Monetary Policy and Exchange Rates
– Breakthrough of Pass-Through

Malin Adolfson

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– BREAKTHROUGH OF PASS-THROUGH

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CONTENTS

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Malin Adolfson

INTRODUCTION AND SUMMARY

How should central banks react to movements in the exchange rate? Can social welfare be improved if the policy maker is giving explicit or implicit consideration to fluctuations in the exchange rate? These are the principal questions addressed in this thesis.

Over the last decade there has been an extensive policy debate of whether exchange rate stabilization improves macroeconomic performance. In an open economy, exchange rate movements affect inflation through direct changes in import prices as well as via aggregate demand, which is influenced by alterations in the relative price between foreign and domestic goods. Consequently, movements in the exchange rate may be of importance for controlling inflation. However, an exchange rate movement need not generate a one-to-one change in import prices, that is, there may be an incomplete exchange rate pass-through, which implies a lower exposure to foreign disturbances. Whether the policy maker should respond to exchange rate movements might, therefore, be contingent upon the degree of pass-through.

This dissertation consists of four self-contained papers, analyzing the influence of exchange rates on prices and monetary policy, from an empirical as well as a theoretical perspective. The thesis sets off by providing some empirical evidence for incomplete exchange rate pass-through. This observation is subsequently incorporated into a theoretical model of a small open economy, to study how exchange rate fluctuations affect monetary policy. In three different papers, the policy consequences of incomplete exchange rate pass-through are investigated in terms of how the open-economy policy maker optimally practices inflation targeting. These papers are somewhat interrelated, which makes it possible to examine a number of questions in a unified framework. The papers deal with questions such as; are the optimal policy responses dependent on the degree of pass-through? Should the delegated policy contain some stabilization of the exchange rate? If the policy maker follows a sub-optimal instrument rule, could the inclusion of an exchange rate response improve social welfare?

The first chapter, *Export Price Responses to Exogenous Exchange Rate Movements,* is an empirical paper studying the relation between exchange rates and prices. The export price responses to three exogenous exchange rate movements are investigated, using data on Swedish exports of automobiles and kraft paper to three destination countries. A price determining error correction model indicates results consistent with price discrimination, and there is, consequently, evidence of incomplete exchange rate pass-through.

In the second chapter, *Monetary Policy with Incomplete Exchange Rate Pass-Through*, a small open economy aggregate supply-aggregate demand model, allowing for incomplete exchange rate pass-through, is developed to analyze the effects of limited pass-through on monetary policy. The results suggest that the optimal policy reaction, both to foreign and domestic shocks, is dependent on the degree of pass-through. First, the policy responses to foreign disturbances are smaller when pass-though is low. Second, the inflation-output variability trade-off becomes more favourable as pass-through decreases. Third, lower pass-through leads to higher exchange rate volatility. The reason behind these observations is that incomplete exchange rate pass-through implies that foreign disturbances have less impact on the domestic economy, which, in turn, involves smaller interest rate adjustments. Incomplete pass-through also implies a lower exposure to policy induced fluctuations in the exchange rate, which means that, for example, domestic demand shocks can more easily be mitigated, reducing the conflict between policy objectives. Further, low pass-through is, in this model, induced by large exogenous import price stickiness, which implies that prices can not costlessly absorb a country-specific shock. Consequently, larger movements in the endogenously determined exchange rate generate the required relative price adjustment.

The third chapter, *Optimal Monetary Policy Delegation under Incomplete Exchange Rate Pass-Through*, utilizes the forward-looking aggregate supply-aggregate demand model, developed in chapter two, to study what the delegated policy should be in an open economy with limited pass-through. In particular, the question of whether to delegate an exchange rate-stabilization objective to the policy maker is investigated. The welfare improving mechanism behind such a scheme is the possible reduction of the stabilization bias that occurs under a discretionary policy (i.e. less inertial policy responses). However, the results show that incorporation of an explicit nominal, or real, exchange-rate term in the (optimized) objective function only improves social welfare marginally (if at all). This result holds, irrespective of the degree of pass-through. Inflation, output, *and* the exchange rate appear to be sufficiently stabilized by an indirect, or implicit, exchange rate response, which is achieved through targeting Consumer Price Index (CPI) inflation. CPI inflation targeting enhances social welfare, compared to if the policy maker would target domestic inflation, *both* in terms of CPI inflation stabilization and domestic inflation stabilization. Further, although an exchange-rate augmented objective function does not seem to alleviate the stabilization bias, it can be mitigated by appointing an interest rate smoothing policy maker. The optimal degree of explicit interest rate smoothing is dependent on the degree of pass-through, and decreases as pass-through decreases. The reason is that low pass-through as such generates more inertial interest rate reactions.

The fourth chapter, *Incomplete Exchange Rate Pass-Through and Simple Monetary Policy Rules*, assumes, in contrast, that monetary policy is implemented through a simple instrument rule. It is examined whether the policy maker's performance, in terms of social welfare, can be improved by adding a reaction to the nominal, or real, exchange rate to such a rule. This is a somewhat different setting than in chapter three, since the policy maker now follows a sub-optimal reaction function. Note also that targeting the exchange rate (as in chapter three) is quite different from responding to it (as is the case in chapter four). In the former setting, the exchange rate development is an explicit policy objective, while the policy maker now, simply exploits the information contained in the exchange rate when setting the interest rate. In this case, an explicit exchange rate response might be less restrictive and reduce the sub-optimality, for instance, because of the possibility to directly internalize the effect of exchange rate fluctuations. Nonetheless, the results indicate that the exchange rate-augmented policy rules do not enhance social welfare, irrespective of the degree of pass-through, compared to using an optimized Taylor rule. Social welfare is, however, improved by an indirect exchange rate response, which is reached using a policy rule based on CPI inflation, rather than on domestic inflation. Moreover, this result is independent of whether society values CPI inflation or domestic inflation stabilization. Lastly, note that the non-optimized (or 'excessively simple') Taylor rule can be improved upon by inclusion of a direct real exchange rate response. This makes the overall interest rate adjustment more aggressive, which, consequently, mitigates the sub-optimality of the other reactions on inflation and output.

CHAPTER 1

EXPORT PRICE RESPONSES TO EXOGENOUS EXCHANGE RATE MOVEMENTS[#]

1

Malin Adolfson*

Abstract

The export price responses to three different exogenous exchange rate movements are investigated, using data on Swedish exports of automobiles and kraft paper to three destination countries. A price determining error correction model indicates results consistent with price discrimination.

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1. Introduction

An extensive empirical literature on the relationship between exchange rates and price adjustments has been built up since the large fluctuations of the U.S. dollar in the mid-eighties (for surveys see Goldberg and Knetter (1997), and Menon (1995)). If exporters have some market power and markets are segmented, an exchange rate change may induce price discrimination across destination markets (pricing to market according to Krugman (1987)) such that exporters set different prices, in the exporters' currency, in different destinations. This implies that the exchange rate pass-through, i.e. the response of the import price to an exchange rate change, is incomplete (local currency price stabilization). The exporters consider the conditions on the different markets when setting their prices and a destination specific markup adjustment thus absorbs part of the exchange rate change so that there are deviations from the law of one price. Consequently, price discrimination gives rise to different sizes of the exchange rate pass-through across the destinations.

Most empirical studies of the producer's price determination are done within a single equation framework, possibly on error correction form (see e.g. Feenstra et al. (1996), and Gagnon and Knetter (1995)). This implies that the pass-through coefficient will estimate the partial effect exchange rate fluctuations have on the price setting relation. However, exchange rate changes are not necessarily exogenous to the price determination, if for example aggregate data are used. By analyzing price data for individual firms or industries and exchange rate movements that can be treated as exogenous, such as a devaluation, the simultaneity between prices and exchange rates will be eliminated which enables one to estimate the pass-through coefficient more accurately.

In this paper the empirical analysis is done in a multivariate setting. This allows for several long run (cointegrating) relations between the variables determining export prices, market shares and exchange rates. This also makes it possible to explicitly treat problems of identifying the price setting relation. However, when leaving the partial-equilibrium, single equation framework the question arises of how to measure exchange rate pass-through. One is forced to make a distinction between partial and total pass-through coefficients. The partial pass-through measures the effect an exchange rate change has on the price setting relation, excluding the effects going through other variables and other equilibrium relations. The total pass-through, in contrast, measures the entire effect on the export price an exchange rate change causes, working through every interaction of prices, quantities and exchange rates. Here, the total pass-through to prices of Swedish exports of automobiles and kraft paper from three different and exogenous exchange rate movements is estimated. The study focuses on the devaluations of the Swedish krona in 1981 and 1982, and the shift from a fixed to a floating exchange rate regime in 1992. For comparison, the partial elasticities of the export prices with respect to the exchange rate are also reported.

2. The model

The model used here follows along the lines suggested by Gagnon and Knetter (1995), Kasa (1992), Feenstra et al. (1996), and Feenstra and Kendall (1997).[1] Assuming adjustment costs on the supply side, implies that the price determination in an imperfectly competitive setting (with differentiated products and segmented markets such that the exporter can price discriminate) can be modelled in an error correction framework. The price change then depends on prior deviations from the long run cointegrating relations as well as prior changes in the explanatory variables and the export price itself. This also seems like a suitable specification of the econometric model given the commonly accepted non-stationarity of nominal variables such as price levels and exchange rates.

The interactions between the export price, export volume and the exchange rate are analyzed using Johansen's (1988) maximum likelihood procedure, which consists in estimating a vector autoregressive (VAR) model. The model (presented in its empirical form) has the following form:

$$(1) \qquad \Delta z_t = \sum_{j=1}^{k-1} \Gamma_j \Delta z_{t-j} + \alpha \left(\beta' \quad \beta_6\right) \begin{pmatrix} z_{t-1} \\ t \end{pmatrix} + \mu + \Phi D_t + \varepsilon_t \qquad t = 1, \ldots, T$$

where z is a five dimensional column vector, $z = (p, ppi, sh, e, p^{sub})'$. p is the export price denoted in the exporter's currency, ppi is a disaggregated producer price index in the exporter's country used as a proxy for the marginal cost, sh is the market share defined as the Swedish export volume of a certain good divided by the total volume of imports of that good to one destination market, e is the exchange rate (exporter's currency per unit of importer's currency) and p^{sub} is the price of competing products, defined as other imports of the good, denoted in the buyer's currency (all variables are logarithmic values). μ is a vector of constants, D is a vector of deterministic variables (three centered seasonal dummies, three intervention dummies and

[1] For a more extensive discussion of the model see Adolfson (1999).

three dummies for excluding apparent outliers) and ε_t is a vector of IID disturbance terms. The intervention dummies consist of the large devaluations of the Swedish krona in September 1981 and October 1982 and the shift to a floating exchange rate in November 1992:

$$D_{i,t} = \begin{cases} 1 & \text{if } t \in I_i \quad i = 1,2,3 \\ 0 & \text{otherwise} \end{cases}$$

where I_1 = {1981:4}[2], I_2 = {1982:4}, I_3 = {1992:4...1994:4}. Γ represents the short-run dynamics, α is a (5×2) matrix of adjustment coefficients toward the long run equilibrium, β' is a (2×5) matrix of the cointegration vectors[3] and t is a linear trend capturing composition effects in unit values and productivity growth.[4]

A total short-run pass-through[5] in the error correction model (equation (1)), due to a pure exogenous shock to the system (i.e. a change in the dummy variables representing the devaluations in 1981 ($D_{1,t}$) and 1982 ($D_{2,t}$) respectively), is calculated by comparing the pricing equation's response with the response in the exchange rate equation.[6] In addition, the total pass-through is determined for the depreciation in 1992 (which is identified by a change in $\Delta D_{3,t}$), following the shift from a fixed to a floating currency regime. However, this dummy variable ($D_{3,t}$) represents the regime shift and not the explicit exchange rate shock per se, so the resulting pass-through might capture the effects of a combination of the depreciation and the switch to a floating currency.

The total exchange rate pass-through estimate includes all the consequences an exogenous exchange rate change causes to the export price, i.e. the effect working through the entire short-run dynamics (all partial coefficients in Γ) as well as the effect working through both cointegration vectors. To see this explicitly, formulate the system in the following way:

---

[2] Since the exchange rate series consist of quarterly averages of the spot rates, the timing (within a quarter) of a fluctuation matters for what quarter a change primarily is reflected in. The devaluation in September 1981 appears, in the data, mainly in the last quarter of 1981.

[3] The cointegration rank is set to two for all markets, in accordance with the regular (trace) likelihood ratio test. The subsequent analysis is carried out with unrestricted cointegration vectors.

[4] The number of lags, k, are two for all destination markets except for the export of automobiles to Germany (three lags). Standard mis-specification tests have been used to determine lag length.

[5] The partial short-run pass-through is found in the dynamics of the pricing equation ($\Gamma_{j,14}$) in the error correction model (see equation (1)).

[6] Apart from the exchange rate changes the dummy variables might also capture some other distortion in the system so the results should be interpreted with caution. With further identifying assumptions one could estimate different pass-through effects from different structural shocks, which though lie beyond the scope of this paper.

$$(2) \quad \begin{bmatrix} \Delta z_t \\ \beta' z_t \end{bmatrix} = \begin{bmatrix} \mu \\ \beta' \mu \end{bmatrix} + \begin{bmatrix} \phi \\ \beta' \phi \end{bmatrix} D_t + \begin{bmatrix} \Gamma & \alpha \\ \beta' \Gamma & (I + \beta' \alpha) \end{bmatrix} \begin{bmatrix} \Delta z_{t-1} \\ \beta' z_{t-1} \end{bmatrix} + \begin{bmatrix} \alpha \beta_6 \\ \beta' \alpha \beta_6 \end{bmatrix} t + \begin{bmatrix} \varepsilon_t \\ \beta' \varepsilon_t \end{bmatrix}$$
$$y_t \;=\; \theta_0 \;+ \theta_1 \; D_t \;+ \quad B \quad y_{t-1} \;+\; \theta_2 \; t + \; \eta_t$$

Hence, the B-matrix will capture the complete effect on all variables and both the channels the exchange rate change is working through (i.e. the short-run run dynamics and both cointegration vectors). The resulting response in vector y_t due to a shift in the dummy variable in period t is thus; (response (y_{t+s})) = $B^s \theta_1$.[7] Since $\Delta z_t = G\, y_t$ where $G = [I_5 \;\; 0_{5\times2}]$, the response in the levels of the z-variables is (in period $t+s$ following a depreciation in period t); (response (z_{t+s})) = $\sum_{j=0}^{s} GB^j\theta_1$. The total pass-through to the export price in period $t+s$ of an exchange rate change in period t could thus be calculated as; (response (p_{t+s})) / (response (e_t)).

3. Empirical results

The model is estimated using quarterly data for exports of automobiles and kraft paper from Sweden to Germany and the United Kingdom for the period 1980:1-1994:4, and to France for 1984:1-1994:4.[8]

The most apparent evidence of a non-zero and incomplete short-run pass-through[9] is seen in the automobile exports to Germany where the export price absorbs about 63 % of the devaluations in 1981 and 1982 within a quarter, implying a total pass-through of +37 % (see Table 1). The overall impression is that the export prices of automobiles and kraft paper have reacted quite strongly to the exchange rate movements implying that the local currency prices are stabilized. Both goods show similar price responses, perhaps with a somewhat smaller pass-through on average for the kraft paper markets.

[7] This follows from; response $(y_{t-1}) = 0$, response $(y_t) = \theta_1$, response $(y_{t+1}) = B \times$ response $(y_t) = B \times \theta_1$ and so on. The response to the depreciation in 1992 is determined by the same formula given that the exchange rate change is captured by $\Delta D_{3,t}$.

