, e.g., Ball (1999)). Second, a policy rule that includes an exchange rate reaction is less restrictive than a rule that just contains a response to the result of the exchange rate movement (i.e., subsequent changes in inflation and output). The exchange rate augmented rule incorporates a direct feedback from the inflationary impulse (i.e., the cause of instability), which implies a possibility to quickly adjust the interest rate and offset the exchange rate effects. This might, consequently, reduce the sub-optimality of the simple policy rule. Third, if a financial disturbance is the cause underlying an exchange rate misalignment, a direct exchange rate reaction may prevent such shocks to have destabilizing effects on the real side of the economy (see Cecchetti et al. (2000)).

Prior literature analyzing open economies and simple monetary policy rules has explored a broad set of exchange rate augmented policy rules, without attaining complete consensus of whether or not it is beneficial to include some feedback from an exchange rate variable in the central bank's instrument rule.[1] The purpose of this paper is to study and describe an appropriate simple policy rule in an open economy with incomplete exchange rate pass-through. In

[1] Among the previously evaluated policies are, for example, rules incorporating either the (current and/or lagged) real exchange rate, the change in the real exchange rate, or the level or change in the nominal exchange rate. In a backward-looking model, Ball (1999, 2000) shows that a simple rule encompassing the current and lagged real exchange rate generates a social welfare enhancement. On the other hand, in forward-looking models the evidence regarding the possible welfare improvements of various exchange rate augmented policy rules are mixed. Batini et al. (2001), Kollmann (2002), Leitemo and Söderström (2005), all assume limited exchange rate pass-through and find that the welfare performance is only marginally improved (if at all) by including a direct feedback from an exchange rate term in the instrument rule. The same result applies to McCallum and Nelson (1999), and Taylor (2001), although they employ full-pass-through models. In contrast, Cecchetti et al. (2000), and Monacelli (1999), display models where there are welfare improvements of using policy rules that incorporate some exchange rate term. Cecchetti et al. (2000) look into forecast based rules for implementing policy, while Monacelli assumes incomplete exchange rate pass-through. Further, using two-country models, Benigno and Benigno (2001), and Weerapana (2000) record substantial (world economy) welfare improvements of interest rate rules including an exchange rate reaction.

particular, the analysis focuses on the importance of the degree of pass-through. If the open economy policy maker implements her policy through an instrument rule, should the nominal or real exchange rate be incorporated into this rule, and is this affected by whether the exchange rate pass-through is incomplete? That is, can inclusion of an exchange rate response among the policy maker's reactions mitigate the sub-optimality of the instrument rule? The analysis is pursued in a simple aggregate demand-aggregate supply model, where incomplete exchange rate pass-through is included in the model via nominal import price rigidities. This, consequently, implies short-run deviations from the law of one price.

The main results obtained in the paper are as follows; *i*) the social welfare improvement of incorporating an exchange rate term in the *fully optimized* policy rule is practically zero, irrespective of the degree of pass-through. However, adding a real exchange rate term to the *non-optimized* Taylor (1993) rule does enhance social welfare somewhat, since it reduces the sub-optimality of the overall policy response. *ii*) An indirect exchange rate response, attained through a policy reaction to CPI inflation rather than domestic inflation, is welfare enhancing. This result holds independent of the degree of pass-through. Moreover, this result is not contingent upon society's preferences for CPI inflation stabilization or domestic inflation stabilization.

In Section 2, the economic model as well as three different exchange rate augmented policy rules are presented. These simple rules incorporate either a nominal or a real exchange rate term, in order to take advantage of any latent exchange rate effects, as discussed above. Section 3 contains the optimal policy reactions and the stabilization outcome of the different policy rules in terms of social welfare. Robustness issues are discussed in Section 4, and lastly some conclusions are provided in Section 5.

## 2. Model

The model is an open economy aggregate supply-aggregate demand model, adjusted for short-run incomplete exchange rate pass-through, and based on agents' optimizing behaviour. The main equations of the model are presented in this Section, while a more thorough discussion of the model's underlying microfoundations can be found in Appendix A. The consumers attain utility from consumption of domestic as well as import goods, supplied by a domestic and a foreign producer, respectively. Both producers sell their goods to the domestic and the foreign market, setting prices optimally under quadratic adjustment costs, following Rotemberg (1982).

The economy of primary interest (called domestic) consists of four (log-linearized) equations determining inflation, output, expected exchange rate changes, and the net foreign asset position:[2]

$$\begin{aligned}\pi_t &= (1-\kappa_M)\pi_t^D + \kappa_M \pi_t^M \\ &= \beta \mathrm{E}_t \pi_{t+1} + \beta_y y_t + \beta_q (p_t^M - p_t^D) + \beta_p (p_t^* + s_t - p_t^M) + \varepsilon_t^\pi ,\end{aligned} \tag{1}$$

$$\begin{aligned}y_t &= \mathrm{E}_t y_{t+1} - \alpha_q \mathrm{E}_t (\pi_{t+1}^M - \pi_{t+1}^D) - \alpha_i (i_t - \mathrm{E}_t \pi_{t+1}) \\ &\quad + \alpha_e (\mathrm{E}_t \pi_{t+1}^D - (\mathrm{E}_t s_{t+1} - s_t) - \mathrm{E}_t \pi_{t+1}^*) - \alpha_y (\mathrm{E}_t y_{t+1}^* - y_t^*) + \varepsilon_t^y ,\end{aligned} \tag{2}$$

$$i_t - i_t^* = \mathrm{E}_t s_{t+1} - s_t - \phi a_t + \varepsilon_t^\phi , \tag{3}$$

$$a_t = \omega_a a_{t-1} + \omega_q \left(p_t^M - p_t^D\right) + \omega_p \left(p_t^* + s_t - p_t^M\right) - \omega_y y_t + \omega_y^* y_t^* . \tag{4}$$

Equation (1) is an aggregate supply relation obtained from the aggregate price index underlying the constant elasticity of substitution (CES) function for consumption and the producers' optimal price setting, assuming nominal rigidities. Aggregate inflation (i.e., consumer price inflation) is a convex combination of inflation of domestically produced goods ($\pi_t^D$) and imported inflation ($\pi_t^M$). The variable $y_t$ denotes aggregate output, ($p_t^M - p_t^D$) is the relative price of imports describing the inverse of the terms of trade (which turns up because of imported intermediate inputs), and $s_t$ is the nominal exchange rate (domestic currency per unit of foreign currency). Deviations from the law of one price arise due to nominal import price stickiness and are captured by the term ($p_t^* + s_t - p_t^M$), where the price stickiness parameter $\beta_p$ governs the degree of exchange rate pass-through. A less complete, or smaller, short-run pass-through occurs in the model by assigning greater import price rigidity, that is, a smaller $\beta_p$. Finally, $\varepsilon_t^\pi$ encapsulates a disturbance to domestic supply (or to be exact, a domestic cost push shock that does not directly affect aggregate output) following the autoregressive process $\varepsilon_{t+1}^\pi = \tau_\pi \varepsilon_t^\pi + u_{t+1}^\pi$, where $u_{t+1}^\pi$ is an iid disturbance with mean zero and variance $\sigma_\pi^2$.

Equation (2) is an aggregate demand relation derived from a standard Euler equation of the households' intertemporal consumption decision, using the demand relations from the

[2] The notation is as follows; lower case letters denote logarithmic values (deviations from steady-state), a superscript indicates whether domestic or import goods are considered, and an asterisk represents foreign variables. A price characterized with an asterisk consequently denotes the foreign currency price. Lastly, $\mathrm{E}_t$ denotes rational expectations as of period *t*.

underlying CES aggregator. Domestic demand shocks (e.g., originating from preference shifts) are captured in $\varepsilon_t^y$ that follows, $\varepsilon_{t+1}^y = \tau_y \varepsilon_t^y + u_{t+1}^y$, with $u_{t+1}^y$ as an iid disturbance term with mean zero and variance $\sigma_y^2$. This output relation differs from its full pass-through equivalence because of short-run deviations from the law of one price for imports, which makes the relative price of imports ($p_t^M - p_t^D$) and the relative price of exports ($p_t^D - s_t - p_t^*$) diverge.[3] The internal relative price (i.e., of imports) appears through its effect on domestic consumers' demand, while the external relative price (i.e., of exports) shows up due to the foreign consumers' demand for domestic goods. Foreign imports are subject to incomplete pass-through, while the domestic exporters, by assumption, follow the law of one price.

Equation (3) is a modified uncovered interest rate parity condition derived from the consumers' optimal holdings of domestic and foreign bonds. Because of imperfect financial integration it is assumed that there is a premium on foreign bond holdings which depends on the aggregate net foreign asset position of the domestic households $a_t$ (see, e.g., Benigno (2001)). $\varepsilon_t^\phi$ is a time varying shock to the risk premium. This shock is a 'pure' exchange rate disturbance capturing autonomous shocks to expectations about the future exchange rate.[4] The risk premium follows the AR(1) process, $\varepsilon_{t+1}^\phi = \tau_\phi \varepsilon_t^\phi + u_{t+1}^\phi$, where $u_t^\phi$ is an iid disturbance with mean zero and variance $\sigma_\phi^2$.

Equation (4) displays the evolution of the net foreign asset position at the aggregate level. The foreign bond holdings in the domestic economy clear the difference between exports and imports in nominal terms. The relative prices of both imports and exports therefore enter the net foreign asset equation.

The domestic economy is small in the sense that conditions in the foreign economy are exogenously given. The foreign inflation and output relations are assumed to consist of persistent AR(1) processes, while the foreign monetary policy is presumed to be implemented

[3] The relative price *change* turns up in equation (2) because it affects the *inter*temporal consumption decision, while the relative price *level* affects the *intra*temporal allocation between consumption of imports and domestic goods. Note, however, that the difference terms disappear when solving equation (2) forward.
[4] Other independent exchange rate disturbances are hard to distinguish since the exchange rate is affected by anything influencing the interest rate differential in equation (3). This implies that any domestic or foreign shock creating a policy reaction also generates an exchange rate movement.

through a simple Taylor rule with some interest rate persistence added, as suggested by empirical evidence (see, e.g., Clarida et al. (1998)):

$$y^*_{t+1} = \rho^*_y y^*_t + u^{y*}_{t+1}, \tag{5}$$

$$\pi^*_{t+1} = \rho^*_\pi \pi^*_t + u^{\pi*}_{t+1}, \tag{6}$$

$$i^*_{t+1} = (1-\rho^*_i)(b^*_\pi \pi^*_{t+1} + b^*_y y^*_{t+1}) + \rho^*_i i^*_t + u^{i*}_{t+1}, \tag{7}$$

where $\rho^*_y$, $\rho^*_\pi$, $\rho^*_i$ are non-negative coefficients less than unity, and $u^{y*}_{t+1}$, $u^{\pi*}_{t+1}$, $u^{i*}_{t+1}$ are iid disturbances with mean zero and variance $\sigma^2_{y*}$, $\sigma^2_{\pi*}$ and $\sigma^2_{i*}$ , respectively.[5, 6]

In brief, the distinguishing features of the model are consequently departures from full pass-through, in both supply and demand relations, and entirely forward-looking agents.

### *2.1. Simple policy rules and social preferences*

Monetary policy is assumed to be implemented through commitment to a 'simple' instrument rule, as suggested by Taylor (1993), where the short-run interest rate is the policy maker's instrument. The policy maker is assumed to follow such a sub-optimal policy rule, rather than explicitly deriving her reaction function from a policy objective function, due to reasons of, for example, transparency (credibility and monitorability). It may be easier for the central bank to explain the conduct of monetary policy when following a simple rule, as well as making it more straightforward for the public to evaluate the policy maker's performance. In addition, there is some notion in the literature that the outcome of simple rules are robust across different models (see, e.g., Levin et al. (1999)). That is, even if there is uncertainty about the underlying economic relations, a simple rule will generate the same response to, for example, an inflationary impulse, irrespective of the theoretical model used. In contrast, reaction functions

[5] The shocks to foreign output and inflation are assumed to be uncorrelated. Note, however, that the subsequent results are not affected by changing this assumption so that $u^{y*}_{t+1}$ and $u^{\pi*}_{t+1}$ are correlated.