[8] The data sources are Statistics Sweden, Bank of International Settlements, OECD Main Economic Indicators, Konjunkturinstitutet, Statistiches Bundesamt, EUROSTAT and Central Statistical Office. See Adolfson (1999) for a more detailed discussion of the data, and Alexius and Vredin (1999) for an earlier application of the same data on export prices.

[9] The concept pass-through is commonly used interchangeably for the effects of an exchange rate change on export or import prices. In this paper pass-through is defined as the import price response to an exchange rate change (measured in local currency, - e), i.e. pass-through = $-[(\partial p / \partial e) - 1]$.

Table 1: Accumulated total short-run exchange rate effect on the export price level (response (p_{t+s}) / response (e_t))

Destination and date of shock	s = 0	s = 1	s = 2	s = 3	s = 4
Automobiles:					
Germany					
81:4	0.2913	0.6232	0.7330	0.6024	0.9021
82:4	0.1526	0.6282	0.7297	0.6472	0.8944
92:4	-0.0952	0.5074	0.4912	0.5513	0.7817
United Kingdom					
81:4	1.1528	1.4792	1.7741	1.7653	1.8479
82:4	0.0308	0.7631	0.5735	0.4230	0.3851
92:4	0.2113	0.8656	0.5470	0.2845	0.1664
France					
92:4	-0.1848	1.1552	0.2762	0.1161	-0.0955
Kraft paper:					
Germany					
81:4	0.7978	1.0750	1.3145	1.3626	1.4591
82:4	0.5000	0.7920	0.7867	0.8523	0.9268
92:4	-0.2714	0.1356	-0.2233	-0.1574	-0.1139
United Kingdom					
81:4	0.4776	1.0886	1.1644	1.2754	1.3458
82:4	0.8031	1.0909	1.1833	1.2742	1.3192
92:4	-0.8182	0.5863	0.0574	-0.0079	0.0956
France					
92:4	-0.4896	0.3005	-0.0029	-0.1694	-0.1009

Note: The sample period for France is 1984:1-1994:4.

Table 2: Partial short-run dynamics of the exchange rate

Destination	Coefficient in the pricing equation Δe_{t-1} ($\Gamma_{1,14}$)	LR-test (p-value) H_0: $\Gamma_{1,14} = 1$
Automobiles:		
Germany	0.032	0.00
United Kingdom	0.466	0.05
France	1.135*	0.83
Kraft paper:		
Germany	0.492*	0.00
United Kingdom	0.174	0.00
France	0.639*	0.15

Note: * denotes significance at the 5 % level.

On average the results indicate no great difference between the two devaluations in the eighties (with an exception for the British automobile market). However, the responses, in all markets, are more unstable after the regime shift and depreciation in 1992 than after the devaluations in 1981 and 1982. Given the costs of adjusting the supplied quantity, the price setting and pass-through will be a result of exchange rate expectations (see Gagnon and Knetter (1995)). Expectations probably varied more after the regime shift in 1992 than after the devaluations under the fixed exchange rate regime. Greater uncertainty about the future development of the exchange rate can thus, in principle, explain the different pricing response 1992-1993. On average the exchange rate change is passed through to the local currency price to a greater extent after the depreciation in 1992 compared to the devaluations in the eighties. There is thus less pricing to market in the 1990's than in the 1980's.

For comparison, the partial short-run dynamics, i.e. the exchange rate coefficient in the pricing equation ($\Gamma_{j,14}$), as well as a likelihood ratio test on whether the partial short-run exchange rate elasticity of the export price is complete ($\Gamma_{1,14} = 1$), are displayed in Table 2. The partial export price responses are, for most destinations, smaller compared to the total responses, implying a larger partial exchange rate pass-through. Note that half of the partial coefficients are insignificant (in that case rendering a full pass-through).

4. Conclusions

Once leaving the single equation, partial equilibrium framework, it is not easy to define and estimate the pass-through of exchange rate changes to export and import prices. There are several long run equilibrium relations between exchange rates and prices. The approach taken in this paper is to look at purely exogenous exchange rate changes such as devaluations. The empirical results reveal large differences between partial and total pass-through coefficients. The differences in the total pass-through coefficients across the destination markets suggest that pricing to market is present in Swedish exports of automobiles and kraft paper.

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CHAPTER 2

MONETARY POLICY WITH INCOMPLETE EXCHANGE RATE PASS-THROUGH

Malin Adolfson*

2

Abstract

The central bank's optimal reaction to foreign and domestic shocks is analyzed in an inflation targeting model allowing for incomplete exchange rate pass-through. Limited pass-through is incorporated through nominal rigidities in an aggregate supply-aggregate demand model derived from some microfoundations. Three main results are obtained. First, the results suggest that the interest rate response to foreign shocks is smaller when pass-through is low. Second, the inflation-output variability trade-off becomes more favourable as pass-through decreases. Third, lower pass-through, that is larger nominal rigidity, leads to higher exchange rate volatility. With exogenous nominal price stickiness, part of the required relative price adjustment is provided through larger movements in the endogenously determined exchange rate.

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1. Introduction

For a central bank to conduct monetary policy efficiently, and respond adequately to different shocks, it is absolutely essential to understand the workings of the economy and the transmission mechanisms of monetary policy. In a small open economy, the exchange rate implies an additional transmission channel for monetary policy apart from the standard aggregate demand channel. Consumer price (CPI) inflation is directly affected by changes in the exchange rate through the effect on import prices. Inflation is also indirectly affected through aggregate demand. Exchange rate changes typically affect the relative price between domestic and foreign goods, thereby influencing aggregate demand. Aggregate demand, in turn, affects inflation through the aggregate supply (or Phillips curve) relation. In an open economy, inflation is thus greatly influenced by how its determinants adjust to exchange rate movements.

Prior work on open economy inflation targeting models has predominantly included open economy aspects by incorporating a foreign good, and thereby the real exchange rate, based on the assumption of a complete and immediate effect of exchange rate movements on import prices (see e.g. Galí and Monacelli (1999), McCallum and Nelson (1999), and Svensson (2000)).[1] However, the empirical evidence for, large and small, open economies seems to suggest that there are systematic deviations from the law of one price, and that the exchange rate pass-through is incomplete both for export and import prices (see e.g. Adolfson (2001), Alexius and Vredin (1999), and Naug and Nymoen (1996)).

Consider a foreign firm selling goods to the domestic market and setting its price in the domestic (buyer's) currency. If prices denoted in domestic currency are sticky, as a consequence of firms facing costs of changing prices, the domestic currency (import) price will not be fully altered even if exchange rate changes affect the marginal cost. This implies that import prices do not move immediately and in a one-to-one relation with the exchange rate (i.e. incomplete exchange rate pass-through).[2] Nominal rigidities thus imply that exchange rate movements have a minor immediate effect on consumer price inflation. In addition, nominal rigidities imply that

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[1] An exception is Monacelli (1999) who permits local importers to price discriminate, thereby allowing an incomplete pass-through. Leitemo (2000) obtains a limited and gradual pass-through via an error correction mechanism for the import prices, making them adjust sluggishly to exchange rate fluctuations. Batini and Haldane (1999), and Bharucha and Kent (1998) also allow for a limited pass-through, but only as sensitivity checks to their full-pass through models.

[2] A related cause for incomplete exchange rate pass-through is pricing to market, which implies deliberate price discrimination, where the destination-specific markup may be adjusted to absorb part of an exchange rate movement. This does, however, require either a specific functional form of the demand curve (i.e. less convex than the constant elasticity case) or strategic pricing, which is not analyzed in this paper.

expectations about future exchange rates as well as expectations about future inflation are important for the inflation-output relation.

Given that the exchange rate pass-through is allowed to be incomplete, the effect of exchange rate movements on CPI inflation is expected to be more limited in the short run but prolonged. In this case, a pass-through adjusted aggregate supply relation may perhaps imply a different optimal monetary policy response to a shock, compared to a full pass-through Phillips curve. Monacelli's (1999) results suggest that the performance of monetary policy (in terms of inflation stabilization) can be improved by a simple instrument rule including a direct feedback from the nominal exchange rate (compared to a rule where the interest rate reacts solely to inflation and output). An explicit interest rate response to changes in the exchange rate reduces the volatility of inflation because of the direct control of the exchange rate channel feeding into inflation.

The purpose of this paper is to examine the monetary policy implications of allowing an incomplete pass-through in an inflation targeting framework. The optimal policy responses to both domestic and foreign shocks are analyzed under various assumptions about the degree of pass-through. The optimal policy reaction is directly derived from the central bank's loss function, in contrast to a Taylor rule (i.e. a simple instrumental rule linking the nominal interest to, for example, inflation and output). Moreover, the concept of exchange rate pass-through is studied in detail. A microfounded small open economy aggregate supply-aggregate demand model, adjusted for incomplete (and gradual) exchange rate pass-through, is derived and used in the analysis. The paper deals with questions such as; is the optimal policy response dependent on the degree of pass-through? How is the trade-off between inflation and output variability affected by the degree of pass-through? Further, how is the degree of pass-through and exchange rate volatility related?

Three main results are obtained in the paper. First, the results show how the monetary policy response, both to foreign and domestic shocks, depends on the degree of pass-through. In contrast to the complete pass-through case, the exchange rate channel has less impact when pass-through is low which, for example, implies that foreign shocks require smaller interest rate adjustments. Second, incomplete pass-through implies less conflict between inflation and output variability because of the lower exposure to exogenous as well as policy induced exchange rate fluctuations. This moves the trade-off frontier closer to the origin as pass-through decreases. Third, the results suggest that the volatility of the nominal exchange rate increases as pass-through decreases. A low pass-through is, in this model, induced by a large exogenous import price stickiness, which in turn implies that prices can not costlessly absorb a country-specific shock. The required relative price adjustment is therefore generated through larger movements in the endogenously determined exchange rate. Lastly, the exchange rate pass-through varies with the degree of shock persistence. Transitory movements have lower influence on expectations about future prices and exchange rates, and accordingly, yield lower pass-through.

In Section 2, the aggregate supply-aggregate demand model, adjusted for incomplete pass-through, is derived and parameterized, and the central bank's loss function is set up. Section 3 contains the optimal policy responses, and their implications, to various foreign and domestic shocks under different degrees of pass-through. Conclusions are provided in Section 4.

2. The model

The theoretical specification is a forward-looking aggregate supply-aggregate demand model modified to allow for incomplete exchange rate pass-through. To determine the effect of incomplete pass-through in this small open economy, the commodity market is primarily considered. Supply and demand relations are explicitly derived from the agents' optimization problems. A local currency pricing framework is considered, along the lines of, for example, Betts and Devereux (2000), where the elasticity of demand is assumed to be constant (and thus, independent of the exchange rate, the competitors' prices and other underlying conditions of competition).[3] Markets are segmented such that different prices can be charged in different markets. However, the constant elastic demand implies that there will not be any 'genuine' pricing to market, or deliberate price discrimination, in terms of a varying markup that responds to exchange rate changes (see Bergin and Feenstra (1999)). Incomplete pass-through occurs due to nominal rigidities, arising from convex costs of adjusting prices (Rotemberg (1982)), and there are no long-run deviations from the law of one price.[4]

[3] Note that Friberg (1998) shows that a sufficient condition, under uncertainty, for an exporter to set the price in the local currency is that demand is not too convex in the local currency price (i.e. less convex than the constant elasticity case). Most studies nevertheless disregard this problem and assume a local currency pricing framework in combination with the constant elastic substitution function (CES) for convenience reasons (see e.g. Betts and Devereux (2000), Devereux and Engel (1998), Monacelli (1999), and Tille (1998)).

[4] The term pricing to market has been commonly used also in such a setting, somewhat misleadingly since that framework only produces an exchange rate driven price discrimination in the presence of nominal rigidities. On the other hand, different degrees of nominal price stickiness across destination markets do imply deviations from the law of one price (as well as inducing different degrees of pass-through). Once the producers are free to adjust their prices, the law of one price will though be re-established. For a discussion of these matters, and a survey of recent research on open economy dynamic general equilibrium models, see Lane (1999).

2.1. Aggregate supply

Consider an open economy with consumption of two different types of goods; domestic (C_t^D) and foreign import goods (C_t^M), supplied by domestic and foreign producers, respectively. The domestic economy is assumed to be small, such that conditions in the rest of the world (the foreign economy) are exogenously given. The producers sell their goods in both the domestic and foreign markets. The foreign market outcome is however not explicitly modeled and thus, in all its essentials, the setting is a one market–two goods framework.

The two product categories are imperfect substitutes, thus rendering the domestic and foreign producers some market power when setting their prices (i.e. each representative producer supplies a differentiated product, $i\in\{D\ ,\ M\}$). However, because of physical costs of changing the price (menu costs) and the producers' concern for a stable price path (reputation), due to imperfectly informed consumers and brand-switching costs in the domestic market, there is a negative effect of changing domestic currency prices. These costs of adjusting the price are assumed to be quadratic.[5] The notation throughout the paper is as follows; lower case letters represent logarithmic values, a hat denotes flexible prices (i.e. prices charged in the absence of adjustment costs), a superindex denotes whether domestic or imported goods are considered, and variables belonging to the foreign market are represented by an asterisk. An asterisk thus labels a price denoted in foreign currency. The monopolistic producers minimize the cost of being away from the optimal price chosen in the absence of adjustment costs:[6]

$$(1)\qquad \min_{\{p_{t+s}^i\}_{s=0}^{\infty}} \quad \mathrm{E}_t \sum_{s=0}^{\infty} \beta^s \left[\left(p_{t+s}^i - \hat{p}_{t+s}^i\right)^2 + \gamma_i \left(p_{t+s}^i - p_{t+s-1}^i\right)^2 \right], \qquad i \in \{D, M\},$$

where E_t denotes the rational expectations as of period t, β is a discount factor, and p_t^i is the price (denoted in the buyer's currency) of good i while $\hat{p}_t^i$ is the equilibrium price charged in the

[5] The specific adjustment-cost technology is not modelled explicitly, why these costs can arise in any currency. That the price stickiness occurs in the buyer's currency is, however, a necessary assumption for obtaining an incomplete pass-through.

[6] This is the dual problem of maximizing the present discounted profits in the absence of adjustment costs, subtracting the cost of deviating from this equilibrium price and the cost of changing prices:

$$\max_{\{p_{t+s}^i\}_{s=0}^{\infty}} \mathrm{E}_t \sum_{s=0}^{\infty} \beta^s \left[\Pi(\hat{p}_{t+s}^i) - (p_{t+s}^i - \hat{p}_{t+s}^i)^2 - \gamma_i (p_{t+s}^i - p_{t+s-1}^i)^2 \right].$$

In reality, the adjustment costs (γ_i) are presumably endogenously related to, for example, the functional form of the demand curve, and the rate of inflation. However, the adjustment costs are assumed to be constant to make the equilibrium tractable. For the underlying structure of the approximation of the producer's optimization problem, see Rotemberg (1982).

absence of adjustment costs. γ_i is a parameter measuring the ratio of the costs of changing the price to the costs of deviating from the equilibrium price, such that γ_i equal to zero implies a fully flexible environment. The first order condition yields

$$(2) \qquad \pi_t^i = \beta \, \mathrm{E}_t \pi_{t+1}^i + \frac{1}{\gamma_i}\left(\hat{p}_t^i - p_t^i\right),$$

where $\pi_t^i = p_t^i - p_{t-1}^i$ denotes the domestic currency inflation of good i. This specification, with convex adjustment costs, will thus lead to gradual changes in the individual (and aggregate) prices implying that the producers alter the price charged in this (and every) period, in the direction of the expected optimal price in future periods.[7]

2.1.1. Imported products

The price of the import good charged in the domestic market is here established in two steps. First, the flexible import price in the absence of any nominal rigidities is determined. Second, this flexible price is combined with the adjustment costs the foreign producer is actually facing and, accordingly, the optimal 'sticky' import price is resolved.