[6] Monetary policy in one country can probably be described by a simple Taylor rule. However, using a single rule to represent the cohesive policy of the 'rest of the world' is less plausible, and therefore requires a disturbance term. $u^{i*}_{t+1}$ captures foreign interest rate changes, or monetary policy changes, that are not encapsulated by the Taylor rule.

directly derived from the policy maker's objective function are more complex and highly contingent upon the particular choice of model representation.[7]

Nevertheless, recall that the use of simple rules was initiated as the outcome of an empirical exercise for a closed economy, and lacks major theoretical foundations.[8] Which policy rule to be followed in an open economy is therefore still a very open question. As mentioned in the Introduction, there have been suggestions that the open economy-policy rule ought to incorporate the exchange rate, so as to exploit the exchange rate's transmission of monetary policy (see, e.g., Ball (1999)). The analysis therefore focuses on the following set of different policy rules:

$$i_t = (1-\rho)\left(b_\pi \pi_t^{CB} + b_y y_t\right) + \rho i_{t-1}, \tag{8a}$$

$$i_t = (1-\rho)\left(b_\pi \pi_t^{CB} + b_y y_t + b_{\Delta e}(s_t - s_{t-1})\right) + \rho i_{t-1}, \tag{8b}$$

$$i_t = (1-\rho)\left(b_\pi \pi_t^{CB} + b_y y_t + b_{(pm-pd)}(p_t^M - p_t^D)\right) + \rho i_{t-1}, \tag{8c}$$

$$i_t = (1-\rho)\left(b_\pi \pi_t^{CB} + b_y y_t + b_{(p^*+e-p)}(p_t^* + s_t - p_t)\right) + \rho i_{t-1}, \tag{8d}$$

where $b_\pi$, $b_y$, $b_{\Delta s}$, $b_{(pm-pd)}$, and $b_{(p^*+s-p)}$ are the policy maker's reaction coefficients, and $\rho$ is the degree of interest rate persistence. $\pi_t^{CB} = \{\pi_t^D, \pi_t\}$ is the inflation measure the central bank bases its instrument rule on. The policy maker sets the interest rate as a linear function of the lagged interest rate and the deviations of domestic inflation (or CPI inflation), output, and possibly some exchange rate variable, from their zero targets.[9] Equation (8a) with $\rho = 0$ is the simple rule suggested by Taylor (1993), while Clarida et al. (2000) advocate that the persistence parameter, $\rho$, is typically 0.8-0.9 for this simple rule to be consistent with the empirical evidence. The three alternative rule specifications incorporate the exchange rate in some form. Equation (8b) states that monetary policy should react to changes in the nominal exchange rate. The reason for this is that the nominal exchange rate difference possibly indicates a direct inflationary impulse, which can be offset by an explicit policy response to the change in the

[7] In such a setting, see Adolfson (2001, 2002) for a discussion of the optimal reaction to different shocks and an analysis of what the fully optimal discretionary policy should be in an open economy with incomplete exchange rate pass-through.

[8] See Svensson (2003) for some critique against the use of instrument rules.

[9] Note that equations (8a)-(8d) are not reaction functions in an exact sense, since inflation, output, and the exchange rate terms are not predetermined state variables. Rather, these equations represent equilibrium relations from which the system's dynamics can be backed out; the dynamics, in turn, relate the forward-looking variables to the

*(footnote continues on next page)*

exchange rate. Recall, though, that such a difference might only reflect temporary fluctuations in the exchange rate.[10] The real exchange rate may also mirror temporary fluctuations, but with sticky prices and incomplete pass-through, that possibility might be smaller, since the real exchange rate is a relative price. Therefore, equations (8c) and (8d) adjust the interest rate to different real exchange rate specifications, but because of incomplete pass-through the two characterizations are not equivalent. The term ( $p^M - p^D$ ) in equation (8c) captures the (inverse of the) terms of trade, while the term ( $p^* + s - p$ ) in equation (8d) captures deviations from purchasing power parity (PPP) between the foreign and the domestic economy. Note also that the degree of pass-through influences these two variables differently in the face of, for instance, a risk premium shock. As pass-through decreases, the deviations from purchasing power parity becomes larger (because of larger departures from the law of one price), while the terms of trade are expected to become more stable (due to smaller movements in the import prices).[11]

The policy rules suggested above are evaluated in terms of a social loss function, which is also used for optimizing the reaction rule coefficients in equations (8a) – (8d). This paper does not attempt to characterize the social welfare by deriving the precise quadratic approximation of the welfare in this particular dynamic small open economy model. In contrast, an arbitrary, but reasonable, loss function is used to describe the social welfare employed for evaluating the different monetary policy rules.[12] Specifically, social preferences are assumed to follow an

predetermined variables. However, note that the subsequent results are qualitatively robust to changing the policy rule so that the interest rate only depends on lagged variables.

[10] There are no transmission lags of monetary policy here, so the policy maker can respond to all disturbances, temporary as well as permanent, as long as they turn up in any of the target variables. However, if interest rate volatility is detrimental to social welfare for some reason, the policy maker may want to disregard transitory exchange rate movements.

[11] The analysis in this paper focuses on an inflation targeting regime with policy rules that include stationary variables which can be captured within the same state-space form. When the state-space representation contains non-stationary variables, such as the nominal exchange rate *level*, it is not clear whether the numerical solution procedure is reliable. Note also that a response to the nominal exchange rate level in the policy rule induces stationarity in the exchange rate *and* in the price level, which entails a different policy regime (price level targeting). Such extensions of the policy rule are therefore left for future research.

[12] In a closed economy, Woodford (2002) shows how to obtain a microfounded quadratic objective function in inflation and output that represents a second-order Taylor approximation of the expected utility for the representative household. However, in a dynamic open economy model such a derivation has proven to be a more complicated undertaking. Sutherland (2002) is able to derive a second order approximation of the agents' welfare criterion, but in a static environment with predetermined prices. In a dynamic setting, Gali and Monacelli (2004) derive a quadratic objective in domestic inflation and output but under certain restrictive assumptions about the agents' preferences and assuming complete pass-through. Benigno and Benigno (2003) have in a recent paper developed a microfounded quadratic loss function consisting of domestic and imported inflation and output as well as the terms of trade, however in a model where the law of one price holds. The open economy welfare objective can thus differ from that of the closed economy depending on the assumptions made. Note also that Benigno (2004), and Benigno and Benigno (2001) present a similar expression for the second order Taylor expansion of the world economy (central planner) welfare in a two-country model where the loss function measures the departures from the flexible price allocation. Further, Kollmann (2002) assumes log utility and uses a quadratic approximation of the utility function to express welfare in terms of consumption. He utilizes numerical simulations to examine the welfare effects of a

*(footnote continues on next page)*

objective function with quadratic deviations of CPI inflation and output from their constant target levels (here normalized to zero for simplicity):

$$\min_{\{i_{t+j}\}_{j=0}^{\infty}} \quad \mathrm{E}_t \sum_{j=0}^{\infty} \beta^j L_{t+j}^S \, , \qquad \qquad (9)$$
$$\text{where} \quad L_t^S = \left[ \pi_t^2 + \lambda^S y_t^2 \right],$$

where $0 < \beta < 1$ is a discount factor, and $\lambda^S$ is the relative weight society puts on output stabilization.[13] To minimize the social loss function and find the optimal simple rule, the model in equations (1) – (7) is expressed in state-space form (see Appendix B). This implies that the minimization in equation (9) can be stated as a linear-quadratic problem. The policy maker is assumed to be able to commit to one of the simple policy rules in equations (8a)-(8d). As the discount factor, $\beta$, approaches unity, it can be shown that the limit of the scaled intertemporal loss function can be expressed as the unconditional mean of the period loss function (see Rudebusch and Svensson (1999)):

$$\mathrm{E}\left[L_t^S\right] = \mathrm{Var}(\pi_t) + \lambda^S \mathrm{Var}(y_t) \, . \qquad (10)$$

The loss function in equation (10) is used to assess which policy rule in equation (8) provides the most efficient stabilization of the economy, as well as for optimizing the reaction coefficients in each rule. Equation (10) is calculated using asymptotic variances that can be obtained from the solution (or transition matrix) of the model, both described in Appendix B. The model is solved using numerical methods, described in for example Söderlind (1999), and so it needs to be parameterized. The parameter values shown in Table 1 are based on underlying deep parameters, which are chosen along the lines of prior literature.[14]

number of shocks under different instrument rules. For a discussion about the pass-through aspects of the open economy-social objective, and robustness issues regarding the social preferences, see Section 4.1. below.

[13] Stabilization of CPI inflation involves joint stabilization of the two inflation components in the consumer price index (i.e. both the domestic and imported inflation). Such a loss function seems suitable in an open economy with incomplete pass-through, since a relative price distortion occurs due to sticky domestic prices *and* sticky import prices. In an open economy with two such distortions Smets and Wouters (2002) find that the social cost of relative price variability (which they postulate is the relevant loss function) is a weighted average of domestic price inflation *and* import price inflation. Using a quadratic approximation of the average utility, Benigno (2003) shows that a weighted mean of the two regional inflation rates in an optimal currency area is the appropriate objective for monetary policy, given nominal rigidities in both regions. Further, Corsetti and Pesenti (2005) argue that the policy objective can be written in different, and equivalent, forms, one of which is the stabilization of CPI inflation. Corsetti and Pesenti use deviations from the utility under flexible prices as the relevant welfare criterion. They do, however, not derive this measure from a microfounded second-order approximation of the agents' welfare.

Table 1: Parameterization

| Social preferences | Benchmark policy rule | Supply relation | Demand relation | Asset equations | Foreign economy | Shock persist-ence | Shock variance |
|---|---|---|---|---|---|---|---|
| $\beta = 0.99$ | $b_\pi = 1.5$ | $\kappa_M = 0.3$ | $\alpha_q = 1.26$ | $\Phi = 0.001$ | $\rho_y^* = 0.8$ | $\tau_\pi = 0.8$ | $\sigma_\pi^2 = 0.4$ |
| $\lambda^S = 0.5$ | $b_y = 0.5$ | $\beta = 0.99$ | $\alpha_i = 0.35$ | $\omega_a = 1.01$ | $\rho_\pi^* = 0.8$ | $\tau_y = 0.8$ | $\sigma_y^2 = 0.6$ |
| | $\rho = 0.8$ | $\beta_y = 0.056$ | $\alpha_e = 1.8$ | $\omega_q = 0.532$ | $\rho_i^* = 0.8$ | $\tau_\phi = 0.8$ | $\sigma_\phi^2 = 0.8$ |
| | | $\beta_q = 0.007$ | $\alpha_y = 0.27$ | $\omega_y^* = 0.273$ | $b_y^* = 0.5$ | | $\sigma_{\pi*}^2 = 0.05$ |
| | | $\beta_p = \{30, 0.6, 0.15, 0.03\}$ | | | $b_\pi^* = 1.5$ | | $\sigma_{y*}^2 = 0.1$ |
| | | | | | | | $\sigma_{i*}^2 = 0.01$ |

The parameter of main interest for this paper is $\beta_p$ which governs the level of adjustment costs, and thereby also the degree of exchange rate pass-through. This parameter is chosen in order to cover four different rates of exchange rate pass-through; a case with almost full pass-through (99%), and three intermediate cases of incomplete pass-through (66%, 33%, and 9%).[15] The rest of the parameter-setup is fairly standard, for example capturing rather moderate import and export shares (30% of aggregate consumption and aggregate demand, respectively), a markup of 20% arising from a substitution elasticity between domestic and imported goods equal to 6, an intertemporal substitution elasticity of 0.5, and rather persistent shocks where the AR(1)-component is 0.8. Further, the variances of the disturbance terms are loosely based on a structural vector auto-regression on Norwegian data (see Leitemo and Røisland (2002)). The benchmark monetary policy rule takes on the standard reaction coefficients of 1.5 and 0.5 on inflation and output, respectively, as well as imposing some interest rate persistence; $\rho = 0.8$.