The imported foreign product's equilibrium flexible price ($\hat{p}_t^M$) is, by assumption, the price charged by a profit-maximizing foreign firm in an imperfectly competitive framework, setting the price in the buyer's currency. The consumers' aggregate demand follows a constant elasticity of substitution (CES) function (see Appendix A), such that the foreign producer sets his price as a constant markup over the marginal cost (which is assumed to be equal across the producer's two different destination markets). The foreign producer faces the following optimization problem in a flexible price environment:[8]

[7] The purpose of the nominal rigidities in this paper, apart from incorporating an incomplete exchange rate pass-through, is to introduce forward-looking behaviour in the aggregate supply relation. Using the Calvo (1983) formulation (see e.g. Monacelli (1999) and Svensson (2000)) renders staggeredness in the *individual* prices, in contrast to Rotemberg (1982). The two formulations though yield a similar behaviour, or path, of *aggregate* prices (Roberts (1995)). Besides, the Calvo representation has an exogenously given price adjustment-probability, which is fixed and independent of both the size of the deviation from the equilibrium flexible price and the size of, for example, an exchange rate shock.

[8] Whether the producer maximizes profits in his own currency, or in the buyers' currency, does not affect the first order conditions, given the constant elastic demand.

$$(3) \quad \begin{aligned} &\max_{\hat{P}_t^M,\hat{P}_t^{M*}} \quad \hat{P}_t^M C_t^M + \hat{P}_t^{M*} E_t C_t^{M*} - H_M (C_t^M + C_t^{M*}, P_t^{Z*}) E_t \\ &\text{s.t} \quad C_t^M + C_t^{M*} = \kappa_M \left(\frac{\hat{P}_t^M}{\hat{P}_t} \right)^{-\eta} C_t + \left(\frac{\hat{P}_t^{M*}}{\hat{P}_t^*} \right)^{-\eta} C_t^*, \end{aligned}$$

where $\hat{P}_t^M$ (denoted in domestic currency) and $\hat{P}_t^{M*}$ (denoted in foreign currency) are the prices charged in the domestic and foreign markets, respectively. C_t^M is the demand for the foreign good in the domestic market, and C_t^{M*} the demand for the foreign good in the foreign market. E_t is the exchange rate (domestic currency per unit of foreign currency), H_M is the foreign producer's total cost function, and P_t^{Z*} is the price of inputs (denoted in foreign currency). κ_M is the domestic import share of consumption, η is the (positive) constant price elasticity of demand, $\hat{P}_t$ is the aggregate price index in the domestic market, and C_t is the aggregate domestic consumption (a star denotes the foreign market counterparts). The foreign economy is large in the respect that the foreign import share is assumed to be negligible in the foreign aggregate price index. This implies that the world market price for domestic import goods is equal to the foreign aggregate price level ($\hat{P}_t^{M*} = \hat{P}_t^*$). The producer's profit maximization yields the following first order condition with respect to the price charged in the domestic market:

$$(4) \quad \hat{P}_t^M = \underbrace{\left(\frac{\eta}{\eta - 1} \right) MC^*(C_t^M + C_t^{M*}, P_t^{Z*})}_{\hat{P}_t^{M*} = \hat{P}_t^*} E_t,$$

where $MC^*(.)$ denotes the foreign currency marginal cost, and η, the price elasticity of demand, determines the constant markup. The producer's equilibrium price in the domestic market is simply the price charged in the foreign market ($\hat{P}_t^*$) corrected for the exchange rate (E_t), which in logarithms can be expressed as $\hat{p}_t^M = \hat{p}_t^* + e_t$ (where $\hat{p}_t^*$ captures the marginal cost (denoted in foreign currency) and the constant markup). Given that the foreign producer faces identical demand elasticities across the two destinations to which he is selling, there are no incentives for the exporter to deviate from the law of one price (i.e. no deliberate price discrimination), although markets are segmented. This implies that, in a flexible price setting, prices (denoted in the producer's own currency) would be the same in both markets, and maintained equal irrespective of any exchange rate changes.[9] The markup is constant which, in this case, would imply that any exchange rate movement is completely reflected in the local currency price, that is, a complete pass-through. Hence, with entirely flexible prices, the long-run inflation rate of import goods would be the imported foreign inflation rate corrected for changes in the nominal exchange rate, $\hat{\pi}_t^M = \hat{\pi}_t^* + (e_t - e_{t-1})$. However, due to nominal rigidities in the domestic market, there may be short-run deviations from the full pass-through equilibrium price, and from the law of one price.

The foreign producer faces price adjustment costs in the domestic market, such that the price actually charged differs from the price that would prevail in a flexible price setting (i.e. $p_t^M \neq \hat{p}_t^M$).[10] Inserting the equilibrium price ($\hat{p}_t^M = \hat{p}_t^* + e_t$) into the adjustment cost minimization in equation (2), yields the following relation:

$$(5) \qquad \pi_t^M = \beta \, \mathrm{E}_t \pi_{t+1}^M + \frac{1}{\gamma_M}\left(\hat{p}_t^* + e_t - p_t^M\right),$$

where $\pi_t^M = p_t^M - p_{t-1}^M$ denotes the domestic currency inflation of import goods. The present price change of import goods is dependent on the expectations about future import price changes, and the contemporaneous difference between the foreign producer's equilibrium price (in the absence of price rigidities) and the price actually charged. Due to the costly price adjustment, exchange rate movements will create a wedge between the price charged in the domestic market (p_t^M) and the price charged in the foreign market ($\hat{p}_t^*$). Consequently, the last term captures deviations from the law of one price. The degree of pass-through is highly dependent on γ_M (i.e. the ratio of the costs of changing the price to the costs of deviating from the equilibrium price). As γ_M increases, i.e. there is a greater nominal rigidity, pass-through decreases. Price discrimination is thus generated by these nominal rigidities. In this framework, price stickiness can render price differentials across destinations, and deviations from the law of one price, both ex ante and ex post an exchange rate change, depending on whether the change is expected to be permanent, transitory, or is entirely unexpected.[11]

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[9] An identical foreign currency price across destinations can also arise if the product is homogenous without any possibilities for price discrimination, such that the world market price is taken as given.

[10] For simplicity, the price setting in the foreign market is assumed to be completely flexible (i.e. $p_t^* = \hat{p}_t^*$). In contrast to the domestic market, the foreign producer is thus able to charge the equilibrium flex price there.

[11] The producer sets his price based on exchange rate expectations, due to the quadratic adjustment costs, which can be seen explicitly by solving equation (5) forward (following Rotemberg (1982)):

(footnote continues on the next page)

2.1.2. Domestically produced products

Now, consider the domestically produced goods sold in the domestic and foreign markets. Given the constant markup, implied by the CES function, the exchange rate will affect the price charged in the domestic market only through its effect on the domestic producer's marginal costs (i.e. via its effect on imported intermediate inputs). The domestic producer faces an optimization problem equivalent to that of the foreign producer (see also equation (A8) in Appendix A), which yields a standard monopolist's first order condition with respect to the price charged in the domestic market:

(6) $$\hat{P}_t^D = \left(\frac{\eta}{\eta - 1}\right) MC(Y_t, P_t^Z),$$

where η is the (positive) constant price elasticity of demand and the elasticity of substitution between domestic and foreign goods. $MC(.)$ is the marginal cost, $Y_t = C_t^D + C_t^{D*}$ is the demand for domestic products (domestic and foreign demand), and P_t^Z is the price of inputs (denoted in the domestic currency). There are decreasing returns to scale, such that the cost function is convex in quantity produced. Furthermore, marginal costs are also affected by exchange rate movements, via their effect on the price of imported inputs.

The price of domestic products on the foreign market will just be the price on the domestic market corrected for the exchange rate ($P_t^{D*} = P_t^D / E_t$), given identical demand elasticities (see equation (A8) in Appendix A). For simplicity, the domestic producer is thus assumed to follow the law of one price, such that there is a full pass-through to her export market.[12]

Taking logarithms of equation (6), and using a first order Taylor approximation around steady-state, yields the following expression for the equilibrium flexible price:

(7) $$\hat{p}_t^D = \xi_y y_t + \xi_z p_t^Z,$$

$$p_t^M = r_1 p_{t-1}^M + \frac{1}{r_2 \gamma_M \beta} \mathrm{E}_t \sum_{s=0}^{\infty} (\tfrac{1}{r_2})^s \left(\hat{p}_{t+s}^* + e_{t+s}\right),$$

where r_1 and r_2 are the stable and unstable roots, respectively.

[12] Differing rates of nominal price stickiness across the domestic producer's two markets would, analogously to the foreign producer, render an incomplete exchange rate pass-through also in domestic exports. It is straightforward to extend the model to allow for this.

where y_t is total demand for domestically produced goods, and ξ_x is a constant measuring how marginal cost is affected by variable X in steady-state. Recognizing that the input price partly consists of imported products as well as domestically produced goods (see equation A7), it evolves according to $p_t^Z = (1-\kappa_W)\, p_t^D + \kappa_W\, p_t^M$, where p_t^D is the price of domestically produced goods, p_t^M the price of imported products (denoted in the buyer's currency), and κ_W the share of imported inputs. Furthermore, for simplicity, assume that the input prices enter multiplicatively in the cost function (i.e. $\xi_z = 1$). Assuming that the domestic producers also face quadratic price adjustment costs, equation (2) holds. Using the above, and inserting (7) into equation (2), yields

$$(8) \qquad \pi_t^D = \beta \mathrm{E}_t \pi_{t+1}^D + \frac{1}{\gamma_D}\left(\xi_y y_t + \kappa_W (p_t^M - p_t^D)\right) + \varepsilon_t^\pi ,$$

where inflation of domestically produced goods (π_t^D) responds positively to both aggregate output and the relative price of imports ($p_t^M - p_t^D$), the latter which can be interpreted as a direct real exchange rate effect on domestic inflation.[13] Recall, however, that the foreign price (p_t^M) is subject to a limited pass-through, via the nominal rigidities in the foreign producer's optimization problem, so that $p_t^M \neq \hat{p}_t^* + e_t$ in the short-run. As mentioned above, an exchange rate-induced increase in the price of import goods feeds back into domestic prices directly through the marginal cost (originating in intermediate foreign inputs), but also indirectly through the effect of relative price changes on aggregate demand. In addition, expectations about future inflation will be modified when the exchange rate changes. An explicit shock to domestic inflation, ε_t^π, has been added as an iid zero mean disturbance. This supply shock enters through shocks to the marginal cost, and consists of a productivity disturbance or a cost-push shock.

The foreign and domestic producers may face different costs of changing their prices, such that $\gamma_D \neq \gamma_M$, for example originating in some bias for one good over the other. Differing nominal price stickiness implies that the effect of an exchange rate movement on the relative price between foreign and domestic goods could be even stronger. Hence, this might possibly render consequences for the optimal policy as well as the inflation-output variability trade-off (see e.g. Walsh (1999)). Moreover, the exposure to the transmission channels of monetary policy differs

[13] See e.g. Hallsten (1999) for empirical evidence, where both the output gap and the real exchange rate enter positively in the supply relation, though with a lag.

between the domestic and foreign producers. In the model used here, domestic inflation responds to interest rate changes through the aggregate demand channel and (to some degree) through the exchange rate channel, while inflation of imported products only responds to exchange rate changes (see equations (8) and (5), respectively).[14]

Total, or CPI, inflation consists, by assumption, of a convex combination of domestic inflation (π_t^D) and import goods' inflation (π_t^M), following $\pi_t = (1-\kappa_M)\pi_t^D + \kappa_M \pi_t^M$, where κ_M denotes the import share of aggregate consumption. This is an approximation motivated by the underlying CES function, and a log-linearization of the corresponding aggregate price index (see Appendix A). Combining equation (5) and (8) yields

$$(9) \qquad \pi_t = \beta\, \mathrm{E}_t \pi_{t+1} + \alpha_Y y_t + \alpha_W (p_t^M - p_t^D) + \alpha_M (\hat{p}_t^* + e_t - p_t^M) + (1-\kappa_M)\varepsilon_t^\pi ,$$

where $\alpha_Y = (1-\kappa_M)\xi_y/\gamma_D$, $\alpha_W = (1-\kappa_M)\kappa_W/\gamma_D$, and $\alpha_M = \kappa_M/\gamma_M$. Note that ε_t^π only captures disturbances specific to the domestic market that do not originate in shocks to the inflation of import goods. The underlying foreign inflation shock, and disturbances to the exchange rate will, however, implicitly feed into the aggregate supply relation, through the variables $\hat{p}_t^*$ and e_t, respectively.

The short-run deviations from the law of one price, captured in the last term ($\hat{p}_t^* + e_t - p_t^M$), constitute the major difference between the aggregate supply relation in equation (9) and a standard open economy supply relation (see e.g. Svensson (2000)). As a result, exchange rate movements have an incomplete pass-through effect on total inflation.[15]

[14] In the case of a 'genuine' pricing to market model, where the markup endogenously responds to exchange rate movements, there would also be an effect of aggregate demand on the price of imports (see e.g. Naug and Nymoen (1996)).

[15] A complete pass-through supply relation is retrieved by assuming a fully flexible environment, $\gamma_M = 0$, such that $p_t^M = \hat{p}_t^* + e_t$ holds also in the short run, which implies that the last term in equation (9) would disappear. In addition, the last term seemingly vanishes if the domestic currency inflation of import goods does not contribute directly to total (CPI) inflation (i.e. $\kappa_M = 0$). However, if import goods enter domestic production as intermediate inputs ($\kappa_W > 0$), the price of imports, which is subject to a limited pass-though, affects marginal costs and consequently also domestic inflation. The corresponding aggregate supply curve must accordingly be different from a full pass-through relation, since the difference between the equilibrium price and the price actually charged (i.e. $\hat{p}_t^* + e_t - p_t^M$) is still fundamental for the foreign producer's price setting (see equation (5)).

2.2. Aggregate demand

Aggregate domestic consumption (c_t) consists of consumption of domestically produced goods (c_t^D) and consumption of imported goods (c_t^M), following a CES function (see equation (A1) in Appendix A). From the CES function follows that the domestic consumption of domestic goods must be given by (see also equation (A3) in Appendix A):

$$(10) \quad \begin{aligned} c_t^D &= c_t - \eta(p_t^D - p_t) \\ &= c_t + \eta\kappa_M (p_t^M - p_t^D), \end{aligned}$$

using $p_t = (1-\kappa_M)p_t^D + \kappa_M p_t^M$ (which is a log-linearization of equation (A2) in Appendix A).