## 3. Results

### *3.1. Non-optimized rule coefficients*

The analysis starts off with studying interest rate rules that use domestic inflation ($\pi_t^D$) as a reaction variable. Figure 1 illustrates the (normalized) social loss from implementing monetary policy through the three exchange rate augmented policy rules, varying the exchange rate coefficients. The reactions on inflation, output and the lagged interest rate are the ones

[14] See Appendix A for an exact mapping between the parameters shown in Table 1 and the deep parameters.
[15] For empirical basis of incomplete exchange rate pass-through in small open economies, see, e.g., Adolfson (1997), Menon (1996), and Naug and Nymoen (1996). Menon's survey reports that empirical estimates of exchange rate pass-through typically lies in the range of 20-80%. Adolfson finds 33% exchange rate pass-through within a month to aggregate Swedish import prices, while Naug and Nymoen obtain about 20% pass-through per quarter for data on aggregate Norwegian imports.

suggested by Taylor (1993) and Clarida et al. (2000), while the response coefficient on the respective exchange rate term is allowed to vary between -1 and 1. Inclusion of a positive exchange rate reaction through any of the three rules seems to reduce social loss. Moreover, the optimal degree of exchange rate response appears to depend on the degree of pass-through (cf. Figures 1a and 1d).

[Figure 1 about here]

This is further shown in Table 2, which displays the optimized exchange rate responses and the resulting social loss. The exchange rate reaction, as well as the welfare enhancement, is increasing in the degree of pass-through.[16] Thus, when pass-through is high, the exchange rate plays a more important role in predicting inflationary impulses and, consequently, the welfare enhancement of including an exchange rate term is larger. Incorporation of either the nominal exchange rate change, the terms of trade, or deviations from PPP yield welfare improvements of 0-6% depending on the degree of pass-through. To give an idea about the magnitude of this enhancement, it is in welfare terms equivalent to a permanent decrease in inflation of 0-0.1%.[17] Moreover, the rules incorporating a real exchange rate term seem to perform somewhat better in terms of social welfare than the rule including the nominal exchange rate change. The largest welfare gain occurs when the policy maker responds to deviations from PPP. One reason for this is that the PPP term better captures the distortions that arise due to the price stickiness in the model, namely departures from the law of one price. Low pass-through implies that foreign disturbances have smaller effects, but on the other hand this low pass-through is here induced by larger nominal import price rigidity. Consequently, the low impact of exchange rate fluctuations is accompanied by large deviations from the flexible price outcome; deviations that the policy maker wants to alleviate.

[16] Note that the benchmark policy shows that the social loss level is increasing in the degree of pass-through. The reason is that low pass-through implies less exposure to foreign disturbances, which in turn implies that output volatility becomes lower. This, together with lower inflation variability (due to more sticky import prices) reduces social loss. However, comparing the absolute loss level across different pass-through cases may be of limited interest since these cases represent different structural economies.

[17] To see this, note that the welfare equivalence in terms of a permanent drop in inflation can be calculated from the social loss function in equation (9). The difference in social loss between the Taylor rule ($L^S_{high}$) and the exchange rate augmented rule ($L^S_{low}$) corresponds to a permanent change in inflation ($\hat{\pi}$) according to the following;

$$\hat{\pi} = \sqrt{(1-\beta)(L^S_{high} - L^S_{low})} .$$

Table 2: Social loss ($L^S$) and optimized exchange rate reaction coefficients ($\hat{b}_{\Delta s}$, $\hat{b}_{(pm-pd)}$, $\hat{b}_{(p^{*}+s-p)}$), using Taylor rule coefficients

| Pass-through | $\pi_t^{CB} = \pi_t^D$, $b_\pi = 1.5$, $b_y = 0.5$, $\rho = 0.8$ | | | | | | |
|---|---|---|---|---|---|---|---|
| | equation (8a) | equation (8b) | | equation (8c) | | equation (8d) | |
| | $L^S$ | $\hat{b}_{\Delta e}$ | Rel. $L^S$ | $\hat{b}_{(pm-pd)}$ | Rel. $L^S$ | $\hat{b}_{(p^{*}+e-p)}$ | Rel. $L^S$ |
| 0.99 | 41.255 | 0.16 | 0.990 | 0.60 | 0.955 | 0.88 | 0.954 |
| 0.66 | 39.069 | 0.08 | 0.997 | 0.44 | 0.971 | 1.01 | 0.943 |
| 0.33 | 37.445 | 0.01 | 1.0 | 0.30 | 0.980 | 1.07 | 0.940 |
| 0.09 | 35.264 | -0.04 | 0.999 | 0.14 | 0.987 | 0.44 | 0.972 |

Note: The optimized exchange rate responses are established using constrained optimization.

### *3.2. Optimized rule coefficients*

The standard Taylor rule coefficients ($b_\pi = 1.5$, $b_y = 0.5$, and $\rho = 0.8$) need not be optimal for the specific model used here, in particular as they are derived from the monetary policy observed in a closed economy (see Taylor (1993)). If the policy rule is excessively simple, or sub-optimal, inclusion of any additional state variable is likely to yield an improvement of the rule. The welfare enhancement recorded in Table 2 could consequently originate from the fact that the exchange rate augmented policy rules simply respond to more variables than a rule without the exchange rate. However, optimization of the coefficients on inflation, output, and the lagged interest rate reduces the sub-optimality of the simple rule, which partly mitigates such a problem. Therefore all the policy coefficients are next optimized.

Table 3a displays the optimized rule coefficients on domestic inflation, output, and the lagged interest rate for the policy rule without the exchange rate (i.e., equation (8a)). Note that the optimized interest rate persistence is very high ($\rho = 0.9$), for all pass-through cases, which is also consistent with the monetary policy conduct actually observed (see Clarida et al. (1998)). Moreover, given a forward-looking model, Woodford (1999) shows that the fully optimal reaction function is inertial. This implies that even if there is no explicit interest rate smoothing in the social loss function, the optimal amount of policy persistence $\rho$ will be large.

Further, note that the response coefficients for the optimized rule do not at all resemble the policy rule suggested by Taylor (1993). Relative to Taylor's rule, the optimized responses to both inflation and output are much larger and the ratio between them is smaller, irrespective of the degree of pass-through (see Table 3a). However, that the optimized policy rule induces a more vigorous policy than what is typically found empirically is not specific to the setting used here, but appears to be a common result in many models (see, e.g., Batini et al. (2001), Rudebusch (2001), and Rudebusch and Svensson (1999)).[18] Note also that the inflation response appears to be slightly larger in the full pass-through case ($\hat{b}_\pi$ = 5.6), compared to the case with very low pass-through ($\hat{b}_\pi$ = 4.8). Since the exchange rate channel transmits shocks to a greater extent in the full pass-through case, this requires a more forceful policy reaction and induces a larger coefficient in the reaction rule. The differences are rather small, however, and moreover, dependent on which disturbances that hit the economy (see Figure 2 for impulse responses).

[Figure 2 about here]

Table 3a: Optimized reaction rule coefficients ($\hat{b}_\pi, \hat{b}_y, \hat{\rho}$)

| | $\pi_t^{CB} = \pi_t^D$, equation (8a) | | |
|---|---|---|---|
| Pass-through | $\hat{b}_\pi$ | $\hat{b}_y$ | $\hat{\rho}$ |
| 0.99 | 5.61 | 4.39 | 0.9 |
| 0.66 | 4.53 | 3.35 | 0.9 |
| 0.33 | 4.42 | 3.31 | 0.9 |
| 0.09 | 4.82 | 4.13 | 0.9 |

Table 3b: Social loss ($L^S$) and optimized exchange rate coefficients ($\hat{b}_{\Delta s}$, $\hat{b}_{(pm-pd)}$, $\hat{b}_{(p^*+s-p)}$), using optimized reaction rule coefficients

| | $\pi_t^{CB} = \pi_t^D$, $\hat{b}_\pi$, $\hat{b}_y$, $\hat{\rho}$ optimized (see Table 3a) | | | | | | |
|---|---|---|---|---|---|---|---|
| | equation (8a) | equation (8b) | | equation (8c) | | equation (8d) | |
| Pass-through | $L^S$ | $\hat{b}_{\Delta s}$ | Rel. $L^S$ | $\hat{b}_{(pm-pd)}$ | Rel. $L^S$ | $\hat{b}_{(p^*+s-p)}$ | Rel. $L^S$ |
| 0.99 | 35.478 | 0.31 | 0.999 | 1.57 | 0.993 | 2.27 | 0.993 |
| 0.66 | 34.766 | 0.28 | 0.999 | 0.91 | 0.996 | 2.05 | 0.991 |
| 0.33 | 33.814 | 0.17 | 0.999 | 0.50 | 0.998 | 2.45 | 0.987 |
| 0.09 | 31.245 | 0.05 | 1.0 | -0.33 | 0.998 | 2.73 | 0.966 |

Note: $b_\pi$, $b_y$, $\rho$ are optimized separately in order to reflect the marginal advantage of incorporating an exchange rate term.

[18] For empirical estimates of the Taylor rule, see, e.g., Clarida et al. (2000) for the US, and Gerlach and Schnabel (2000) for the EMU countries.

Can an exchange rate response further improve the optimized instrument rule's outcome in terms of social welfare? Table 3b shows the social loss resulting from the optimized rule when adding different degrees of exchange rate responses to it. The responses on domestic inflation, output, and the lagged interest rate are optimized separately, in order to scrutinize the marginal value of incorporating the exchange rate.[19] None of the augmented rules appears to significantly reduce the social loss, even if most of the optimized exchange rate reactions are different from zero. In contrast to the case with sub-optimal responses to inflation and output, augmenting the *optimized* policy rule with an exchange rate term does not seem to enhance social welfare. The welfare improvement of incorporating the nominal exchange rate change or one of the two real exchange rate terms is in most pass-through cases practically zero. The only case where a real exchange rate response enhances welfare by more than 2% (or, equivalently, decreases inflation by more than 0.07%, see Footnote 17) is when pass-through (PT) is very low (PT = 0.09). Further, note that the optimized reactions on the nominal exchange rate change and the terms of trade are increasing in the degree of pass-through, as expected. However, the response to deviations from PPP does not appear to increase monotonically with larger pass-through. Note, though, that these PPP deviations are larger when pass-through is low, which is the distortion that the policy maker wants to mitigate.

The exchange rate channel of transmitting monetary policy can perhaps explain the negative reaction coefficients that turn up in some cases. It follows from equation (3) that a positive domestic-foreign interest rate differential implies an expected future depreciation, which, in turn, induces an inflationary impulse that raises the interest rate even further. A negative policy response to the exchange rate mitigates the interest rate adjustment when the exchange rate depreciates. All policy effects are thus internalized, which eases this goal conflict. Note also that the volatility in the endogenously determined exchange rate is decreasing in the degree of pass-through.[20] Low pass-through consequently induces larger exchange rate variability, which causes a more negative policy reaction to the exchange rate. However, the overall interest rate response to a depreciation is still positive, since the policy reaction to inflation raises the interest rate.

[19] Another way of measuring the additive value of the exchange rate is to simultaneously optimize all reaction coefficients and then measure the welfare loss when excluding the exchange rate. Leaving out the exchange rate in that case does, however, present a different, and sub-optimal, relation between the inflation and output reactions why the marginal loss of excluding the exchange rate is more difficult to assess. However, for a comparison of the different reaction coefficients in the two approaches, see Section 4.3. where the overall optimization is reported.

[20] In this model, lower pass-through is induced by larger structural import price stickiness, why the required relative price adjustment is accomplished through larger exchange rate fluctuations (see Table A1 in the Appendix for unconditional variances).

Altogether, the results thus indicate that social welfare might possibly be improved by adding an exchange rate term to the *non-optimized* policy rule, but not to the *optimized* policy rule. These contrasting findings are simply explained from the optimized responses to, for example, inflation and output. The optimized responses to inflation and output are larger than the ones suggested by Taylor (1993), which implies a more aggressive interest rate adjustment. Inclusion of an exchange rate term (i.e., a positive exchange rate reaction) precisely implies a larger interest rate response to inflationary impulses reflected in the exchange rate. This more forceful interest rate adjustment does, in turn, result in an implicit development towards the optimized policy rule *without* the exchange rate.

*3.3. Responding to Consumer Price Index (CPI) inflation*

When the policy maker uses a rule based on domestic inflation ($\pi^D$), most of the direct exchange rate impact is excluded from the interest rate adjustment.[21] This might explain part of the explicit role for the exchange rate in the policy rule with non-optimized Taylor rule reaction coefficients. If, in contrast, the policy maker adjusts the interest rate to CPI inflation the instrument rule already contains an implicit response to the exchange rate, which is realized through the reaction to CPI inflation. This might imply that the exchange rate augmented rules are only marginally welfare improving. In a similar way, Taylor (2001) suggests that the CPI inflation-interest rate rule includes a sufficient exchange rate response. Hence, if the exchange rate does play an explicit role in the policy rule, its emphasis ought to be higher when responding to domestic inflation compared to reacting to CPI inflation. To test this hypothesis, the exchange rate augmented rules are analyzed using CPI inflation as a reaction variable.

Table 4 presents the social loss and the optimized response coefficients when the policy rule consists of CPI inflation, output, the interest rate, and the various exchange rate terms. Comparing the social loss under the domestic inflation rules and the CPI inflation rules indicates that implementing monetary policy through a rule based on CPI inflation yields a better outcome in terms of social welfare, both when using the standard Taylor rule coefficients and when using an optimized policy rule (see Tables 4a and 4b). Furthermore, the results in Tables 2, 3b and 4 show that inclusion of any exchange rate term is *relatively* more welfare enhancing under a domestic inflation rule than under a CPI inflation rule, although the differences are very small. This reflects the fact that some of the exchange rate reaction, in fact,

[21] Note, however, that the exchange rate still indirectly affects domestic inflation in this model, through imported inputs and expenditure switching effects via aggregate demand.

is inherent in the CPI inflation response, as discussed above. Recall, though, that there is no strong indication that a *direct* exchange rate response should be added to the optimized policy rule even if it is based on domestic inflation.

Table 4a: Relative social loss and optimized exchange rate reaction coefficients, using Taylor rule coefficients and policy rules based on CPI inflation ($\pi_t$)

| Pass-through | $\pi_t^{CB} = \pi_t$ , $b_\pi = 1.5$, $b_y = 0.5$, $\rho = 0.8$ | | | | | | |
|---|---|---|---|---|---|---|---|
| | equation (8a) | equation (8b) | | equation (8c) | | equation (8d) | |
| | $L_c^S / L^S$ | $\hat{b}_{\Delta s}$ | Rel. $L_c^S$ | $\hat{b}_{(pm-pd)}$ | Rel. $L_c^S$ | $\hat{b}_{(p^*+s-p)}$ | Rel. $L_c^S$ |
| 0.99 | 0.980 | 0.16 | 0.976 | 0.55 | 0.948 | 0.81 | 0.947 |
| 0.66 | 0.988 | 0.09 | 0.973 | 0.41 | 0.952 | 0.96 | 0.927 |
| 0.33 | 0.993 | 0.04 | 0.968 | 0.27 | 0.953 | 1.04 | 0.915 |
| 0.09 | 0.993 | 0.01 | 0.962 | 0.12 | 0.953 | 0.44 | 0.933 |

Table 4b: Relative social loss and optimized reaction rule coefficients, policy rule based on CPI inflation ($\pi_t$)

| Pass-through | equation (8a) | | | | equation (8b) | | equation (8c) | | equation (8d) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $\hat{b}_\pi$ | $\hat{b}_y$ | $\hat{\rho}$ | $L_c^S / L^S$ | $\hat{b}_{\Delta s}$ | Rel. $L_c^S$ | $\hat{b}_{(pm-pd)}$ | Rel. $L_c^S$ | $\hat{b}_{(p^*+s-p)}$ | Rel. $L_c^S$ |
| 0.99 | 5.53 | 4.15 | 0.9 | 0.989 | 0.18 | 1.0 | 1.31 | 0.995 | 1.90 | 0.995 |
| 0.66 | 4.92 | 3.59 | 0.9 | 0.991 | 0.16 | 1.0 | 0.91 | 0.996 | 1.89 | 0.993 |
| 0.33 | 4.71 | 3.48 | 0.9 | 0.992 | 0.12 | 1.0 | 0.52 | 0.998 | 2.26 | 0.990 |
| 0.09 | 5.68 | 4.79 | 0.9 | 0.982 | -0.09 | 1.0 | -0.29 | 0.999 | 2.76 | 0.973 |

Note: $L_c^S / L^S$ denotes the relative loss from following policy rule (8a) based on CPI inflation compared to basing it on domestic inflation. Rel. $L_c^S$ represents the relative loss between the respective exchange rate augmented rule and equation (8a) based on CPI inflation (i.e., the loss reduction from exchange rate stabilization under CPI inflation targeting). $b_\pi$ , $b_y$ , $\rho$ are optimized separately.

## 4. Robustness issues

### *4.1. Social preferences*

As seen above, the welfare gain of incorporating the exchange rate in the open economy-policy rule is related to which inflation measure the interest rate adjustment is based on. This in turn might, however, be dependent on the society's particular objective function. Given that the loss function used here is not derived from a quadratic approximation of the welfare in this specific dynamic open economy model, the results' sensitivity to the chosen loss function should be tested.

The appropriate structure and arguments of the social objective function in an open economy depends on the model assumptions made. For instance, Galí and Monacelli (2004) argue, from a second order Taylor approximation of the consumer's utility, that the welfare function in an open economy is characterized with *domestic* inflation stabilization. However, they assume full exchange rate pass-through and certain preferences in their model. On the other hand, in a model with incomplete pass-through and predetermined prices, Sutherland (2005) derives the welfare function in terms of the variances of *both* domestic and foreign prices, as well as the exchange rate.[22] Depending on model choice, there are thus cases in which CPI inflation stabilization or domestic inflation stabilization is more or less suitable. Since the degree of exchange rate pass-through can be varied in the model used here, the alternative exchange rate augmented policy rules are also evaluated using a social loss function that together with output only includes stabilization of domestic inflation and not imported inflation, that is $L_t^D = \text{var}(\pi_t^D) + \lambda^S \text{var}(y_t)$.

The results presented above are however robust to evaluating the rules against this loss function, also in the cases with incomplete exchange rate pass-through.[23] This is shown in Tables 5a and 5b, which display the social loss ($L_t^D$), and the optimized policy reactions, from policy rules based on either domestic inflation or CPI inflation. Note in particular that the implicit exchange rate reaction achieved through targeting CPI inflation is beneficial for the outcome, even if society values domestic inflation stabilization (see column 5 in Table 5b). The reason is that exchange rate volatility is lower under a policy rule based on CPI inflation (cf. Tables A1b-A1c in the Appendix). This, in turn, is helpful also for stabilizing domestic inflation, since domestic inflation is affected by exchange rate fluctuations through imported intermediate inputs. The

[22] The intuition behind this is that in a model with nominal rigidities, where deviations between sticky and flexible prices occur, unnecessary variation in the relative price of goods (which, in turn, generates inflationary impulses) can be avoided by keeping the *general* price level stabilized (see Woodford (2002) for closed economy derivation of the welfare function). The effects of the nominal rigidities, i.e. the relative price distortions, can thereby be neutralized. Under the assumption of full pass-through, such that import prices are fully flexible, this relative price distortion can be alleviated by stabilizing domestic inflation only, to which the price stickiness pertains. On the other hand, in an open economy with incomplete exchange rate pass-through, distortions apply to both foreign and domestic producers, given that these models in general contain sticky import prices (to induce low pass-through) *as well as* sticky domestic prices. Consequently, in order to alleviate all distortions *both* inflation rates, that are subject to some price stickiness, must be stabilized.

[23] Note, moreover, that the results are not (qualitatively) affected by whether an interest rate smoothing-objective is included in either of the two social loss functions.

lower exchange rate volatility improves the variance trade-off between domestic inflation and output, which thus is more favourable than if the policy maker would respond to domestic inflation (see Figure 3). Consequently, interest rate rules based on CPI inflation are welfare enhancing relative to the rules reacting to domestic inflation.

[Figure 3 about here]

Table 5a: Social loss ( $L^D = \text{var}(\pi^D) + \lambda^S \text{var}(y)$ ), and optimized reaction rule coefficients, policy reaction to domestic inflation ( $\pi_t^D$ )

| Pass-Throug | equation (8a) | | | | equation (8b) | | equation (8c) | | equation (8d) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $\hat{b}_\pi$ | $\hat{b}_y$ | $\hat{\rho}$ | $L^D$ | $\hat{b}_{\Delta s}$ | Rel. $L^D$ | $\hat{b}_{(pm-pd)}$ | Rel. $L^D$ | $\hat{b}_{(p^*+s-p)}$ | Rel. $L^D$ |
| 0.99 | 5.18 | 4.05 | 0.9 | 35.830 | 0.27 | 0.999 | 1.27 | 0.995 | 1.84 | 0.995 |
| 0.66 | 4.63 | 3.44 | 0.9 | 35.423 | 0.21 | 0.999 | 0.86 | 0.997 | 1.88 | 0.993 |
| 0.33 | 4.38 | 3.42 | 0.9 | 34.968 | 0.17 | 0.999 | 0.45 | 0.999 | 2.25 | 0.989 |
| 0.09 | 4.86 | 4.56 | 0.9 | 33.562 | 0.05 | 1.0 | -0.33 | 0.998 | 2.64 | 0.969 |

Table 5b: Social loss ( $L^D = \text{var}(\pi^D) + \lambda^S \text{var}(y)$ ), and optimized reaction rule coefficients, policy reaction to CPI inflation ( $\pi_t$ )

| Pass-Throug | equation (8a) | | | | equation (8b) | | equation (8c) | | equation (8d) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $\hat{b}_\pi$ | $\hat{b}_y$ | $\hat{\rho}$ | $L_c^D / L^D$ | $\hat{b}_{\Delta s}$ | Rel. $L_c^D$ | $\hat{b}_{(pm-pd)}$ | Rel. $L_c^D$ | $\hat{b}_{(p^*+s-p)}$ | Rel. $L_c^D$ |
| 0.99 | 5.10 | 3.82 | 0.9 | 0.990 | 0.16 | 1.0 | 1.05 | 0.996 | 1.52 | 0.996 |
| 0.66 | 4.71 | 3.44 | 0.9 | 0.992 | 0.15 | 1.0 | 0.77 | 0.997 | 1.63 | 0.995 |
| 0.33 | 4.67 | 3.42 | 0.9 | 0.992 | 0.12 | 1.0 | 0.46 | 0.999 | 2.05 | 0.992 |
| 0.09 | 5.74 | 4.56 | 0.9 | 0.983 | -0.08 | 1.0 | -0.30 | 0.999 | 2.67 | 0.977 |

Note: $L_c^D / L^D$ denotes the relative loss from following policy rule (8a) based on CPI inflation compared to basing it on domestic inflation. Rel. $L_c^D$ represents the relative loss between the respective exchange rate augmented rule and equation (8a) based on CPI inflation (i.e., the loss reduction from exchange rate stabilization under CPI inflation targeting). $b_\pi$ , $b_y$ , $\rho$ are optimized separately.

*4.2. Parameterization*

As mentioned in the Introduction, Cecchetti et al. (2000) show that financial disturbances may cause the exchange rate to have destablilizing effects that should be mitigated by monetary policy. Do the size and persistence of fluctuations in the exchange rate affect the exchange rate's role in policy? If the persistence in the risk premium shock increases, it induces larger and more prolonged exchange rate movements, which thus have a larger effect on the economy. Consequently, there are reasons for a more aggressive and long-lasting policy reaction. As shown in Table 6, social loss is reduced somewhat when the central bank follows a rule that incorporates a real exchange rate response. However, neither in this case do the exchange rate augmented rules imply any greater welfare improvements compared to the fully optimized policy rule. Note moreover that the larger reactions on inflation and output compensate for the lack of an explicit exchange rate term, so that the resulting policy rule is in any case more vigorous.