The representative domestic consumer's intertemporal utility function is assumed to take the form:[16]

$$(11) \quad \begin{aligned} &\max_{\{C_{t+s}, B_{t+s}, B^*_{t+s}\}_{s=0}^{\infty}} \quad \mathrm{E}_t \sum_{s=0}^{\infty} \beta^s U(C_{t+s}^D, C_{t+s}^M) = \mathrm{E}_t \sum_{s=0}^{\infty} \beta^s \frac{(C_{t+s})^{1-\frac{1}{\sigma}} - 1}{1-\frac{1}{\sigma}} \\ &\text{s.t} \qquad P_t C_t + \frac{1}{1+I_t} B_t + \frac{1}{(1+I_t^*)(1+\phi_t)} B_t^* E_t = \Pi(Y_t, P_t^D) + B_{t-1} + B_{t-1}^* E_t\ , \end{aligned}$$

where C_t is the CES aggregate of consumption of domestic and imported goods. σ is the constant intertemporal elasticity of substitution, B_t denotes (end of period t) bond holdings denominated in domestic currency units, and I_t is the nominal domestic interest rate implying that $1/(1+ I_t)$ is the price of a domestic bond. B_t^* represents (the domestic consumers') foreign currency bond holdings, which are sold at a risk-adjusted price, $1/[(1+ I_t^*)(1+\phi_t)]$, where ϕ_t is a risk premium that will reflect temporary deviations from uncovered interest rate parity (see McCallum and Nelson (1999)), and I_t^* is the nominal foreign interest rate. $\Pi(Y_t, P_t^D)$ are profits from production with Y_t denoting aggregate output (which is equal to total demand for domestically produced goods). Government transfers and money holdings are disregarded, and the domestic producers are assumed to follow the law of one price on their export markets,

[16] Assuming the function to be separable in consumption and leisure, the marginal utility of consumption is only dependent on the level of consumption, thereby making any disutility of production (or labor) superfluous for the purposes here.

implying a complete pass-through.[17] The first order condition with respect to consumption implies an Euler equation of the form

$$(12) \qquad c_t = \mathrm{E}_t c_{t+1} - \sigma(i_t - \mathrm{E}_t \pi_{t+1}),$$

where i_t is the (log) short-term nominal interest rate, which is assumed to be the monetary policy instrument. Inserting (10) into (12) yields

$$(13) \qquad c_t^D = \mathrm{E}_t c_{t+1}^D - \eta \kappa_M (\mathrm{E}_t \pi_{t+1}^M - \mathrm{E}_t \pi_{t+1}^D) - \sigma(i_t - \mathrm{E}_t \pi_{t+1}).$$

Since the domestic goods are traded, aggregate demand (Y_t) for domestically produced goods is given by the sum of domestic and foreign demand (C_t^D and C_t^{D*}, respectively). A log-linear approximation around steady-state yields; $y_t = (1-\kappa_D)c_t^D + \kappa_D c_t^{D*}$, where κ_D is the export (steady-state) share of total demand for the domestic good. Foreign demand for domestic goods follows, $c_t^{D*} = -\eta(p_t^D - e_t - \hat{p}_t^*) + a_y^* y_t^*$, where a_y^* denotes the income elasticity of foreign consumption (see also equation (A8) in Appendix A). Inserting this and equation (13) into the aggregate demand relation implies

$$(14) \qquad \begin{aligned} y_t &= \mathrm{E}_t y_{t+1} + (1-\kappa_D)\left(-\kappa_M \eta \mathrm{E}_t(\pi_{t+1}^M - \pi_{t+1}^D) - \sigma(i_t - \mathrm{E}_t \pi_{t+1})\right) - \kappa_D\left(\mathrm{E}_t c_{t+1}^{D*} - c_t^{D*}\right) + \varepsilon_t^y \\ &= \mathrm{E}_t y_{t+1} - \beta_q \mathrm{E}_t\left(\pi_{t+1}^M - \pi_{t+1}^D\right) - \beta_i\left(i_t - \mathrm{E}_t \pi_{t+1}\right) + \beta_e\left(\mathrm{E}_t \pi_{t+1}^D - (\mathrm{E}_t e_{t+1} - e_t) - \mathrm{E}_t \hat{\pi}_{t+1}^*\right) \\ &\quad - \beta_y^*\left(\mathrm{E}_t y_{t+1}^* - y_t^*\right) + \varepsilon_t^y, \end{aligned}$$

where $\beta_q = \kappa_M \eta(1-\kappa_D)$, $\beta_i = \sigma(1-\kappa_D)$, $\beta_e = \kappa_D \eta$, and $\beta_y^* = \kappa_D a_y^*$. ε_t^y has been added as an iid zero mean disturbance to domestic demand. This could be motivated by a shock to domestic preferences that shifts aggregate demand. The difference between this demand relation and a full pass-through demand curve is the implicit deviation from the law of one price (i.e. $p_t^M \neq \hat{p}_t^* + e_t$), which makes the relative price of imports ($p_t^M - p_t^D$) diverge from the (inverse) relative price of exports ($p_t^D - e_t - \hat{p}_t^*$). Due to different degrees of price stickiness across markets, an exchange rate change affects demand differently in the domestic and foreign markets. At first glance, some of the signs of the coefficients might seem surprising. For

[17] Changing any of these assumptions would not alter the consumers' Euler equation.

example, an expected future depreciation has a negative effect on today's output. However, some intertemporal substitution is at hand, but also expectations about future output and future inflation rates change, and thus, the effect on today's output is ambiguous. Recall furthermore that the complete model consists of a simultaneous system of equations, why analyzing separate coefficients in one equation might be of limited interest.[18]

2.3. Parity and foreign conditions

Combining the first order conditions for domestic and foreign currency bond holdings (see equation (11)), assuming perfect capital mobility, implies that the exchange rate fulfills a modified uncovered interest rate parity (UIP) condition:

(15) $$i_t - i_t^* = \mathrm{E}_t e_{t+1} - e_t + \phi_t ,$$

where ϕ_t is the risk premium that creates deviations from UIP. Since anything that influences this interest rate differential also affects the exchange rate (such as foreign interest rate disturbances, e.g. originating in foreign inflation and output shocks, or disturbances to the domestic interest rate), it is hard to distinguish a 'genuine' exchange rate shock that is not a reaction to some other underlying disturbance in the model. A shock to the risk premium can, however, be interpreted as capturing an autonomous disturbance to expectations about future exchange rate changes (e.g. due to some exogenous change in perceived risk), resulting in a 'pure' exchange rate shock.

Moreover, the domestic economy is assumed to be small, relative to the rest of the world, so that foreign output (working as a demand shifter), and inflation of foreign products (that is, the change in marginal cost; see equation (4)) are taken as exogenously given. These variables are assumed to follow AR(1) processes:

(16) $$y_{t+1}^* = \rho_y^* y_t^* + u_{t+1}^{y^*} ,$$

[18] Note that the relative price *level* affects the intratemporal allocation between consumption of imports and domestic goods, while the *change* in relative price affects the intertemporal consumption decision (see equations (10) and (13), respectively). However, observe additionally that all difference terms disappear when solving equation (14) forward;

$$y_t = \beta_q (p_t^M - p_t^D) - \beta_i \sum_{s=0}^{\infty} \mathrm{E}_t (i_{t+s} - \pi_{t+s+1}) - \beta_e (p_t^D - e_t - \hat{p}_t^*) + \beta_y^* y_t^* + \sum_{s=0}^{\infty} \mathrm{E}_t \varepsilon_{t+s}^y ,$$

using the appropriate transversality conditions.

(17) $\hat{\pi}^*_{t+1} = \rho^*_{\pi}\hat{\pi}^*_t + u^{\pi^*}_{t+1}$,

where the coefficients are non-negative and less than unity. The shocks are uncorrelated zero mean iid disturbances with variance σ^2_{y*} and $\sigma^2_{\pi*}$, respectively. The foreign interest rate is assumed to follow a simple Taylor rule with some persistence added, that is, a linear function of foreign inflation, output and the lagged interest rate (see e.g. Clarida et al. (1998)):

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

where the coefficients are constant and positive, and ρ_i^* specifies the degree of interest rate smoothing. u_t^{i*} is a zero mean iid shock, with variance σ^2_{i*}, capturing foreign monetary policy disturbances.

The exogenous shocks to domestic inflation and output (added to equations (8) and (14)) and to the exchange rate (i.e. the risk premium shock in equation (15)), are assumed to follow

(19a) $\varepsilon^{\pi}_{t+1} = \tau_{\pi}\varepsilon^{\pi}_t + \upsilon^{\pi}_{t+1}$,

(19b) $\varepsilon^{y}_{t+1} = \tau_{y}\varepsilon^{y}_t + \upsilon^{y}_{t+1}$,

(19c) $\phi_{t+1} = \tau_{\phi}\phi_t + \upsilon^{\phi}_{t+1}$,

where the disturbances are zero mean iid shocks with variance σ^2_{π}, σ^2_{y}, and σ^2_{ϕ}, respectively. All coefficients are positive and less than one. The shocks entering the economy are thus not permanent, but persistent. Since there are no backward-looking components in the aggregate supply or aggregate demand curves, the persistence in inflation and output is thus entirely due to the serially correlated exogenous shocks.[19]

[19] Endogenous persistence in the inflation of foreign and domestic goods could though be justified by simply assigning an adjustment cost to the speed of changing price (i.e. including a cost of changing inflation in equation (1)). However, Hallsten (1999) shows that this backward-looking component in the inflation relation lacks significance for Swedish data. For the aggregate demand relation, the consumer's utility function does not motivate any endogenous persistence without an assumption of either some sort of adjustment costs or habit formation (see e.g. Svensson (2000), and McCallum and Nelson (1999)).

2.4. The central bank's loss function

The central bank's objective is to stabilize both inflation and output (as in e.g. Svensson (2000)). It chooses a path for the policy instrument, the short-term interest rate i_t, in order to minimize its intertemporal loss function, which is quadratic in the deviations of inflation and output from their constant targets (here normalized to zero, for simplicity).[20] The central bank assumes the output target to be equal to the natural output level, such that there is no inflation bias (i.e. no deviation of average inflation from the constant inflation target). The central bank's optimization problem is

(20a) $$\min_{\{i_{t+s}\}_{s=0}^{\infty}} \ \mathrm{E}_t \sum_{s=0}^{\infty} \delta^s L_{t+s} \ ,$$

(20b) $$L_t = \left[\pi_t^2 + \lambda (y_t)^2 + \nu_i (i_t - i_{t-1})^2 \right],$$

where L_t is the period loss function. λ measures the relative weight on output stabilization, ν_i corresponds to the weight on interest rate smoothing, and δ is a discount factor. $\lambda > 0$ implies that the central bank does not immediately force the inflation rate back to the long-run target after a given shock, but adjusts the instrument less and hence gradually brings the inflation rate into line with the targeted level. The higher is λ, the slower is the adjustment of the inflation rate.

Even if the central bank's objective is only to stabilize inflation and output, interest rate smoothing can be optimal due to data and model uncertainty, i.e. measurement errors in the data, and uncertainty about the economic structure and the transmission of monetary policy, respectively, (see e.g. Sack and Wieland (1999)). Another motivation is the central bank's concern for financial stability. Furthermore, with forward-looking behaviour, a gradual and persistent adjustment of the short interest rate induces expectations about future interest rate changes. This implies a larger effect on the long rates, thereby also yielding a substantial impact on aggregate demand, without sizeable short interest rate variability (Woodford (1999)). In that case, interest rate smoothing ($\nu_i > 0$) can be interpreted as a way of bringing the discretionary outcome closer to the outcome under commitment, where expectations of future policy matters.

The state-space representation of the model (i.e. equations (5), (8), (9) and (14)-(19); see also Appendix B) follows

$$(21)\qquad \tilde{A}_0\begin{bmatrix} x_{1,t+1} \\ \mathrm{E}_t x_{2,t+1} \end{bmatrix} = \tilde{A}\begin{bmatrix} x_{1,t} \\ x_{2,t} \end{bmatrix} + \tilde{B}i_t + \tilde{\upsilon}_{t+1},$$

$$x_{1,t} = \begin{bmatrix} i_{t-1} & y_t^* & i_t^* & \hat{\pi}_t^* & \varepsilon_t^{\pi} & \varepsilon_t^{\phi} & \varepsilon_t^{y} & (p_{t-1}^M - p_{t-1}^D) & (\hat{p}_{t-1}^* + e_{t-1} - p_{t-1}^M) \end{bmatrix}',$$

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

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

where $x_{1,t}$ is a 9×1 vector of predetermined state variables, $x_{2,t}$ is a 4×1 vector of forward-looking variables, and $\tilde{\upsilon}_{t+1}$ is a 13×1 vector of disturbances. This implies that the intertemporal control problem can be expressed as a stochastic linear quadratic regulator problem:

$$(22)\qquad J(x_t) = \min_{i_t}\left\{ x_t'\tilde{Q}x_t + \delta\,\mathrm{E}_t J(x_{t+1}) \right\}.$$

Consider the discretionary case where the policy maker reoptimizes every period, taking expectations about future policy outcomes as given (i.e. independent of the current choice of the short interest rate). The central bank thus lacks commitment mechanisms. Since the objective function is quadratic and the constraint linear, the value function of the Bellman equation will be quadratic in the predetermined state variables, $x_{1,t}'V_t x_{1,t} + \omega_t$, and the forward-looking variables will be a linear function of the predetermined variables, $x_{2,t} = Hx_{1,t}$, (see e.g. Söderlind (1999)). In that case, the central bank's optimal reaction function will be to set the short interest rate as a linear function of the predetermined state variables (see Appendix B):[21]

$$(23)\qquad i_t = -Fx_{1,t},$$

where the policy reaction coefficients (F) are determined by iterating on the value function. The optimal policy is certainty equivalent, such that it is independent of the distribution of the

[20] Note that the Rotemberg (1982), as well as the Calvo (1983), pricing framework per se implies that monetary policy can affect the mean of output. However, the objective function of the central bank stabilizes the model. This yields a stationary inflation rate, implying that the policy maker does not influence the average output level.

[21] In the commitment case, the optimal policy additionally depends on the shadow prices of the forward-looking variables.

disturbances, and thus only the expected value of the state variables are of importance (see e.g. Currie and Levine (1993)).

A policy change in the nominal interest rate is transmitted into the model economy through two channels, via the real interest rate and via the exchange rate, which is affected by all (nominal) interest rate changes. Both channels affect aggregate demand, and thereby indirectly influence inflation, but the exchange rate also affects inflation directly through changes in the price of imports (see equations (14) and (9), respectively). The degree of pass-through will hence influence how monetary policy is transmitted via the exchange rate channel.

The model is solved using numerical methods and consequently, needs to be parameterized. The values for the model parameters shown in Table 1 are selected along the lines of Svensson (2000), without any attempt to calibrate or estimate the model.

Table 1: Parameterization

Central bank loss function	Supply relations	Demand relation	Foreign Taylor rule	Shock persistence	Shock variance
$\lambda = 0.5$	*price stickiness:*	*consumer utility function:*	$b_\pi^* = 1.5$	$\tau_\pi = 0.8$	$\sigma_\pi^2 = 1$
$\nu_i = 0.1$	$\gamma_M = \{0.01, 0.5, 2, 100\}$	$\eta = 6$	$b_y^* = 0.5$	$\tau_\phi = 0.8$	$\sigma_y^2 = 1$
$\delta = 0.99$	$\gamma_D = 10$	$\sigma = 0.5$	$\rho_i^* = 0.8$	$\tau_y = 0.8$	$\sigma_\phi^2 = 1$
	foreign influence:	$\beta = 0.99$			$\sigma_{y^*}^2 = 1$
	$\kappa_M = 0.3$	*foreign economy elements:*			$\sigma_{\pi^*}^2 = 1$
	$\kappa_W = 0.1$	$\kappa_D = 0.3$			$\sigma_{i^*}^2 = 1$
	production function:	$a_y^* = 0.9$			
	$\xi_y = 0.8$	$\rho_y^* = 0.8$			
	producer discount rate:	$\rho_\pi^* = 0.8$			
	$\beta = 0.99$				

These parameters imply a discount factor yielding an annual interest rate of 4% (assuming a quarterly model), a price elasticity of demand generating a 20 % markup over marginal cost, an import share consisting of 30 % of total consumption, and an export share of 30 % of aggregate demand. The rate of nominal rigidity (γ_M), or import price stickiness, is chosen such that the degree of pass-through captures the standard open economy case of almost full pass-through, two intermediate cases of incomplete pass-through, and one case of approximately no pass-through, hence basically approaching a closed economy setting. The intermediate pass-through cases appear most relevant for small open economies, since the empirical evidence typically suggests that the degree of exchange rate pass-through is in the range of 20-80% (see e.g.

Menon (1996) for a survey of the empirical literature).[22] The domestic price stickiness (γ_D), in turn, is chosen to obtain a reasonable output elasticity in the aggregate supply relation.

3. Policy responses under different degrees of pass-through

The optimal discretionary policy is examined, under different degrees of pass-through, in terms of reaction functions, the inflation-output variability trade-off, and the overall variation in some key variables. To describe the effects of incomplete exchange rate pass-through on the central bank's reaction, and its implications, simple impulse response exercises are carried out when foreign and domestic disturbances hit the economy.

3.1. Exchange rate pass-through

The term 'exchange rate pass-through' is generally used to characterize the percentage change in import prices, caused by an unidentified shock to the exchange rate. However, the degree of pass-through possibly depends on whether this exchange rate movement is caused by a 'genuine' exchange rate shock, or whether some other disturbance to the economy generates an implicit exchange rate change. If, for example, different shocks have different degrees of persistence, this will affect the resulting degree of pass-through. The pass-through is also dependent on whether it is defined as partial - only measuring the direct effect on the price relation, excluding the effect on other variables - or total - determining the entire effect an exchange rate change causes, working through every interaction of the price determination.[23] Moreover, in the model used here, incomplete pass-through is caused by nominal rigidities, and thus, the pass-through additionally depends on the structural parameter governing the price stickiness (i.e. γ_M).

[22] Even though all pass-through coefficients resulting from the chosen γ_Ms seem reasonable, some reservation could possibly be raised regarding the largest structural parameter, $\gamma_M = 100$. Roberts (1995) reports estimates of 0.25 to 0.36 for (β / γ_i), where β denotes the supply elasticity of the product, using survey data for the US. A structural parameter of $\gamma_M = 100$ would, in that case, require a supply elasticity of 25-36, which seems rather far-fetched.

[23] Apart from the exchange rate, the import price in this model is only dependent on the exogenously given foreign price ($\hat{p}_t^*$), which is not affected by any exchange rate changes. However, a movement in the exchange rate might additionally affect expectations about future import prices, and thus, the partial and total pass-through need not be equivalent;

$$\frac{\partial p_t^M}{\partial e_t} \neq \frac{dp_t^M}{de_t} = \frac{\partial p_t^M}{\partial e_t} + \frac{\partial p_t^M}{\partial p_{t+1}^M}\frac{dp_{t+1}^M}{de_t},$$

see equation (5).

The degree of pass-through is thus contingent upon a row of factors and assumptions. In Table 2 the resulting contemporaneous pass-through, for different choices of the structural import price stickiness (γ_M), and alternative sources of exchange rate movements, is displayed. Pass-throughs caused by identified structural shocks, as well as initiated by unspecified exchange rate movements, are presented. The latter, 'unspecified', (partial) pass-through category is derived directly from the price setting relation in equation (5), while the 'identified' (total) pass-through characterization is derived from simulations of the entire model and the actual responses of the import price level and the exchange rate, when different types of shocks enter the economy. As the nominal rigidity increases (larger γ_M), the exchange rate pass-through becomes smaller, no matter what type of shock hits the economy (see Table 2). Consequently, although the import price stickiness parameter (γ_M) directly determines only the partial pass-through, the relation between the nominal rigidity and the total (as well as partial) pass-through is monotonic. The unspecified, or partial, pass-through is somewhat smaller than the total pass-through caused by identified shocks. This difference is most evident when the nominal rigidity is large, or equivalently, when pass-through is small. Risk premium shocks (i.e. exchange rate shocks) and domestic demand shocks imply a total pass-through fairly similar to the unspecified partial pass-through, while domestic cost-push shocks, in contrast, appear to render a much larger total pass-through. The reason is that the domestic cost-push disturbance is the most costly shock in terms of the size and persistence of the inflationary impulse. Since the price adjustment is gradual, this also induces higher expectations about future inflation which, in turn, increases the total exchange rate pass-through. Further, the total pass-through is negative for the foreign cost-push shock, since it yields an import price increase at the same time as the foreign policy reaction induces an exchange rate appreciation.

Table 2: Partial and total pass-through under different degrees of price stickiness; (contemporaneous responses, $\Delta p_t^M / \Delta e_t$)

Structural price stickiness	Partial pass-through, *unspecified* Δe_t	Total pass-through derived from a:				
		risk premium shock	*foreign inflation shock*	*foreign demand shock*	*domestic cost-push shock*	*domestic demand shock*
γ_M	$\frac{1}{1+\gamma_M}$	v_t^{ϕ}	$u_t^{\pi *}$	$u_t^{y *}$	v_t^{π}	v_t^{y}
0.01	0.99	0.987	-0.624	0.991	0.998	0.989
0.5	0.66	0.675	-0.556	0.742	0.929	0.682
2	0.33	0.402	-0.461	0.498	0.811	0.411
100	0.01	0.034	-0.098	0.065	0.237	0.035

Note: The partial pass-through, caused by an unspecified exchange rate movement, is constructed from equation (5) by solving for the price level of import goods, assuming that the expectations of future inflation are zero (i.e. the partial derivative with respect to the exchange rate). The total pass-through is derived from simulations of the entire model under identified shocks to the system.

It is believed that price setters respond differently to temporary and permanent exchange rate movements (see e.g. Froot and Klemperer (1989)). Transitory exchange rate movements are expected to result in low pass-through, or no pass-through at all, while permanent exchange rate changes are believed to yield larger import price responses. In the model used here, this can be examined using different degrees of persistence in the risk premium disturbance (τ_{ϕ}). A highly persistent risk premium shock will induce larger and more persistent exchange rate movements. Figure 1 displays the total exchange rate pass-through under varying assumptions about the risk premium persistence. The total pass-through seems to be increasing in the degree of persistence, irrespective of the amount of price stickiness. Consequently, transitory exchange rate changes yield lower import price responses than more persistent movements in the exchange rate do. This occurs because the costly price adjustment implies gradual price changes, based on expectations about the future development of the exchange rate (see Footnote 11). With transitory exchange rate movements, the incentives for a gradual price adjustment towards the new short-lived equilibrium price, will thus be smaller.[24] However, the range in which the degree of pass-through fluctuates appears to be predominantly contingent upon the degree of import price stickiness. With low nominal rigidity, also a temporary exchange rate change induces a quite large pass-through, while the opposite is true for large price stickiness and permanent exchange rate changes (cf. Figures 1a and 1d).

[24] Note, however, that also the initial exchange rate movement becomes smaller when the risk premium persistence is low. A smaller exchange rate movement implies, per se, that the price adjustment is relatively more expensive, since the deviation from the equilibrium flex price is small, thereby inducing lower pass-through.

3.2. Pass-through and exchange rate volatility

Prior empirical literature has related evidence of incomplete exchange rate pass-through to, for example, the considerable amount of observed short-run nominal exchange rate volatility and costs of changing prices. In contrast to these studies, where exchange rate movements are treated as exogenous, the nominal exchange rate is determined endogenously in this model. Moreover, by here treating the degree of price stickiness as exogenously given, the causality between pass-through and the nominal exchange rate volatility can be examined more closely.

Given the central bank's objective of targeting inflation (as well as some output and interest rate stabilization), the price levels of domestic and foreign goods are not controlled in this type of model.[25] As long as the inflation rate is stabilized, the price levels are assumed to be irrelevant to the policy maker, whatever they happen to be. Consequently, the exchange rate level is non-stationary within this system. The interest rate parity condition governing the exchange rate's development in equation (15) only pins down the expected exchange rate *change*, disregarding the *level* of the exchange rate. Consider for example a positive risk premium shock. Although the shock eventually expires, it depreciates the exchange rate permanently (see Figure 2d). The law of one price for imported goods is satisfied in the long run, which implies that a cointegrating relation between the foreign and domestic prices determines the limit of the exchange rate. The exchange rate must balance the difference between the import price denoted in the domestic currency (p_t^M), that is permanently affected (i.e. raised) by the shock, and the foreign currency price ($\hat{p}_t^*$), which is exogenously determined and thus, not reacting to the risk premium shock.[26] Consequently, the exchange rate stays permanently depreciated, and as its new steady-state level does not induce any further inflationary impulses, the policy maker must be indifferent to such a movement.

In addition, the exchange rate responds more to the risk premium shock when the degree of pass-through is low, and the initial depreciation is hence larger. For all shocks except foreign cost-push shocks, the common feature seems to be that the initial movement in the exchange rate becomes larger as pass-through decreases (see e.g. Figure 4d). Furthermore, the

[25] This is thus not specific to the setting used here, but typical for all inflation targeting models.

[26] In this model, the law of one price states that, $(\hat{p}^* + e - p^M) \sim I(0)$. This cointegrating relation enters through equation (5), given that $\pi^M \sim I(0)$. Together with the unaltered foreign currency price, this implies that;

$$\lim_{s \to \infty} \mathrm{E}_t e_{t+s} = \lim_{s \to \infty} \mathrm{E}_t p_{t+s}^M .$$

unconditional variance of the exchange rate difference clearly increases when pass-through decreases (see Table 3). The volatility in the exchange rate is thus negatively related to the degree of pass-through. The reason is that the prices of foreign and domestic products are *exogenously* rigid in this model and can not costlessly absorb a shock. This implies that a large exchange rate response is required when there is a country-specific shock, in order to create the necessary adjustment of the relative price between foreign and domestic products.[27] Hence, since the exchange rate is *endogenously* determined, the structural pass-through parameter (γ_M) will affect the development of the exchange rate. In that case, as pass-through decreases, that is as the nominal rigidity increases, the exchange rate is expected to fluctuate more because part of the relative price adjustment is accomplished through the exchange rate (as in Betts and Devereux (2000)).[28]

Table 3: Unconditional variances

Partial pass-through	var(π)	var(π^D)	var(π^M)	var(y)	var(Δe)	var($p^M - p^D$)	var(i)
0.99	54.649	54.717	56.685	2.088	58.556	9.662	41.585
0.66	54.415	54.926	54.637	1.745	60.505	8.824	40.984
0.33	53.17	54.621	50.824	1.393	63.229	9.803	40.255
0.01	24.996	34.731	11.342	0.246	66.778	379.86	34.611

Note: See Appendix B for the variance-covariance matrix, and calculations of the asymptotic variances.

A larger degree of nominal import price stickiness (i.e. lower pass-through) does not necessarily imply larger real volatility in this model. Rather, the unconditional variance of output appears to be increasing in the degree of pass-through (see Table 3). The reason behind this somewhat surprising result is probably the fact that output is directly affected by the degree of pass-through. Larger price rigidity induces lower pass-through, which, in turn, implies less exposure to foreign shocks through the exchange rate channel. Consequently, output is less sensitive to such disturbances when pass-through is low. Besides, if prices are less affected by the shock, the smaller is the required output adjustment.[29] Moreover, this induces fewer interest rate adjustments overall, and the interest rate volatility is therefore increasing in the degree of pass-through.

[27] Given the quadratic adjustment costs, a larger exchange rate movement implies that the producer is further away from the equilibrium flex price, which makes the price adjustment relatively cheaper (see equation (1)).

[28] Still, the relative price of imports moves less as the nominal rigidity increases (see e.g. Figure 2g). However, if the exchange rate did not fluctuate more in those cases, the relative price adjustment would perhaps be even smaller.

[29] Then again, this result is consistent with the findings of De Long and Summers (1986). They show that an increased price flexibility may increase the steady-state variance of output as long as the current price level and expectations about future price changes affect output in different directions.

3.3. Policy reaction function

The policy reaction function is explicitly derived from the central bank's objective function in equation (20). This implies that the policy maker does not restrict her use of information, but acts optimally and responds directly to inflationary impulses, such as, for example, a risk premium shock. This yields a policy rule, or reaction function, that does not resemble a simple Taylor rule. A simple Taylor rule implies that the central bank reacts on certain variables, like inflation and output, in contrast to responding to direct shocks. Consequently, the Taylor policy maker merely adjusts the interest rate indirectly to a disturbance, as it is reflected in inflation or output.

Consider once more a shock to the exchange rate through a positive risk premium disturbance. As expected, less price stickiness (larger pass-through) results in stronger inflationary impulses, and thereby also larger interest rate responses (see Figures 2a and 2c). This follows from the central bank's reaction function, where the response coefficient on the risk premium shock becomes larger as pass-through increases (see Table 4). Hence, this implies the largest policy adjustment when the effect of the exchange rate shock is the greatest, that is, in the full pass-through case. Recall, on the other hand, that the exchange rate volatility decreases as pass-through increases. However, since the policy maker reacts on the risk premium (ϕ_t), and not on the exchange rate (e_t) per se, this does not directly affect the interest rate response.

Furthermore, note that the reaction on the lagged interest rate is decreasing in the degree of pass-through (see Table 4). This reflects that a smaller pass-through requires a more persistent interest rate response, since the effect of an exchange rate movement is more prolonged in this case. Nevertheless, the interest rate persistence is also implicitly incorporated in the reaction function through the persistence in other variables, and the policy maker's response to these variables. Take, for example, the lagged relative price of imports ($p_{t-1}^{M} - p_{t-1}^{D}$), which enters with a positive coefficient. Since a high lagged relative price indicates that the lagged inflation, and thereby also the lagged interest rate, is large, some of the interest rate smoothing is induced in this way.

The reaction coefficients on the risk premium shock, and on foreign output, inflation, and interest rate, are all increasing in the degree of pass-through. As pass-through increases, the inflationary impulses become larger which, in turn, requires larger interest rate adjustments. In contrast to these foreign variables, the response coefficients on the domestic demand and cost-push disturbances (i.e. ε_t^y and ε_t^π) are decreasing in the degree of pass-through (see Table 4). The interest rate adjustment to domestic shocks is thus larger when pass-through is low (see e.g. Figure 5c). The reason for this is the effect working through the exchange rate channel, which transmits monetary policy to a greater extent, the larger pass-through is. Consider, for example, a positive domestic demand shock. To counter this demand disturbance, the interest rate is raised, implying a concurrent appreciation of the exchange rate which, in turn, induces lower inflation of imported goods (π^M) (see Figure 5). As pass-through increases, the appreciation feeds into import prices to a greater extent. Consequently, this counteracts the demand disturbance more, which requires less adjustment of the interest rate when pass-through is complete. In this case, the exchange rate thus works as a shock absorber, with larger impact, the larger pass-through is. Overall, the flipside is a larger exposure to foreign disturbances when the exchange rate pass-through becomes more complete.[30]

Table 4: Reaction function of the policy maker; coefficients in $-F$ ($i_t = -Fx_{1,t}$)

Partial pass-through	i_{t-1}	y_t^*	i_t^*	$\hat{\pi}_t^*$	ε_t^π	ε_t^ϕ	ε_t^y	$(p_{t-1}^M - p_{t-1}^D)$	$(\hat{p}_{t-1}^* + e_{t-1} - p_{t-1}^M)$
0.99	0.015	0.034	0.913	-0.66	3.523	0.913	0.192	-0.024	0
0.66	0.025	0.025	0.842	-0.655	3.503	0.842	0.36	0.067	0
0.33	0.033	0.022	0.797	-0.647	3.529	0.797	0.46	0.12	0
0.01	0.038	0.029	0.796	-0.623	3.688	0.796	0.446	0.109	0

That the direct reaction on the wedge term ($\hat{p}_{t-1}^* + e_{t-1} - p_{t-1}^M$) is zero should not be interpreted as the nonexistence of a policy response to deviations from the law of one price (see Table 4). Rather than responding directly to the wedge term, recall that the central bank reacts to the underlying components, such as foreign inflation ($\hat{\pi}_t^*$), and the risk premium (ϕ_t). Note additionally that the central bank responds to all disturbances, permanent as well as temporary, in the absence of transmission lags of monetary policy.