Table 6: Social loss ( $L_c^S$ ) and optimized reaction rule coefficients, larger risk premium persistence

| Pass-through | equation (8a) | | | | equation (8b) | | equation (8c) | | equation (8d) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $\hat{b}_\pi$ | $\hat{b}_y$ | $\hat{\rho}$ | $L_c^S$ | $\hat{b}_{\Delta s}$ | Rel. $L_c^S$ | $\hat{b}_{(pm-pd)}$ | Rel. $L_c^S$ | $\hat{b}_{(p^*+s-p)}$ | Rel. $L_c^S$ |
| 0.99 | 6.37 | 5.19 | 0.9 | 36.16 | 0.58 | 0.997 | 1.14 | 0.985 | 1.63 | 0.985 |
| 0.66 | 5.55 | 4.37 | 0.9 | 35.37 | 0.42 | 0.998 | 0.94 | 0.985 | 1.44 | 0.982 |
| 0.33 | 5.12 | 4.03 | 0.9 | 34.36 | 0.32 | 0.999 | 0.78 | 0.988 | 1.36 | 0.979 |
| 0.09 | 5.40 | 4.77 | 0.9 | 31.63 | 0.14 | 1.0 | 0.19 | 0.999 | 1.65 | 0.963 |

Note: $\pi_t^{CB} = \pi_t$ . The risk premium persistence is $\tau_\phi$ = 0.95. $b_\pi$ , $b_y$ , $\rho$ are optimized separately.

The same applies if the relative variances of the foreign disturbances are larger (see Table 7). For example, increasing the relative importance of risk premium disturbances does not change the main results. In this case, the welfare improvement of adding an exchange rate term to the standard Taylor rule is somewhat larger, but the exchange rate augmented rules do not seem to greatly outperform the optimized CPI rule. It is only in the case with very low pass-through (PT = 0.09) that a real exchange rate response appears to enhance social welfare to any larger extent. The welfare gain of 7% relative to the rule without the exchange rate in this case is though comparable to a permanent decrease in inflation of a mere 0.1% (see also Footnote 17).

Table 7: Social loss ( $L_c^S$ ) and optimized reaction coefficients, larger risk premium variance

| Pass-through | equation (8a) | | | | equation (8b) | | equation (8c) | | equation (8d) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $\hat{b}_\pi$ | $\hat{b}_y$ | $\hat{\rho}$ | $L_c^S$ | $\hat{b}_{\Delta s}$ | Rel. $L_c^S$ | $\hat{b}_{(pm-pd)}$ | Rel. $L_c^S$ | $\hat{b}_{(p^*+s-p)}$ | Rel. $L_c^S$ |
| 0.99 | 9.67 | 9.40 | 0.9 | 37.149 | 1.22 | 0.996 | 3.68 | 0.987 | 5.30 | 0.987 |
| 0.66 | 8.23 | 7.81 | 0.9 | 36.435 | 0.91 | 0.997 | 2.62 | 0.991 | 5.03 | 0.982 |
| 0.33 | 7.47 | 7.10 | 0.9 | 35.40 | 0.69 | 0.998 | 1.24 | 0.997 | 5.58 | 0.971 |
| 0.09 | 7.70 | 8.09 | 0.9 | 32.37 | 0.31 | 0.999 | -1.13 | 0.994 | 6.10 | 0.934 |

Note: $\pi_t^{CB} = \pi_t$ . The risk premium variance is five times larger than in the basecase parameterization; $\sigma_\phi^2$ = 4.0. $b_\pi$ , $b_y$ , $\rho$ are optimized separately.

Consequently, the results do not seem to be sensitive to the particular parameterization chosen here. Note, moreover, that the results are not contingent upon the fully forward-looking model specification. The results are qualitatively robust to using a model with some backward-looking components in the demand and supply relations.[24]

*4.3. Overall optimization*

So far the paper has dealt with the marginal advantage of incorporating an exchange rate term in the policy rule. In order to compare these findings, where the exchange rate reaction was chosen separately, all coefficients in the different policy rules are optimized simultaneously in the following. Since the policy responses to, for example, inflation and output in this case endogenize the effects of the central bank's exchange rate reaction, it naturally tilts the results somewhat more in favour of the exchange rate augmented rules compared to the separate optimization. However, the welfare gains of adding an exchange rate response in the policy rule are rather small even in the case when all coefficients are chosen optimally.

When responding to domestic inflation in the policy rule, it follows from Table 8a that the welfare gain is less than 2% in the cases with large and moderate degrees of pass-through, compared to the optimized rule without the exchange rate (see Table 3). This implies an equivalent drop in inflation by less than 0.09%. There are no major differences in reacting to the nominal exchange rate, or responding to the terms of trade or the deviations from PPP in terms of welfare gains. Note moreover that when optimizing all coefficients in the rule, the nominal exchange rate reaction comes out a lot stronger compared to when the exchange rate response is chosen separately. The reason for this is that the inflation reaction also changes and is weaker than in the optimized rule without the exchange rate. The responses to inflation and the nominal exchange rate change, consequently, appear to have common elements.

A similar pattern appears when using CPI inflation in the policy rule. There are no large differences between the different policy rules regarding their usefulness in minimizing social loss, and the welfare gains are very small, see Table 8b. The welfare gains are slightly lower, of around 1%, compared to the rule with domestic inflation, since the CPI inflation rule already incorporates an implicit response to the exchange rate through the imported component in the CPI inflation measure.

[24] Results from this model are available upon request.

Table 8a: Social loss ($L^S$) and optimized coefficients ($\hat{b}_\pi, \hat{b}_y$ , $\hat{\rho}$ , $\hat{b}_{\Delta s}$, $\hat{b}_{(pm-pd)}$, $\hat{b}_{(p*+s-p)}$), policy rules based on domestic inflation ($\pi_t^D$)

| PT | equation (8b) | | | | | equation (8c) | | | | | equation (8d) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $\hat{b}_\pi$ | $\hat{b}_y$ | $\hat{\rho}$ | $\hat{b}_{\Delta s}$ | $L_c^S$ | $\hat{b}_\pi$ | $\hat{b}_y$ | $\hat{\rho}$ | $\hat{b}_{(pm-pd)}$ | $L_c^S$ | $\hat{b}_\pi$ | $\hat{b}_y$ | $\hat{\rho}$ | $\hat{b}_{(p*+s-p)}$ | $L_c^S$ |
| 0.99 | 1.01 | 3.93 | 0.9 | 4.51 | 34.59 | 5.57 | 3.82 | 0.9 | 1.95 | 35.16 | 5.55 | 3.81 | 0.9 | 2.79 | 35.15 |
| 0.66 | 1.01 | 3.24 | 0.9 | 3.69 | 33.99 | 4.96 | 3.29 | 0.9 | 1.47 | 34.53 | 4.59 | 3.10 | 0.9 | 2.26 | 34.40 |
| 0.33 | 1.01 | 2.84 | 0.9 | 3.11 | 33.23 | 4.63 | 3.05 | 0.9 | 1.03 | 33.69 | 3.97 | 2.91 | 0.9 | 2.30 | 33.35 |
| 0.09 | 2.97 | 3.61 | 0.9 | 1.41 | 31.21 | 4.85 | 5.46 | 0.9 | -1.3 | 31.06 | 1.81 | 4.79 | 0.8 | 5.53 | 28.57 |

Table 8b: Social loss ($L^S$) and optimized coefficients ($\hat{b}_\pi, \hat{b}_y$ , $\hat{\rho}$ , $\hat{b}_{\Delta s}$, $\hat{b}_{(pm-pd)}$, $\hat{b}_{(p*+s-p)}$), policy rules based on CPI inflation ($\pi_t$ )

| PT | equation (8b) | | | | | equation (8c) | | | | | equation (8d) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $\hat{b}_\pi$ | $\hat{b}_y$ | $\hat{\rho}$ | $\hat{b}_{\Delta s}$ | $L_c^S$ | $\hat{b}_\pi$ | $\hat{b}_y$ | $\hat{\rho}$ | $\hat{b}_{(pm-pd)}$ | $L_c^S$ | $\hat{b}_\pi$ | $\hat{b}_y$ | $\hat{\rho}$ | $\hat{b}_{(p*+s-p)}$ | $L_c^S$ |
| 0.99 | 1.01 | 3.85 | 0.9 | 4.44 | 34.54 | 5.49 | 3.70 | 0.9 | 1.62 | 34.85 | 5.48 | 3.69 | 0.9 | 2.32 | 34.84 |
| 0.66 | 1.01 | 3.21 | 0.9 | 3.67 | 33.95 | 5.04 | 3.31 | 0.9 | 1.32 | 34.28 | 4.70 | 3.15 | 0.9 | 2.00 | 34.20 |
| 0.33 | 1.01 | 2.84 | 0.9 | 3.13 | 33.18 | 4.95 | 3.24 | 0.9 | 1.04 | 33.43 | 4.26 | 3.10 | 0.9 | 2.16 | 33.19 |
| 0.09 | 4.95 | 2.78 | 0.8 | -1.4 | 30.58 | 5.66 | 5.90 | 0.9 | -1.1 | 30.57 | 1.31 | 2.02 | 0.5 | 2.22 | 28.42 |

## 5. Conclusions

This paper analyzes the performance of various open-economy policy rules within a forward-looking aggregate supply-aggregate demand model, adjusted for incomplete exchange rate pass-through. The results show that policy rules with direct exchange rate reactions only yield marginal improvements relative to an optimized Taylor rule. Neither nominal, nor real, exchange rate responses enhance stabilization of the economy. Given optimized policy reactions to inflation and output, there do not seem to be any sizeable welfare improvements from using exchange rate augmented rules, irrespective of the degree of pass-through.

However, an indirect, or implicit, exchange rate response is welfare improving. A policy rule responding to CPI inflation does better in social welfare terms than a rule based on domestic inflation, in all pass-through cases. The inherent exchange rate reaction included in the CPI inflation response appears to be one of the reasons why a direct exchange rate response is redundant. This result is not contingent upon social preferences for either CPI inflation stabilization or domestic inflation stabilization. Consequently, in this model, it is better for the policy maker to base her policy rule on CPI inflation, since this induces lower exchange rate volatility, which, in turn, also reduces domestic inflation variability.

The only case where social welfare improves from inclusion of a *direct* exchange rate reaction is when a real exchange rate response is added to the *non-optimized* Taylor rule with standard reaction coefficients on inflation, output, and the lagged interest rate (i.e., 1.5, 0.5, and 0.8, respectively). Adding a real exchange rate response to this Taylor rule makes the interest rate adjustment somewhat more aggressive. This reduces the sub-optimality of the resulting overall policy reaction, which thus enhances welfare. The exchange rate reaction, as well as the welfare gain, is increasing in the degree of pass-through.

Consequently, an exchange rate response can be a substitute for optimizing the Taylor rule coefficients, but once these other policy responses have been optimized there are no additional welfare gains from inclusion of an exchange rate term in the policy rule.

## Appendix

### A.1. Households

The representative consumer maximizes the intertemporal utility function:

$$\max_{\{C_{t+s},B_{t+s},B^*_{t+s}\}_{s=0}^{\infty}} \quad \mathrm{E}_{\mathrm{t}} \sum_{s=0}^{\infty} \beta^s \Psi_{t+s} \frac{(C_{t+s})^{1-\frac{1}{\sigma}} - 1}{1-\frac{1}{\sigma}}$$

$$\text{s.t} \qquad P_t C_t + \frac{1}{1+I_t} B_t + \frac{1}{(1+I_t^*)\mathrm{e}^{-\phi A_t + \varepsilon_t^{\phi}}} B_t^* S_t = \Pi_t + B_{t-1} + B_{t-1}^* S_t \ , \tag{A1}$$

where $\mathrm{E_t}$ denotes rational expectations as of period $t$, $\beta$ is a discount factor, $\Psi$ a preference shock, $C_t$ the aggregate consumption index (defined below), $P_t$ the corresponding aggregate price index, $\sigma$ the constant intertemporal elasticity of substitution, $B_t$ (end of period $t$) bond holdings denominated in domestic currency units, and $I_t$ the nominal domestic interest rate. $B_t^*$ represents (the domestic consumers') foreign currency bond holdings, which are sold at a risk-adjusted price, $1/[(1+ I_t^*)\mathrm{e}^{-\phi A_t + \varepsilon_t^{\phi}}]$, where $I_t^*$ is the nominal foreign interest rate. Following Benigno (2001), $\mathrm{e}^{-\phi A_t + \varepsilon_t^{\phi}}$ is a premium on foreign bond holdings which depends on the aggregate net foreign asset position of domestic economy $A_t$ , and where $\varepsilon_t^{\phi}$ is a time-varying shock to the risk premium (for example interpreted as a change in the investors' preferences). The risk premium function will reflect temporary deviations from uncovered interest rate parity. Making the risk premium dependent on the aggregate net foreign asset position will also ensure that the steady state is well defined and that the net foreign assets follow a stationary process. $S_t$ is the nominal exchange rate, and $\Pi_t$ are profits from imperfectly competitive production.