[30] In contrast, for domestic cost-push shocks the exchange rate, surprisingly, counteracts the policy maker's objective of bringing down inflation, since it depreciates and thus adds to the inflationary impulse.

3.4. Policy trade-offs

In a closed economy the policy maker can, in general, entirely wipe out a domestic demand shock by simply raising the interest rate, without affecting output and inflation.[31] In contrast, for the open economy case here, the policy maker can not counter a demand shock by raising the interest rate, without also affecting the exchange rate and thereby, inflation. Consequently, the demand shock can not be completely neutralized, and the central bank is forced to trade off output variability for reduced inflation variability (see Walsh (1999) for a discussion of these matters). Hence, the policy maker faces a trade-off not only when the economy is hit by cost-push shocks but also by, for example, demand and exchange rate disturbances (see Figure 7). However, exchange rate disturbances, domestic demand shocks, as well as foreign demand and inflation shocks, generate much less variance in both inflation and output for equal shock magnitudes, compared to the domestic cost-push shocks. As the economy is hit by a combination of shocks, most of the unconditional variance in inflation and output therefore originates from the domestic cost-push disturbances.[32,33] Nevertheless, the policy maker still faces a trade-off between inflation and output variability for the other shocks, but in a different scale than for the domestic cost-push shock. If the variance of, for example, an exchange rate disturbance were larger, the trade-off curve would be located further away from the origin. Still, in the model used here, the exchange rate disturbance (or any other of the 'minor' shocks) must be outsized by orders of magnitude, so as to generate the same dimension of inflation and output variability as caused by a domestic cost-push shock. Consequently, these results imply that cost-push shocks are not the only shocks that should be offset by the central bank (in contrast to the closed economy; see Clarida et al. (1999)). Nonetheless, the cost-push shocks appear to be the most 'costly' disturbances, which require firmer interest rate responses.

How is the inflation-output variance trade-off affected by the exchange rate pass-through? As pass-through decreases, the exchange rate channel becomes less important in transmitting policy, implying that, for example, a domestic demand shock involves a less severe conflict

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[31] Note that this is not the case if the policy maker's objective function penalizes interest rate changes.

[32] See Appendix B for the variance-covariance matrix. The variances of all shocks are, by assumption, identical and set to one, making the shock vector equal to; $\upsilon_0 = \begin{bmatrix} 0 & 1 & (1+(1-\rho_i)(b_y^* + b_\pi^*)) & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}'$. The assumption that all structural shocks have the same variance might be excessively restrictive in 'reality'. However, the domestic cost-push shock is the primary source of inflation and output variability, also when allowing for different variances in the disturbances.

[33] Recall that only the magnitude of the loss function, and the inflation-output trade-off, are affected by the size of the shocks. The policy maker's reaction function is certainty equivalent and thus, independent of the disturbances' covariance matrix.

between stabilizing inflation or output. An interest rate change still yields an exchange rate movement, but this movement does not pass-through to prices to the same extent. An open economy with incomplete pass-through thus obtains some of the characteristics of a closed economy setting, which makes the trade-off between inflation and output variability less considerable. Furthermore, when pass-through is small, autonomous exchange rate disturbances will have less impact on the economy, which makes both inflation and output variances smaller. These effects, running through the exchange rate - the less serious conflict between policy objectives, and the lower exposure to foreign shocks - together imply that also the inflation-output variability trade-off in the face of a combination of shocks will be located closer to the origin (see Figure 8). For a given output variability, the inflation variance is thus smaller when the exchange rate pass-through is low. However, quantitatively, the degree of pass-through seems to have a rather small effect on the inflation-output variability frontier. The difference in central bank loss is, for example, less than 3% between the case with 99% partial pass-through and the case with 33% partial pass-through (not shown).

3.5. Robustness issues

How is monetary policy affected by the degree of openness in the economy, and what does this imply in terms of, for example, inflation and output variability? A more open economy implies that the exposure to foreign disturbances increases, and that the exchange rate channel plays a more important role in the monetary policy transmission. Recall that a larger exchange rate pass-through has similar implications, why openness and pass-through are somewhat related questions, although their specific mechanisms work differently. In this model, the degree of openness is captured through three different parameters, the import and export shares (κ_M and κ_D, respectively), and the share of imported intermediate inputs in production (κ_W). For instance, increasing the import share of consumption (κ_M) implies that deviations from the law of one price more significantly affect total (CPI) inflation, as is the case when pass-through becomes larger. However, a more open economy also implies that the real exchange rate directly influences both inflation and output to a greater extent (see e.g. equation (9)).

The results discussed above mostly appear to be qualitatively robust to changing the degree of openness. For example, the exchange rate volatility is decreasing in the degree of pass-through, and the policy reaction to a risk premium disturbance decreases as pass-through decreases, irrespective of the degree of openness.[34] Note, however, that the size of the reaction coefficients and the resulting variability change as the degree of openness changes (see Tables C1 and C2 in Appendix C). In analogy with the complete pass-through case, a more open economy implies larger policy reactions to foreign disturbances, since their impact on inflation and output is larger in this case. In contrast, the policy response to domestic disturbances appears to decrease when the economy becomes more open. This also affects the variability in the economy. The exchange rate volatility becomes lower as the degree of openness increases. Given that foreign shocks influence, for example, domestic prices to a greater extent in this case, there is less need for exchange rate induced relative price adjustments.[35] Consequently, the variability in nominal and real exchange rates is smaller when the economy is more open. Nonetheless, the output volatility is, in contrast, increasing in the degree of openness. This occurs because the impact of foreign shocks is larger when the economy is more open, with a greater influence on prices, which also requires larger adjustments in output. Stabilization is thus provided through output rather than via real exchange rate movements.

4. Conclusions

A small open economy aggregate supply-aggregate demand model, allowing for incomplete exchange rate pass-through, has been developed to analyze the effects of limited exchange rate pass-through on monetary policy. Solving for the endogenous policy response to foreign and domestic shocks, indicates that the optimal policy reaction and its implications are dependent on the degree of pass-through. Exchange rate pass-through, in turn, is contingent upon many factors and assumptions. In this model, incomplete pass-through is incorporated through the exogenously imposed nominal import price stickiness. However, pass-through is additionally dependent on what type of shock enters the economy. The results suggest that transitory exchange rate movements yield lower import price responses than persistent movements. Consequently, pass-through is increasing in the degree of shock persistence. Nonetheless, the predominant source for incomplete pass-through appears to be the degree of price stickiness, rather than the degree of shock persistence.

[34] The results are also robust to changes in other parameters, such as, for example, the degree of substitutability between goods, and the amount of exogenous persistence in the disturbances. Changing the variance-covariance matrix, for instance to allow for different variances in the disturbances, does not affect the main results either.

[35] Compare with the complete pass-through case, where the same mechanism is at work (see Section 3.2.).

In contrast to the full pass-through case, exchange rate movements do not induce large inflationary impulses under incomplete pass-through, when, for example, foreign disturbances hit the economy. Consequently, the optimal policy reaction to risk premium changes (i.e. exchange rate shocks), foreign interest rate changes, and foreign demand changes, decreases as pass-through becomes lower. The impact on the domestic economy, both on prices and on output, appears to be smaller when pass-through is low, which implies that the short interest rate adjustment will be smaller.

Contrary to this, the optimal response to domestic disturbances, such as demand and cost-push shocks, increases as pass-through decreases. With complete pass-through, the policy induced exchange rate movement has a larger effect on prices, implying that the exchange rate channel of transmitting policy has a more sizeable influence. Consequently, some of the stabilization is provided through the resultant exchange rate change, and the policy maker does not need to adjust the interest rate to the same extent.

The exchange rate channel of monetary transmission also implies that the policy maker faces a trade-off between inflation and output variability, not only in presence of cost-push shocks, but also for demand shocks and foreign disturbances. The trade-off frontier is located closer to the origin as pass-through decreases, because of the lower exposure to foreign shocks and to policy induced exchange rate fluctuations.

In models where exchange rate changes are exogenously given and prices are not very responsive to these changes, monetary policy makers can not rely on exchange rates to provide the necessary adjustments to real shocks (Devereux and Engel (2000)). In the model used here, the exchange rate is endogenously determined and its development is, among other things, dependent on the exogenously given import price stickiness. In order to induce the necessary relative price adjustment, the exchange rate response is required to be larger as the price rigidity increases, since nominal prices are sticky and can not costlessly absorb a shock. The results also indicate that the exchange rate volatility increases with the nominal rigidity, or in other words, it is decreasing in the degree of pass-through.

Appendix A

A.1. The consumers' preferences

Domestic consumers

Domestic consumption follows a CES function, such that the aggregate consumption index (C_t) consists of consumption of imported goods (C_t^M) and consumption of domestic goods (C_t^D), in the following form:

$$\text{(A1)} \quad C_t = \left[(1-\kappa_M)^{\frac{1}{\eta}} (C_t^D)^{\frac{\eta-1}{\eta}} + (\kappa_M)^{\frac{1}{\eta}} (C_t^M)^{\frac{\eta-1}{\eta}} \right]^{\frac{\eta}{\eta-1}},$$

where κ_M denotes the total import share of consumption in the domestic country. The corresponding aggregate price index (CPI) is

$$\text{(A2)} \quad P_t = \left[(1-\kappa_M)(P_t^D)^{1-\eta} + \kappa_M (P_t^M)^{1-\eta} \right]^{\frac{1}{1-\eta}}.$$

A log-linearization of (A2), taking first differences, yields the following simplified expression for aggregate (CPI) inflation, $\pi_t = (1-\kappa_M)\pi_t^D + \kappa_M \pi_t^M$.[36] For simplicity, it is assumed that all products within a category are alike, such that issues of substitution between different types of goods within a category are disregarded. Equation (A1) implies that the demand for domestic and imported goods, respectively follow:

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

$$\text{(A3b)} \quad C_t^M = \kappa_M \left(\frac{P_t^M}{P_t} \right)^{-\eta} C_t.$$

The relative consumption allocation is then given by

[36] The share of import goods in CPI inflation is constant for small deviations around the steady-state and hence, equal to κ_M.

(A4) $$\frac{C_t^D}{C_t^M} = \frac{(1-\kappa_M)}{\kappa_M}\left(\frac{P_t^D}{P_t^M}\right)^{-\eta}.$$

Foreign consumers

The conditions in the foreign economy is assumed to be exogenously given, and the domestic economy is small in that the domestic export good plays a negligible part in the foreign aggregate consumption and price indices. This is modelled through a CES (Dixit-Stiglitz) aggregator over foreign consumption of a continuum (with unit mass) of differentiated goods, assuming the elasticity of substitution between them to be η (i.e. the same elasticity of substitution as between domestic and foreign goods). This implies that the foreign demand for the domestic export good and the foreigners' demand for their own good (i.e. domestic import good), respectively follow:

(A5a) $$C_t^{D*} = \left(\frac{P_t^D / E_t}{P_t^*}\right)^{-\eta} C_t^*,$$

(A5b) $$C_t^{M*} = \left(\frac{P_t^{M*}}{P_t^*}\right)^{-\eta} C_t^*.$$

A.2. The domestic producer's optimization problem

The domestic producer is assumed to use a composite (Cobb-Douglas) input (Z_t), consisting of domestic intermediate goods (Z_t^D) and foreign import goods (Z_t^M), in her production (Y_t) such that the production function follows

(A6) $$Y_t = (Z_t)^{1-\theta} = \left[(Z_t^D)^{1-\kappa_W}(Z_t^M)^{\kappa_W}\right]^{1-\theta}, \qquad 0 \le \theta < 1.$$

The compound intermediate input price, in domestic currency units, is given by

(A7) $$P_t^Z = \frac{(P_t^D)^{1-\kappa_W}(P_t^M)^{\kappa_W}}{(1-\kappa_W)^{1-\kappa_W}\kappa_W^{\kappa_W}},$$

where κ_W denotes the share of imported inputs in the domestic production. The profit-maximization problem of this firm, in an imperfectly competitive setting with flexible prices, is given by

$$\text{(A8)} \quad \begin{aligned} &\max_{\hat{P}_t^D, \hat{P}_t^{D*}, Z_t} \quad \hat{P}_t^D C_t^D + \hat{P}_t^{D*} E_t C_t^{D*} - P_t^Z Z_t \\ &\text{s.t} \quad Y_t = (Z_t)^{1-\theta} \geq C_t^D + C_t^{D*} = (1-\kappa_F)\left(\frac{\hat{P}_t^D}{\hat{P}_t}\right)^{-\eta} C_t + \left(\frac{\hat{P}_t^{D*}}{\hat{P}_t^*}\right)^{-\eta} C_t^*, \end{aligned}$$

where domestic and foreign aggregate consumption follow CES functions. The producer satisfies the demand for domestic products, which is equal to $Y_t = C_t^D + C_t^{D*}$ (domestic and foreign demand). E_t is the exchange rate (domestic currency per unit of foreign currency), C_t is the aggregate (domestic) consumption index consisting of a composite bundle of domestic and foreign goods, $\hat{P}_t$ is the corresponding price index, and κ_M is the import share of consumption (a star denotes the foreign counterparts). The goods are well differentiated, such that the domestic producer disregards her own effect on aggregate prices, as well as takes the competitor's price (i.e. the price of import goods, $\hat{P}_t^M$) as fixed, implying that any strategic interaction is absent.

The first order conditions, with respect to the (flexible) prices charged in the domestic and foreign markets ($\hat{P}_t^D$ and $\hat{P}_t^{D*}$, denoted in domestic and foreign currency, respectively), are given by

$$\text{(A9a)} \quad \hat{P}_t^D = \left(\frac{\eta}{\eta-1}\right) MC(Z_t, P_t^Z),$$

$$\text{(A9b)} \quad \hat{P}_t^{D*} = \left(\frac{\eta}{\eta-1}\right) MC(Z_t, P_t^Z)\frac{1}{E_t},$$

where η is the (positive) constant price elasticity of demand, and MC is the marginal cost; $MC = P_t^Z / \left((1-\theta)Z_t^{-\theta}\right) = P_t^Z / \left((1-\theta)Y_t^{\frac{-\theta}{1-\theta}}\right)$. The equilibrium prices of the domestic good, in a flexible price environment, hence consist of a constant and identical markup over marginal costs.