The aggregate consumption index ( $C_t$ ) is composed of consumption of domestic and imported goods ( $C_t^D$ and $C_t^M$ , respectively) according to a constant elastic substitution (CES) function:

$$C_t = \left[ (1-\kappa_M)^{\frac{1}{\eta}} (C_t^D)^{\frac{\eta-1}{\eta}} + (\kappa_M)^{\frac{1}{\eta}} (C_t^M)^{\frac{\eta-1}{\eta}} \right]^{\frac{\eta}{\eta-1}}, \tag{A2}$$

where $\kappa_M$ is the share of imports in domestic consumption, and $\eta > 1$ the elasticity of substitution between domestic and foreign goods (and the price elasticity of demand). The optimal allocation of a given expenditure implies that the (domestic) demand for domestic and imported goods, respectively follows

$$C_t^D = (1-\kappa_M)\left(\frac{P_t^D}{P_t}\right)^{-\eta} C_t, \tag{A3a}$$

$$C_t^M = \kappa_M \left(\frac{P_t^M}{P_t}\right)^{-\eta} C_t, \tag{A3b}$$

where $P_t = \left[(1-\kappa_M)(P_t^D)^{1-\eta} + \kappa_M (P_t^M)^{1-\eta}\right]^{\frac{1}{1-\eta}}$ is the aggregate (CPI) price index corresponding to equation (A2), and $P_t^D$ and $P_t^M$ the prices of domestic and imported products, respectively.

The first order conditions of the consumer's intertemporal utility maximization in equation (A1) with respect to consumption and bond holdings yield a (log-linearized) Euler equation and a (log-linearized) interest parity condition of the form:

$$c_t = \mathrm{E}_t c_{t+1} - \sigma(i_t - \mathrm{E}_t \pi_{t+1}) - \sigma \mathrm{E}_t \Delta\psi_{t+1}, \tag{A4}$$

$$i_t - i_t^* = \mathrm{E}_t e_{t+1} - s_t - \phi a_t + \varepsilon_t^\phi. \tag{A5}$$

Inserting the log-linearized version of equation (A3a) into (A4) implies

$$c_t^D = \mathrm{E}_t c_{t+1}^D - \eta\kappa_M (\mathrm{E}_t \pi_{t+1}^M - \mathrm{E}_t \pi_{t+1}^D) - \sigma(i_t - \mathrm{E}_t \pi_{t+1}) - \sigma \mathrm{E}_t \Delta\psi_{t+1}. \tag{A6}$$

The domestic economy is small in the sense that the domestic export goods play a negligible part in the aggregate foreign consumption. Assuming a Dixit-Stiglitz CES aggregator over foreign consumption, implies that the foreign demand for domestic goods follows:

$$c_t^{D*} = -\eta(p_t^D - s_t - \hat{p}_t^*) + a_y^* y_t^*, \tag{A7}$$

where $a_y^*$ denotes the income elasticity of foreign consumption, $y_t^*$ foreign output, and where the law of one price, by assumption, holds for domestically produced goods. Inserting equations

(A6) and (A7) into the market clearing condition for aggregate demand for domestically produced goods, $y_t = (1-\kappa_D) c_t^D + \kappa_D c_t^{D*}$, yields after some manipulation the aggregate demand relation in the main text:

$$\begin{aligned} y_t &= \mathrm{E}_t y_{t+1} - \alpha_q \mathrm{E}_t(\pi_{t+1}^M - \pi_{t+1}^D) - \alpha_i (i_t - \mathrm{E}_t \pi_{t+1}) \\ &\quad + \alpha_e (\mathrm{E}_t \pi_{t+1}^D - (\mathrm{E}_t s_{t+1} - s_t) - \mathrm{E}_t \pi_{t+1}^*) - \alpha_y (\mathrm{E}_t y_{t+1}^* - y_t^*) + \varepsilon_t^y , \end{aligned} \tag{A8}$$

where $\alpha_q = \kappa_M \eta (1-\kappa_D)$, $\alpha_i = \sigma(1-\kappa_D)$, $\alpha_e = \kappa_D \eta$, $\alpha_y = \kappa_D a_y^*$, and $\varepsilon_t^y = (1-\kappa_D)\sigma(\psi_t - \mathrm{E}_t \psi_{t+1})$.

To clear the foreign bond market, the evolution of the net foreign assets must follow:

$$\frac{S_t B_t^*}{(1+I_t^*)\mathrm{e}^{-\phi A_t + \varepsilon_t^\phi}} = P_t^D C_t^{D*} - S_t P_t^* C_t^M + S_t B_{t-1}^* . \tag{A9}$$

Defining the net foreign asset position as $A_t = \dfrac{S_t B_t^*}{P_t}$ and log-linearizing (A9) implies

$$a_t = \omega_a a_{t-1} + \omega_q \left(p_t^M - p_t^D\right) + \omega_p \left(p_t^* + s_t - p_t^M\right) - \omega_y y_t + \omega_y^* y_t^* , \tag{A10}$$

where $\omega_a = 1/\beta$, $\omega_q = \left[\kappa_M c\left(2\eta - 1 + \eta\kappa_D/(1-\kappa_D)\right)\right]/\beta$,
$c = \left[\eta/\left((\eta-1)(1-\theta)(1-\kappa_W)^{(1-\kappa_w)}\kappa_w^{\kappa_w}\right)\right]^{(\theta-1)/\theta}$, $\omega_p = \left[\kappa_M c\left(\eta - 1 + \eta\kappa_D/(1-\kappa_D)\right)\right]/\beta$,
$\omega_y = \kappa_m c/\left(\beta(1-\kappa_D)\right)$, and $\omega_y^* = a_y^* \kappa_m c/\left(\beta(1-\kappa_D)\right)$.

### A.2. Firms

There are two categories of firms in this economy. The *domestic firms* produce differentiated goods using intermediate domestic and imported inputs. The *importing firms* buy a homogenous good in the world market and turn it into differentiated import goods, used in both consumption and production. Both categories of firms are subject to quadratic costs of adjusting their prices, following Rotemberg (1982).

The profit-maximization problem of firm $i \in (0,1)$ in sector $j \in \{D, M\}$ is given by

$$\max_{\hat{P}^j_{i,t}} \quad \sum_{s=0}^{\infty} \beta^s \upsilon_{t+s} \left[ P^j_{i,t+s} Y^j_{i,t+s} - MC^j_{i,t+s} Y^j_{i,t+s} - \frac{\tilde{\gamma}_j}{2} P^j_{t+s} \left( \frac{P^j_{i,t+s}}{\pi^j P^j_{i,t+s-1}} - 1 \right)^2 Y^j_t \right]$$

$$\text{s.t} \qquad Y^j_{i,t} \geq \left( \frac{P^j_{i,t}}{P^j_t} \right)^{-\eta} Y^j_t \,, \tag{A11}$$

where $\beta \upsilon_t$ is the stochastic discount factor, and where $\upsilon_t$ is the households' marginal utility of an additional (nominal) income unit. $P^j_{i,t}$ denotes the price of good *i* in sector *j*, and $\pi^j$ the steady state inflation. $\tilde{\gamma}_j$ is an exogenous parameter measuring the costs of changing the price in sector *j*, such that $\tilde{\gamma}_j$ equal to zero implies a fully flexible price environment. $Y^D_{i,t} = \left[ \left( Z^D_{i,t} \right)^{1-\kappa_W} \left( Z^M_{i,t} \right)^{\kappa_W} \right]^{1-\theta}$ is production of the domestic good, and $Z^D_{i,t}$, $Z^M_{i,t}$ the intermediate domestic and imported inputs. The supply must satisfy the demand from both the domestic market ($C^D_{i,t}$) and the foreign market ($C^{D*}_{i,t}$), i.e., $Y^D_{i,t} \geq \left( P^D_{i,t} / P^D_t \right)^{-\eta} \left( C^D_t + C^{D*}_t \right)$. The marginal cost for the domestic good follows

$$MC^D_{i,t} = \frac{1}{1-\theta} P^Z_t \left( Y^D_{i,t} \right)^{\frac{\theta}{1-\theta}} \,, \tag{A12a}$$

where $P^Z_t = \dfrac{(P^D_t)^{1-\kappa_W} (P^M_t)^{\kappa_W}}{(1-\kappa_W)^{1-\kappa_W} \kappa_W{}^{\kappa_W}}$. The imported good, in turn, is bought in the world market at price $P^{Z*}_t$ implying the following marginal cost

$$MC^M_t = S_t P^{Z*}_t \,. \tag{A12b}$$

Each importing firm faces the demand $Y^M_{i,t} \geq \left( P^M_{i,t} / P^M_t \right)^{-\eta} C^M_t$ .

The first order condition of equation (A11) is

$$\left(\frac{P_{i,t}^j}{P_t^j}\right)^{-\eta}\left[(1-\eta)+\eta MC_{i,t}^j\left(\frac{P_{i,t}^j}{P_t^j}\right)^{-1}\right]-\tilde{\gamma}_j P_t^j\left(\frac{P_{i,t}^j}{\pi^j P_{i,t-1}^j}-1\right)\frac{1}{\pi^j P_{i,t-1}^j}$$
$$+\beta\frac{\upsilon_{t+1}}{\upsilon_t}\tilde{\gamma}_j P_{t+1}^j\left(\frac{P_{i,t+1}^j}{\pi^j P_{i,t}^j}-1\right)\left(\frac{P_{i,t+1}^j}{\pi^j\left(P_{i,t}^j\right)^2}\right)\frac{C_{t+1}^j}{C_t^j}=0. \tag{A13}$$

Note that in a flexible price environment without adjustment costs ($\tilde{\gamma}_j=0$) this implies the following optimal prices for the domestic and imported goods, respectively (using equations (A12a) and (A12b) in (A13)):

$$P_{i,t}^D=\left(\frac{\eta}{\eta-1}\right)\frac{1}{1-\theta}P_{i,t}^Z\left(Y_{i,t}^D\right)^{\frac{\theta}{1-\theta}}, \tag{A14a}$$

$$P_{i,t}^M=\left(\frac{\eta}{\eta-1}\right)S_t P_t^{Z*}, \tag{A14b}$$

Assuming a symmetric equilibrium and log-linearzing equation (A13) yields

$$\pi_t^j=\beta\,\mathrm{E}_t\,\pi_{t+1}^j+\frac{(\eta-1)}{\tilde{\gamma}_j}mc_t^j, \tag{A15}$$

where $\pi_t^j=p_t^j-p_{t-1}^j$ denotes (the domestic currency) inflation in sector *j*. Inserting the log-linearized marginal costs (i.e., the log-linearized versions of equations (A12a) and (A12b)) into (A15) gives the following inflation relations in the domestic and importing sectors, respectively:

$$\pi_t^D=\beta\,\mathrm{E}_t\,\pi_{t+1}^D+\frac{\xi_y}{\gamma_D}y_t+\frac{\kappa_w}{\gamma_D}(p_t^M-p_t^D)+\frac{1}{(1-\kappa_M)}\varepsilon_t^\pi, \tag{A16a}$$

$$\pi_t^M=\beta\,\mathrm{E}_t\,\pi_{t+1}^M+\frac{1}{\gamma_M}(p_t^*+s_t-p_t^M), \tag{A16b}$$

where $\gamma_j=\frac{(\eta-1)}{\tilde{\gamma}_j}$, and where a domestic cost-push shock $\varepsilon_t^\pi$ has been added. The log-linearization of the aggregate price index corresponding to the underlying CES consumption basket follows

$$\pi_t = (1-\kappa_M)\pi_t^D + \kappa_M \pi_t^M, \tag{A17}$$

where CPI inflation consists of a combination of domestic and imported inflation. Inserting equations (A16a) and (A16b) into equation (A17) yields

$$\pi_t = \beta \mathrm{E}_t \pi_{t+1} + \beta_y y_t + \beta_q (p_t^M - p_t^D) + \beta_p (p_t^* + s_t - p_t^M) + \varepsilon_t^\pi, \tag{A18}$$

which is the aggregate supply relation in the main text, and where $\beta_y = (1-\kappa_M)\xi_y / \gamma_D$, $\beta_q = (1-\kappa_M)\kappa_W / \gamma_D$, and $\beta_p = \kappa_M / \gamma_M$.

### B.1. State-space representation, model dynamics, and asymptotic variances

To formulate the model (i.e., equations (1) – (7)) in state-space form, the following shock processes, and identities are used:

$$\varepsilon_{t+1}^{\pi} = \tau_{\pi}\varepsilon_{t}^{\pi} + \upsilon_{t+1}^{\pi}, \tag{B1a}$$

$$\varepsilon_{t+1}^{y} = \tau_{y}\varepsilon_{t}^{y} + \upsilon_{t+1}^{y}, \tag{B1b}$$

$$\varepsilon_{t+1}^{\phi} = \tau_{\phi}\varepsilon_{t}^{\phi} + \upsilon_{t+1}^{\phi}, \tag{B1c}$$

$$(p_t^M - p_t^D) = (p_{t-1}^M - p_{t-1}^D) + \pi_t^M - \pi_t^D, \tag{B2a}$$

$$(p_t^* + s_t - p_t^M) = (p_{t-1}^* + s_{t-1} - p_{t-1}^M) + \pi_t^* + \Delta s_t - \pi_t^M. \tag{B2b}$$

The state-space representation is

$$\widetilde{A}_0 \begin{bmatrix} x_{1,t+1} \\ \mathrm{E}_t x_{2,t+1} \end{bmatrix} = \widetilde{A} \begin{bmatrix} x_{1,t} \\ x_{2,t} \end{bmatrix} + \widetilde{B}\, i_t + \widetilde{\upsilon}_{t+1}, \tag{B3}$$

$$x_{1,t} = \begin{bmatrix} i_{t-1} & y_t^* & i_t^* & \pi_t^* & \varepsilon_t^{\pi} & \varepsilon_t^{\phi} & \varepsilon_t^{y} & (p_{t-1}^M - p_{t-1}^D) & (p_{t-1}^* + s_{t-1} - p_{t-1}^M) & a_{t-1} \end{bmatrix}',$$

$$x_{2,t} = \begin{bmatrix} y_t & \pi_t^D & \pi_t^M & \Delta s_t \end{bmatrix}',$$

$$\widetilde{\upsilon}_{t+1} = \begin{bmatrix} 0 & u_{t+1}^{y*} & u_{t+1}^{i*} & u_{t+1}^{\pi*} & u_{t+1}^{\pi} & u_{t+1}^{\phi} & u_{t+1}^{y} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}',$$

where $x_{1,t}$ is a 10×1 vector of predetermined state variables, $x_{2,t}$ is a 4×1 vector of forward-looking variables, and $\widetilde{\upsilon}_{t+1}$ is a 14×1 vector of disturbances,

$$\widetilde{A}_0 = \begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -b_y^*(1-\rho_i^*) & 1 & -b_\pi^*(1-\rho_i^*) & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & -\omega_q & -\omega_p & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & (1-\kappa_M)\alpha_i + \alpha_q + \alpha_e & \kappa_M\alpha_i - \alpha_q & -\alpha_e \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{\beta_q}{(1-\kappa_M)} & 0 & 0 & 0 & \beta & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{\beta_p}{\kappa_M} & 0 & 0 & 0 & \beta & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix},$$

$$
\widetilde{A}=\begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & \rho_y^* & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & \rho_i^* & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & \rho_\pi^* & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & \tau_\pi & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & \tau_\phi & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & \tau_y & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & -1 & 1 & 0\\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & -1 & 1\\
0 & \omega_y^* & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \omega_a & -\omega_y & 0 & 0 & 0\\
0 & -\alpha_y(1-\rho_y^*) & 0 & \rho_\pi^*\alpha_e & 0 & 0 & -1 & 0 & 0 & 0 & 1 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & -\frac{1}{(1-\kappa_M)} & 0 & 0 & 0 & 0 & 0 & -\frac{\beta_y}{(1-\kappa_M)} & 1 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0\\
0 & 0 & -1 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix},
$$

$$
\widetilde{B}=\begin{bmatrix}1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & (\beta_i+\beta_e) & 0 & 0 & 1\end{bmatrix}'.
$$

Premultiplying (B3) with $\widetilde{A}_0^{-1}$, and inserting the monetary policy reaction, $i_t = -F\begin{bmatrix} x_{1,t} & x_{2,t} \end{bmatrix}'$, yields

$$
\begin{bmatrix} x_{1,t+1} \\ \mathrm{E}_t x_{2,t+1} \end{bmatrix} = \left(A - BF\right)\begin{bmatrix} x_{1,t} \\ x_{2,t} \end{bmatrix} + \begin{bmatrix} \upsilon_{1,t+1} \\ 0_{4\times 1} \end{bmatrix}, \tag{B4}
$$

where $A = \widetilde{A}_0^{-1}\widetilde{A}$, $B = \widetilde{A}_0^{-1}\widetilde{B}$, and $\begin{bmatrix} \upsilon_{1,t+1} & 0_{4\times 1} \end{bmatrix}' = \widetilde{A}_0^{-1}\widetilde{\upsilon}_{t+1}$. Provided that the policy rule, $F$, implies a unique equilibrium, the dynamics of the model is given by

$$
x_{1,t+1} = M^s x_{1,t} + \upsilon_{1,t+1}, \tag{B5a}
$$

$$
x_{2,t+1} = H^s x_{1,t+1}, \tag{B5b}
$$

where $M^s$ and $H^s$ can be found using a Schur decomposition of ($A - BF$), see Söderlind (1999).

Given the system's dynamics in equation (B5), the variance-covariance matrix of the predetermined variables results from

$$
\Sigma_{x1} = M^s \,\Sigma_{x1}\, M^{s'} + \Sigma_{\upsilon 1}, \tag{B6a}
$$

$$
\mathrm{vec}\left(\Sigma_{x1}\right) = \left[I_{n1^2} - (M^s \otimes M^s)\right]^{-1} \mathrm{vec}\left(\Sigma_{\upsilon 1}\right), \tag{B6b}
$$

where the unconditional variance-covariance matrix of the disturbance vector, $\upsilon_{t+1}$, is given by $\Sigma_{\upsilon} = \left(\Sigma_{\upsilon 1} \quad 0_{10\times 4}\right)$, where $\Sigma_{\upsilon 1}$ is defined as

$$\Sigma_{\upsilon 1} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \sigma_{y*}^2 & (1-\rho_i^*)b_y^*\sigma_{y*}^2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & (1-\rho_i^*)b_y^*\sigma_{y*}^2 & \sigma_{i*}^2 + (1-\rho_i^*)^2(b_\pi^{*2}\sigma_{\pi*}^2 + b_y^{*2}\sigma_{y*}^2) & (1-\rho_i^*)b_\pi^*\sigma_{\pi*}^2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & (1-\rho_i^*)b_\pi^*\sigma_{\pi*}^2 & \sigma_{\pi*}^2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \sigma_\pi^2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \sigma_\phi^2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \sigma_y^2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}.$$

The variables of interest ( $z_t$ ) can be expressed as a function of the predetermined variables,

$$\begin{aligned} z_{t+1} &= T_x x_{t+1} + T_i i_{t+1} \\ &= \begin{bmatrix} T_{x1} & T_{x2} \end{bmatrix} \begin{bmatrix} x_{1,t+1} \\ x_{2,t+1} \end{bmatrix} + T_i i_{t+1} \\ &= \begin{bmatrix} T_{x1} & T_{x2} \end{bmatrix} \begin{bmatrix} x_{1,t+1} \\ H^s x_{1,t+1} \end{bmatrix} - T_i \begin{bmatrix} F_1 & F_2 \end{bmatrix} \begin{bmatrix} x_{1,t+1} \\ H^s x_{1,t+1} \end{bmatrix} \\ &= T^s x_{1,t+1} \ , \end{aligned}$$

yielding the following variance-covariance matrix for ( $z_t$ ):

$$\Sigma_z = T^s \, \Sigma_{x1} \, T^{s'} . \tag{B7}$$

Table A1a

Unconditional variances and social loss, using standard reaction coefficients

| | $\pi_t^{CB} = \pi_t^D$, $b_\pi = 1.5$, $b_y = 0.5$, $\rho = 0.8$ equation (8a); $i_t = (1-\rho)(b_\pi \pi_t^D + b_y y_t) + \rho i_{t-1}$ | | | | | | |
|---|---|---|---|---|---|---|---|
| Pass-through | var ($\pi$) | var ($y$) | var ($p^M$-$p^D$) | var ($\Delta s$) | var ($i$) | var ($\pi^D$) | var ($\pi^M$) |
| 0.99 | 18.231 | 46.047 | 7.754 | 21.721 | 7.706 | 18.034 | 21.499 |
| 0.66 | 17.483 | 43.172 | 6.672 | 22.630 | 7.465 | 17.940 | 17.507 |
| 0.33 | 16.562 | 41.766 | 7.749 | 23.854 | 7.092 | 17.632 | 14.766 |
| 0.09 | 14.427 | 41.673 | 19.662 | 26.016 | 6.328 | 16.489 | 11.015 |

Table A1b

Unconditional variances and social loss, using optimized reaction coefficients

| | $\pi_t^{CB} = \pi_t^D$, optimized reactions (see Table 3a) equation (8a); $i_t = (1-\rho)(b_\pi \pi_t^D + b_y y_t) + \rho i_{t-1}$ | | | | | | |
|---|---|---|---|---|---|---|---|
| Pass-through | var ($\pi$) | var ($y$) | var ($p^M$-$p^D$) | var ($\Delta s$) | var ($i$) | var ($\pi^D$) | var ($\pi^M$) |
| 0.99 | 23.132 | 24.690 | 5.769 | 23.983 | 13.674 | 23.505 | 23.792 |
| 0.66 | 22.113 | 25.308 | 5.627 | 24.753 | 11.980 | 22.772 | 21.422 |
| 0.33 | 21.569 | 24.488 | 7.087 | 26.318 | 11.522 | 22.724 | 19.562 |
| 0.09 | 20.905 | 20.680 | 21.567 | 30.234 | 12.254 | 23.246 | 16.874 |

Table A1c

Unconditional variances and social loss, policy rule based on CPI inflation

| | $\pi_t^{CB} = \pi_t$, optimized reactions (see Table 4) equation (8a); $i_t = (1-\rho)(b_\pi \pi_t + b_y y_t) + \rho i_{t-1}$ | | | | | | |
|---|---|---|---|---|---|---|---|
| Pass-through | var ($\pi$) | var ($y$) | var ($p^M$-$p^D$) | var ($\Delta s$) | var ($i$) | var ($\pi^D$) | var ($\pi^M$) |
| 0.99 | 22.396 | 25.369 | 5.677 | 23.024 | 13.087 | 22.795 | 22.844 |
| 0.66 | 21.731 | 25.460 | 5.591 | 23.916 | 11.966 | 22.419 | 20.920 |
| 0.33 | 21.144 | 24.797 | 7.095 | 25.610 | 11.260 | 22.304 | 19.116 |
| 0.09 | 20.373 | 20.606 | 21.485 | 29.287 | 12.047 | 22.703 | 16.366 |