Appendix B

B.1. The central banker's optimization problem

The central bank's period loss function can be stated as $L_t = (z_t' K z_t)$ where $z_t = [\pi_t \quad y_t \quad (i_t - i_{t-1})]'$ denotes a vector of goal variables composed of $z_t = T_x x_t + T_i i_t$, such that T_x is a 3×13 matrix mapping the goal variables to the state variables, T_i is a 3×1 matrix, and K is a 3×3 diagonal matrix with diagonal (1, λ, v_i),

$$T_x = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & (1-\kappa_M) & \kappa_M & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix},$$

$$T_i = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}.$$

This implies that the intertemporal control problem can be expressed as:

$$\text{(B1)} \quad \begin{aligned} J(x_t) &= \min_{\{i_{t+s}\}_{s=0}^{\infty}} \mathrm{E}_t \sum_{s=0}^{\infty} \delta^s \begin{bmatrix} x_{t+s}' & i_{t+s}' \end{bmatrix} \begin{bmatrix} Q & U \\ U' & R \end{bmatrix} \begin{bmatrix} x_{t+s} \\ i_{t+s} \end{bmatrix} \\ &= \min_{\{i_{t+s}\}_{s=0}^{\infty}} \mathrm{E}_t \sum_{s=0}^{\infty} \delta^s (x_{t+s}' Q x_{t+s} + 2x_{t+s}' U i_{t+s} + i_{t+s}' R i_{t+s}), \end{aligned}$$

where $Q = T_x' K T_x$, $U = T_x' K T_i$ and $R = T_i' K T_i$.

The model, i.e. the system of equations (5), (8), (9), and (14)-(19), can be rewritten in state-space form

$$\text{(B2)} \quad \tilde{A}_0 \begin{bmatrix} x_{1,t+1} \\ \mathrm{E}_t x_{2,t+1} \end{bmatrix} = \tilde{A} \begin{bmatrix} x_{1,t} \\ x_{2,t} \end{bmatrix} + \tilde{B} i_t + \tilde{\upsilon}_{t+1},$$

$$x_{1,t} = \begin{bmatrix} i_{t-1} & y_t^* & i_t^* & \hat{\pi}_t^* & \varepsilon_t^{\pi} & \varepsilon_t^{\phi} & \varepsilon_t^{y} & (p_{t-1}^M - p_{t-1}^D) & (\hat{p}_{t-1}^* + e_{t-1} - p_{t-1}^M) \end{bmatrix}',$$

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

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

where $x_{1,t}$ is a 9×1 vector of predetermined state variables, $x_{2,t}$ is a 4×1 vector of forward-looking variables and $\tilde{\upsilon}_{t+1}$ is a 13×1 vector of disturbances,

$$\tilde{A}_0 = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -b_y^*(1-\rho_i^*) & 1 & -b_\pi^*(1-\rho_i^*) & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & ((1-\kappa_D)(\sigma-\kappa_M(\sigma-\eta))+\kappa_D\eta) & (1-\kappa_D)\kappa_M(\sigma-\eta) & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{\kappa_W}{\gamma_D} & 0 & 0 & \beta_\pi & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{\gamma_M} & 0 & 0 & \beta_\pi & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix},$$

$$\tilde{A} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \rho_y^* & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \rho_i^* & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \rho_\pi^* & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \tau_\pi & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \tau_\phi & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \tau_y & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & -1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & -1 & 1 \\ 0 & -\kappa_D a_y^*(1-\rho_y^*) & -\kappa_D\eta & \rho_\pi^*\kappa_D\eta & 0 & -\kappa_D\eta & -1 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & -\frac{\xi_y}{\gamma_D} & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & -1 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix},$$

$$\tilde{B} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & (1-\kappa_D)\sigma+\kappa_D\eta & 0 & 0 & 1 \end{bmatrix}'.$$

The predetermined state vector is defined from stationary variables only, in order to avoid problems with the numerical algorithm used to capture the discretionary solution. If the number of stable eigenvalues of the solution, or transition, matrix (see equation (B13)) equals the number of predetermined variables[37], the system has a stable solution, which is captured by the numerical algorithm. In contrast, if the state vector contains non-stationary variables yielding unstable roots, it is unclear whether the algorithm captures the solution to the policy maker's

[37] In the case of commitment, this is a necessary condition for a stable solution (Blanchard and Kahn (1980)).

problem. Hence, the system is written such that the non-stationary variables like the price level and the exchange rate enter the state-space representation only in relative or difference forms[38].

Premultiplying equation (B2) with $\tilde{A}_0^{-1}$ yields

$$\text{(B3)} \quad \begin{bmatrix} x_{1,t+1} \\ \mathrm{E}_t x_{2,t+1} \end{bmatrix} = A \begin{bmatrix} x_{1,t} \\ x_{2,t} \end{bmatrix} + B i_t + \upsilon_{t+1},$$

where $A = \tilde{A}_0^{-1}\tilde{A}$, $B = \tilde{A}_0^{-1}\tilde{B}$, and $\upsilon_{t+1} = \tilde{A}_0^{-1}\tilde{\upsilon}_{t+1}$.

In the discretionary case, where the central banker reoptimizes every period, the forward-looking variables can be expressed as a linear function of the predetermined variables, $x_{2,t} = Hx_{1,t}$. Using this, partitioning equation (B3) according to the predetermined state variables and forward-looking variables, and taking expectations:

$$\text{(B4)} \quad \begin{bmatrix} \mathrm{E}_t x_{1,t+1} \\ \mathrm{E}_t x_{2,t+1} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} x_{1,t} \\ x_{2,t} \end{bmatrix} + \begin{bmatrix} B_1 \\ B_2 \end{bmatrix} i_t,$$

$$\text{(B5)} \quad \begin{bmatrix} I_{13\times 13} \\ H_{4\times 13} \end{bmatrix} \mathrm{E}_t x_{1,t+1} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} x_{1,t} \\ x_{2,t} \end{bmatrix} + \begin{bmatrix} B_1 \\ B_2 \end{bmatrix} i_t,$$

$$\text{(B6)} \quad \begin{bmatrix} \mathrm{E}_t x_{1,t+1} \\ x_{2,t} \end{bmatrix} = \begin{bmatrix} I & -A_{12} \\ H & -A_{22} \end{bmatrix}^{-1} \left(\begin{bmatrix} A_{11} \\ A_{21} \end{bmatrix} x_{1,t} + \begin{bmatrix} B_1 \\ B_2 \end{bmatrix} i_t \right),$$

$$\text{(B7)} \quad \begin{aligned} x_{2,t} &= (A_{22} - HA_{12})^{-1}(HA_{11} - A_{21})x_{1,t} + (A_{22} - HA_{12})^{-1}(HB_1 - B_2)\, i_t = \\ &= D\, x_{1,t} + G\, i_t , \end{aligned}$$

$$\text{(B8)} \quad \begin{aligned} \mathrm{E}_t x_{1,t+1} &= A_{11}x_{1,t} + A_{12}x_{2,t} + B_1 i_t \\ &= (A_{11} + A_{12}D)\, x_{1,t} + (B_1 + A_{12}G)\, i_t \\ &= A^* x_{1,t} + B^* i_t . \end{aligned}$$

Rewriting the central banker's period loss function (see equation (B1)) in terms of the predetermined variables, using equation (B7), yields

[38] Consequently, the following identities are also used to put up the state space representation;
$(p_t^M - p_t^D) = (p_{t-1}^M - p_{t-1}^D) + \pi_t^M - \pi_t^D$ and $(\hat{p}_t^* + e_t - p_t^M) = (\hat{p}_{t-1}^* + e_{t-1} - p_{t-1}^M) + \hat{\pi}_t^* + \Delta e_t - \pi_t^M$.

$$
\begin{aligned}
L_t &= \begin{bmatrix} x_{1,t}^{'} & D' x_{1,t}^{'} + G' i_t^{'} \end{bmatrix} \begin{bmatrix} Q_{11} & Q_{12} \\ Q_{21} & Q_{22} \end{bmatrix} \begin{bmatrix} x_{1,t} \\ D x_{1,t} + G i_t \end{bmatrix} + 2 \begin{bmatrix} x_{1,t} \\ D x_{1,t} + G i_t^{'} \end{bmatrix} U\, i_t + i_t^{'} R\, i_t \\
\text{(B9)} \quad &= x_{1,t}^{'} \left(Q_{11} + D' Q_{21} + Q_{12} D + D' Q_{22} D \right) x_{1,t} + 2 x_{1,t}^{'} \left(Q_{12} G + D' Q_{22} G + U_1 + D' U_2 \right) i_t \\
&\quad + i_t^{'} \left(G' Q_{22} G + G' U_2 + U_2^{'} G + R \right) \\
&= x_{1,t}^{'} Q^{*} x_{1,t} + 2 x_{1,t}^{'} U^{*} i_t + i_t^{'} R^{*} i_t \; .
\end{aligned}
$$

Using equations (B8) and (B9) implies that the Bellman equation of the optimization problem, considering the discretionary case, can be written

$$
\begin{aligned}
J(x_{1,t}) &= x_{1,t}^{'} V_t x_{1,t} + \omega_t \\
\text{(B10)} \quad &= \min_{i_t} \left\{ L_t + \delta \, \mathrm{E}_t \left[x_{1,t+1}^{'} V_{t+1} x_{1,t+1} + \omega_{t+1} \right] \right\} \\
&= \min_{i_t} \left\{ x_{1,t}^{'} Q^{*} x_{1,t} + 2 x_{1,t}^{'} U^{*} i_t + i_t^{'} R^{*} i_t + \delta \, \mathrm{E}_t \left[(A^{*} x_{1,t} + B^{*} i_t)' V_{t+1} (A^{*} x_{1,t} + B^{*} i_t) + \omega_{t+1} \right] \right\},
\end{aligned}
$$

where V_t is a negative semidefinite matrix and ω_t is a scalar, both yet to be determined by iterating on the value function. The first order condition yields,

$$2(R^{*} + \delta B^{*}{}' V_{t+1} B^{*}) i_t + 2(U^{*}{}' + \delta B^{*}{}' V_{t+1} A^{*}) x_{1,t} = 0 \, ,$$

implying that the interest rate is equal to

$$
\begin{aligned}
\text{(B11)} \quad i_t &= -\left(R^{*} + \delta B^{*}{}' V_{t+1} B^{*} \right)^{-1} \left(U^{*}{}' + \delta B^{*}{}' V_{t+1} A^{*} \right) x_{1,t} \\
&= -F_t x_{1,t} \; .
\end{aligned}
$$

By combining (B11) with (B7) and (B3), respectively, the forward-looking variables and the predetermined state variables can be written as

$$\text{(B12)} \quad x_{2,t} = (D - GF) x_{1,t} \, ,$$

$$
\begin{aligned}
\text{(B13)} \quad x_{1,t+1} &= \left(A_{11} + A_{12}(D - GF) - B_1 F \right) x_{1,t} + \upsilon_{t+1} = \\
&= M x_{1,t} + \upsilon_{t+1} \; .
\end{aligned}
$$

Using (B11) in equation (B7) and inserting into (B10) yields,

$$J(x_{1,t}) = x_{1,t}^{'} (Q^{*} - U^{*} F_t - F_t^{'} U^{*}{}' + F_t^{'} R^{*} F_t + \delta (A^{*} - B^{*} F_t)' V_{t+1} (A^{*} - B^{*} F_t)) x_{1,t} + \delta \, \omega_{t+1} \, ,$$

implying that the value function (the so-called Ricatti equation) is equal to

(B14) $V_t = Q^* - U^* F_t - F_t' U^{*\prime} + F_t' R^* F_t + \delta (A^* - B^* F_t)' V_{t+1} (A^* - B^* F_t))$.

In contrast, if the central banker can credibly commit to a certain policy solution, the monetary policy will also be transmitted through the private agents' expectations about current central bank behaviour. The commitment solution does not require a numerical algorithm (see Söderlind (1999) for the different optimization procedures). The optimal reaction function, is in that case, determined by a decomposition of the stable eigenvalues from the first order condition of the optimization problem (i.e. the intertemporal loss function (B1), subject to the transition equation (B3)).

B.2. Variance-covariance matrices

The unconditional variance-covariance matrix of the disturbance vector, υ_{t+1}, is given by $\Sigma_\upsilon = [\Sigma_{\upsilon 1} \quad 0_{9\times 4}]$, where $\Sigma_{\upsilon 1}$ is defined as

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

The dynamics of the predetermined variables can be written as (B13), implying that the asymptotic unconditional variance-covariance matrix of x_1 is given by

(B15) $\Sigma_{x1} = M \Sigma_{x1} M' + \Sigma_{\upsilon 1}$,

(B16) $\text{vec}(\Sigma_{x1}) = [I_{n1^2} - (M \otimes M)]^{-1} \text{vec}(\Sigma_{\upsilon 1})$,

using $\text{vec}(A+B) = \text{vec}(A) + \text{vec}(B)$, and $\text{vec}(ABC) = (C' \otimes A)\text{vec}(B)$, (see Rudebusch and Svensson (1999)). The variables of interest (z_t^g) can be written as a function of the predetermined variables (x_{1t}),

$$
\begin{aligned}
z^g_{t+1} &= T^g_x x_{t+1} + T^g_i i_{t+1} \\
&= \begin{bmatrix} T^g_{x1} & T^g_{x2} \end{bmatrix} \begin{bmatrix} x_{1t+1} \\ x_{2t+1} \end{bmatrix} + T^g_i i_{t+1} \\
&= \begin{bmatrix} T^g_{x1} & T^g_{x2} \end{bmatrix} \begin{bmatrix} x_{1t+1} \\ Hx_{1t+1} \end{bmatrix} - T^g_i F x_{1t+1} \\
&= T x_{1t+1} \ ,
\end{aligned}
$$

implying that the variance-covariance matrix of the interest variables is

(B17) $\Sigma_z = T \Sigma_{x1} T'$.

Appendix C: Robustness

Table C1: Unconditional variances, different degrees of openness

Partial pass-through	var(π)	var(π^D)	var(π^M)	var(y)	var(Δe)	var($p^M - p^D$)	var(i)
	$\kappa_M = 0.15,\ \kappa_D = 0.15,\ \kappa_W = 0.05$						
0.99	54.998	55.045	62.806	1.841	64.128	30.235	40.638
0.66	54.889	55.188	58.144	1.644	67.698	26.802	39.86
0.33	54.310	55.107	52.7	1.434	72.704	24.458	39.212
0.01	37.194	43.145	15.833	0.552	91.102	477.697	40.176
	$\kappa_M = 0.6,\ \kappa_D = 0.6,\ \kappa_W = 0.2$						
0.99	53.919	54.047	54.257	2.477	56.614	3.06	41.847
0.66	53.220	54.245	52.833	1.875	57.67	3.05	41.496
0.33	50.275	53.199	48.677	1.295	58.237	5.535	40.463
0.01	10.148	23.597	5.611	0.052	39.411	282.388	23.325

Note: See Appendix B for the variance-covariance matrix, and calculation of the asymptotic variances.