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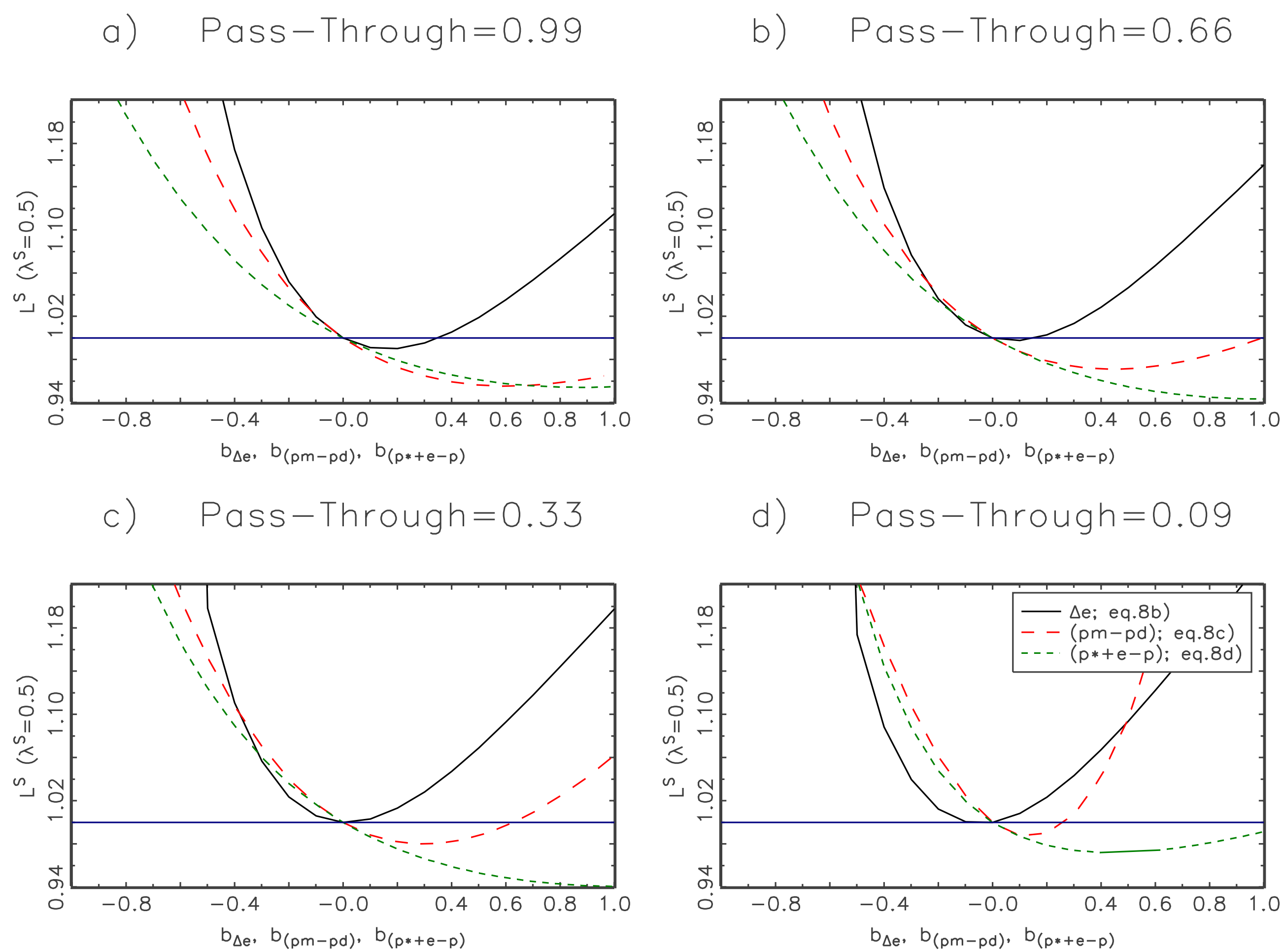
Figure 1: Social loss under varying degrees of exchange rate reactions added to the Taylor rule ($\pi_t^{CB} = \pi_t^D$).




Note: Relative social loss compared to the social loss under the Taylor rule *without* the exchange rate.

Figure 2: Impulse responses for the case with full pass-through (99%; solid) and with incomplete pass-through (33%; dashed), using optimized rules.

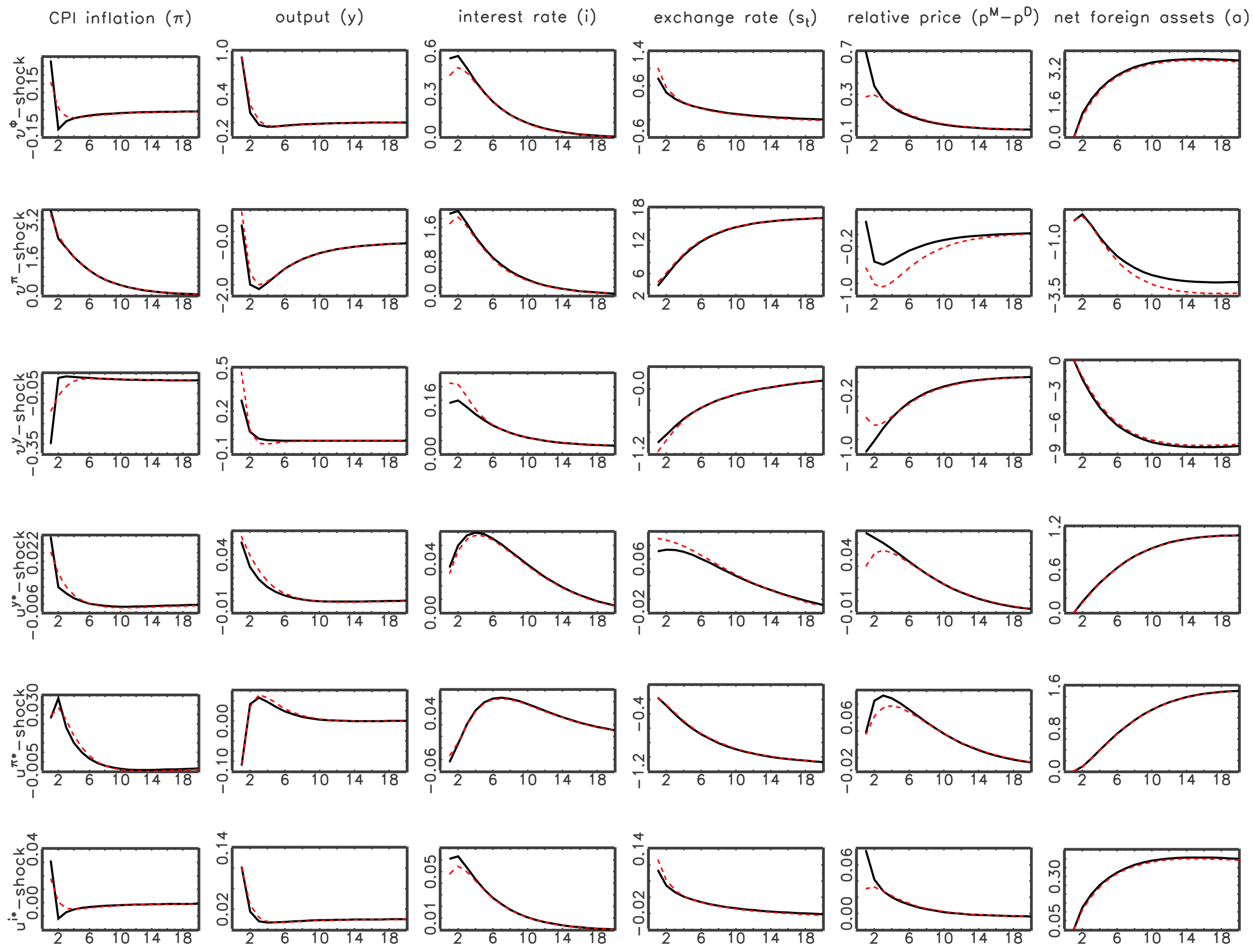
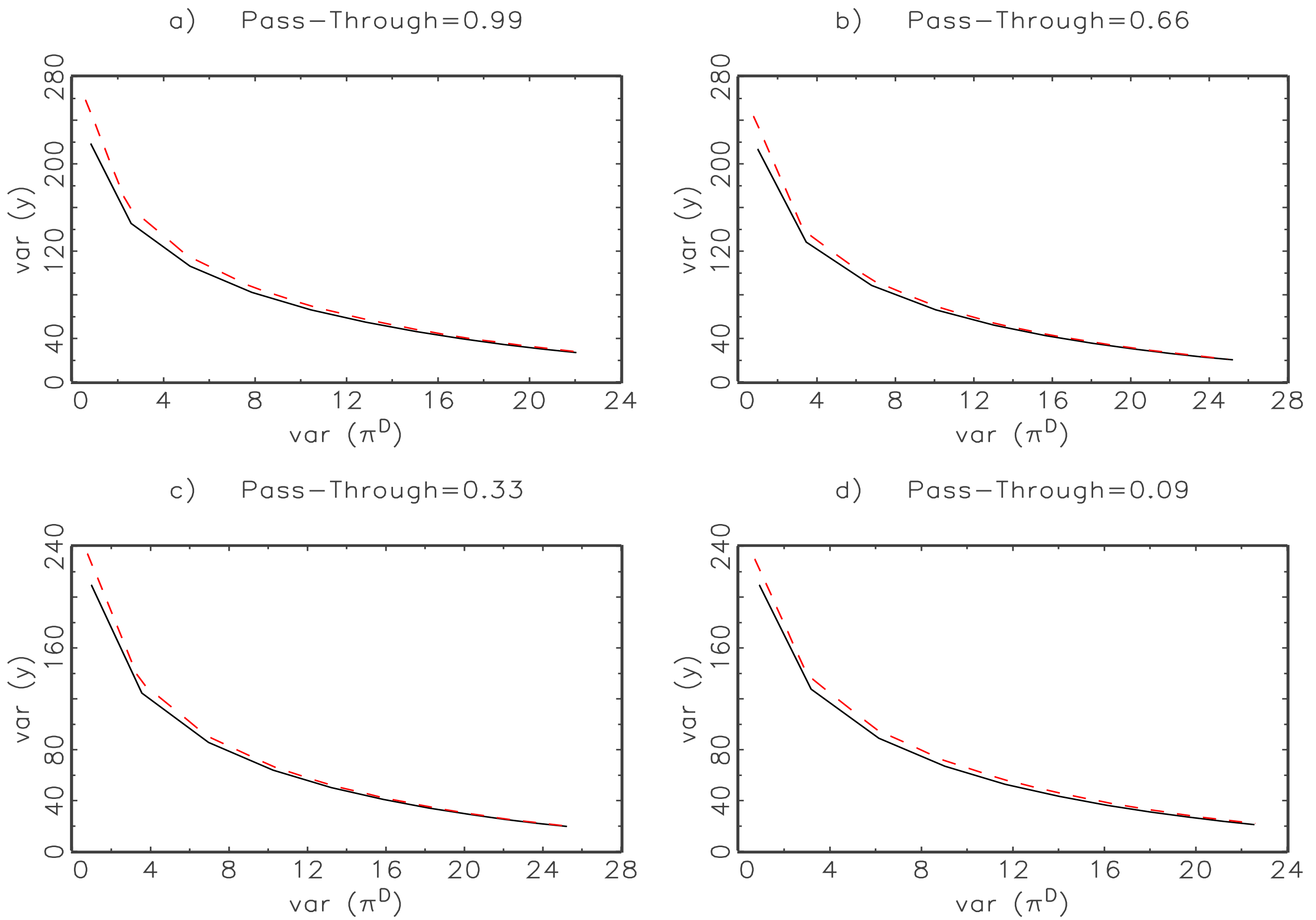


Figure 3: Domestic inflation-output variance trade-off, CPI inflation based rule (solid) vs. domestic inflation based rule (dashed).




Note: Optimized policy rules, varying the degree of output response between 0-4, step 0.4. For inflation and interest rate reactions, see Tables 3a and 4, respectively.