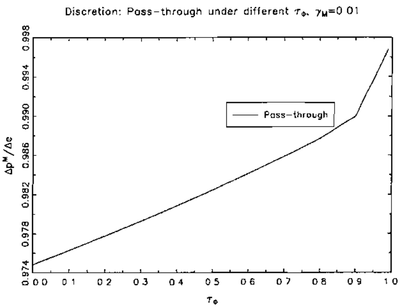
Table C2: Policy reaction function, different degrees of openness; coefficients in $-F$

$(i_t = -Fx_{1,t})$

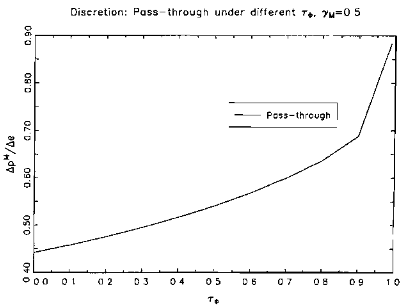
Partial pass-through	i_{t-1}	y_t^*	i_t^*	$\hat{\pi}_t^*$	ε_t^π	ε_t^ϕ	ε_t^y	$(p_{t-1}^M - p_{t-1}^D)$	$(\hat{p}_{t-1}^* + e_{t-1} - p_{t-1}^M)$
	$\kappa_M = 0.15,\ \kappa_D = 0.15,\ \kappa_W = 0.05$								
0.99	0.038	0.037	0.793	-0.555	3.460	0.793	0.373	-0.016	0
0.66	0.058	0.013	0.67	-0.547	3.409	0.67	0.606	0.063	0
0.33	0.072	0.000	0.594	-0.534	3.413	0.594	0.741	0.108	0
0.01	0.080	0.021	0.603	-0.475	3.812	0.603	0.696	0.078	0
	$\kappa_M = 0.6,\ \kappa_D = 0.6,\ \kappa_W = 0.2$								
0.99	0.006	0.024	0.978	-0.734	3.525	0.978	0.071	-0.037	0
0.66	0.01	0.028	0.954	-0.732	3.521	0.954	0.166	0.042	0
0.33	0.012	0.031	0.940	-0.729	3.525	0.940	0.22	0.086	0
0.01	0.014	0.031	0.932	- 0.734	2.954	0.932	0.248	0.127	0

Figure 1: Exchange rate pass-through under varying degrees of risk premium persistence (τ_ϕ)

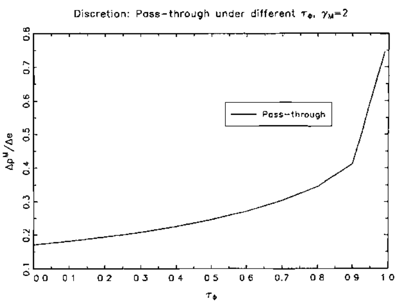
a) $\gamma_M = 0.01$



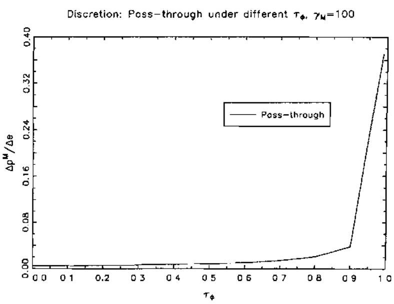
b) $\gamma_M = 0.5$



c) $\gamma_M = 2$



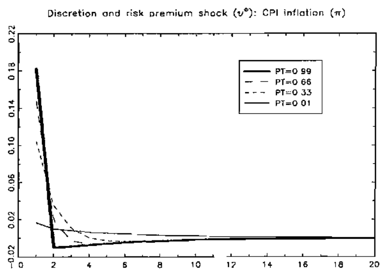
d) $\gamma_M = 100$



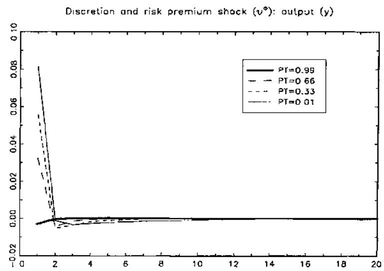
Note: Range of variation, $\tau_\phi = [0, 0.99]$

Figure 2: Impulse responses under different degrees of pass-through, risk premium shock ($\upsilon^{\phi}=1$)

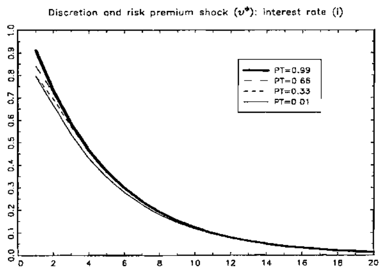
a)



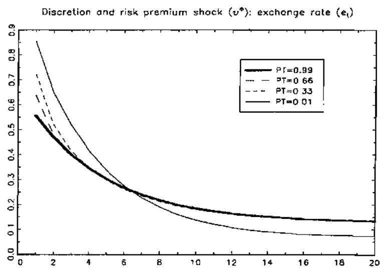
b)



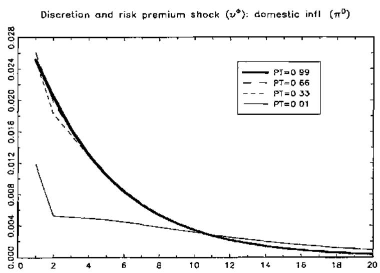
c)



d)



e)



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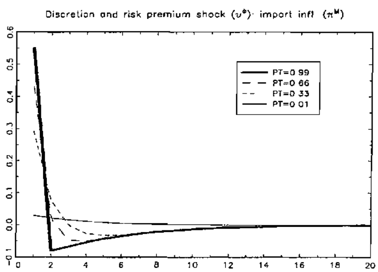
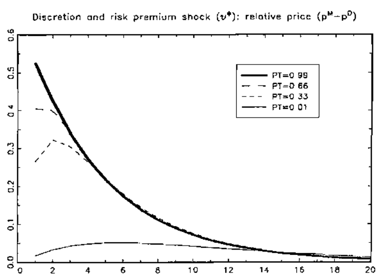


g)



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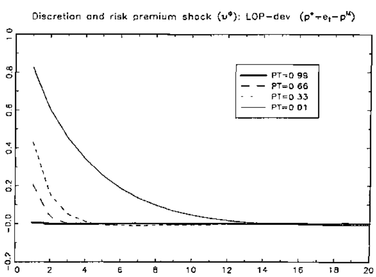
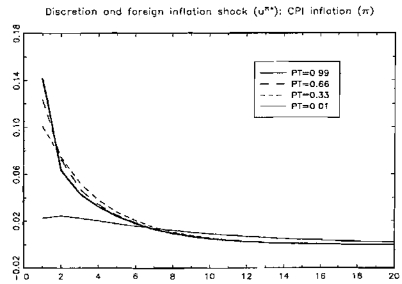
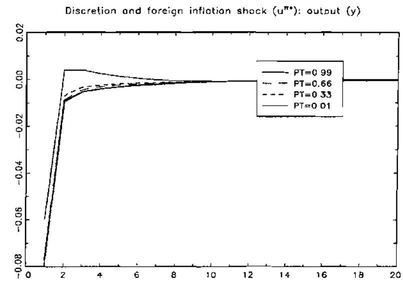


Figure 3: Impulse responses under different degrees of pass-through, foreign inflation shock ($u^{\pi^*}=1$)

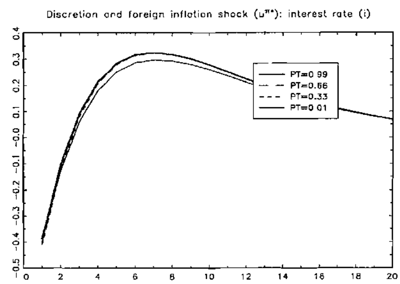
a)



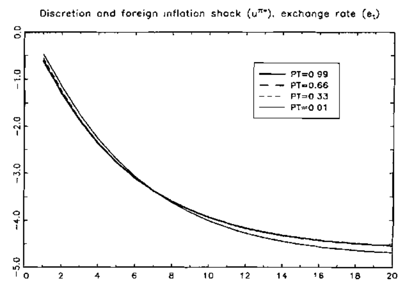
b)



c)



d)



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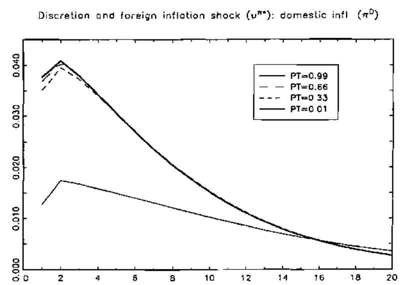

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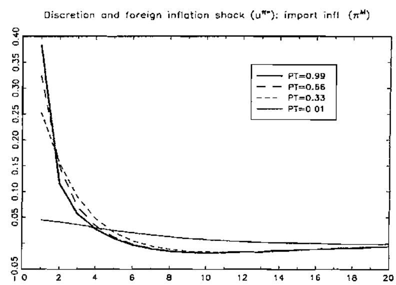

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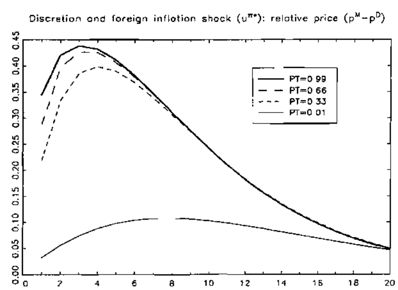


h)

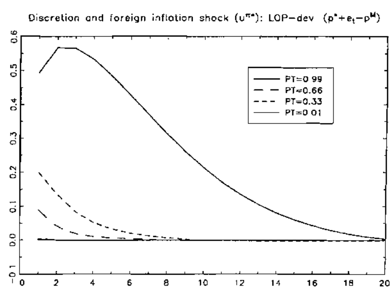
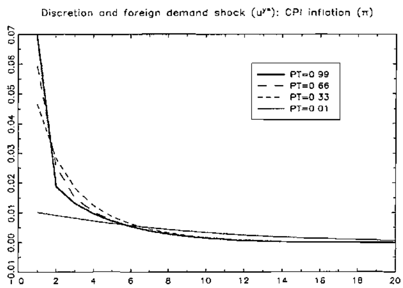
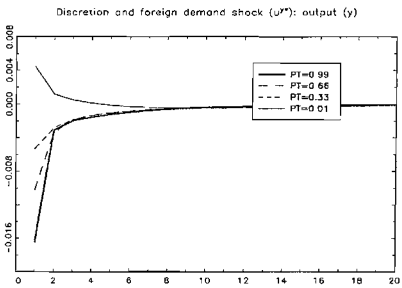


Figure 4: Impulse responses under different degrees of pass-through, foreign demand shock ($u^{y^*}=1$)

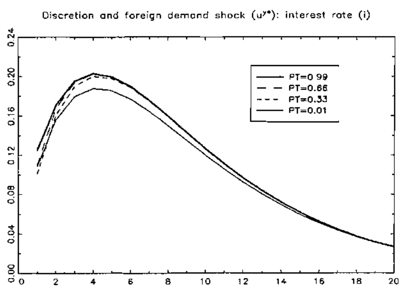
a)



b)



c)



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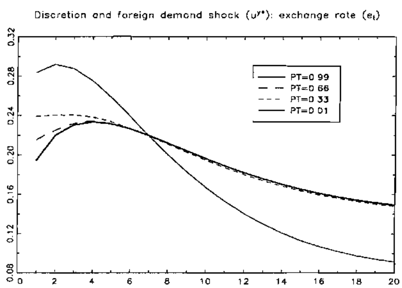

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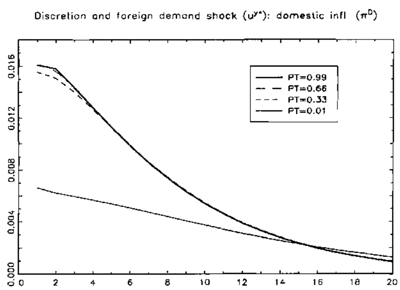

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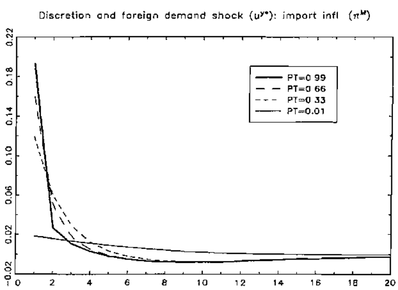
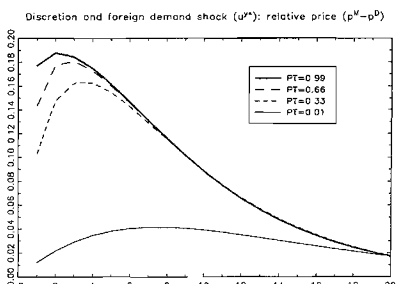


g)



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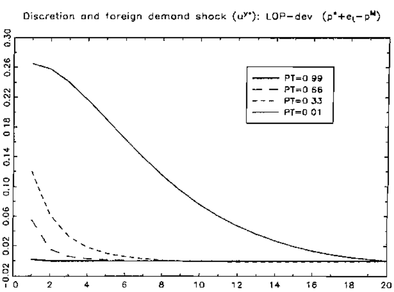
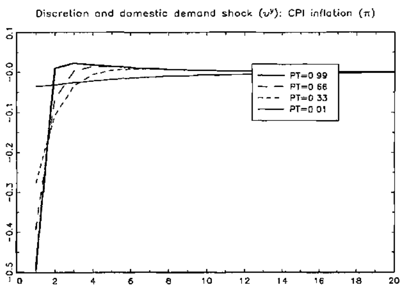
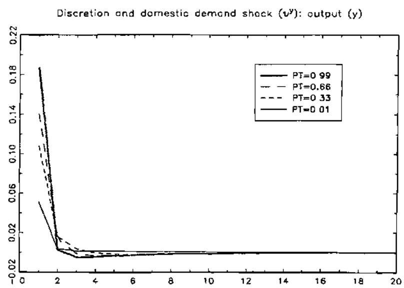


Figure 5: Impulse responses under different degrees of pass-through, domestic demand shock ($\upsilon^y = 1$)

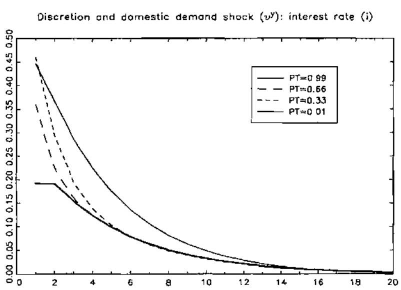
a)



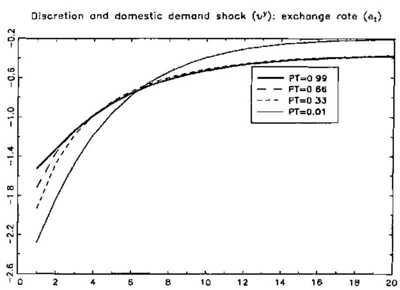
b)



c)



d)



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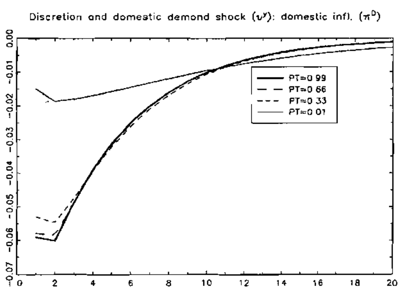

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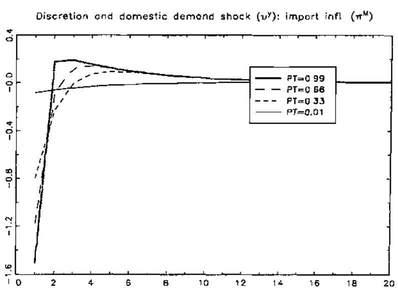
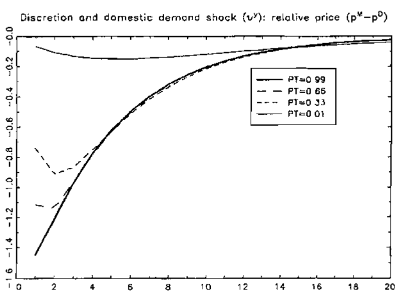


g)



h)

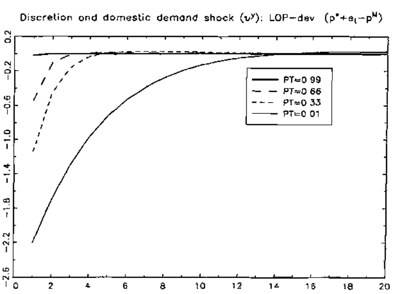


Figure 6: Impulse responses under different degrees of pass-through, domestic cost-push shock ($\upsilon^{\pi}=1$)

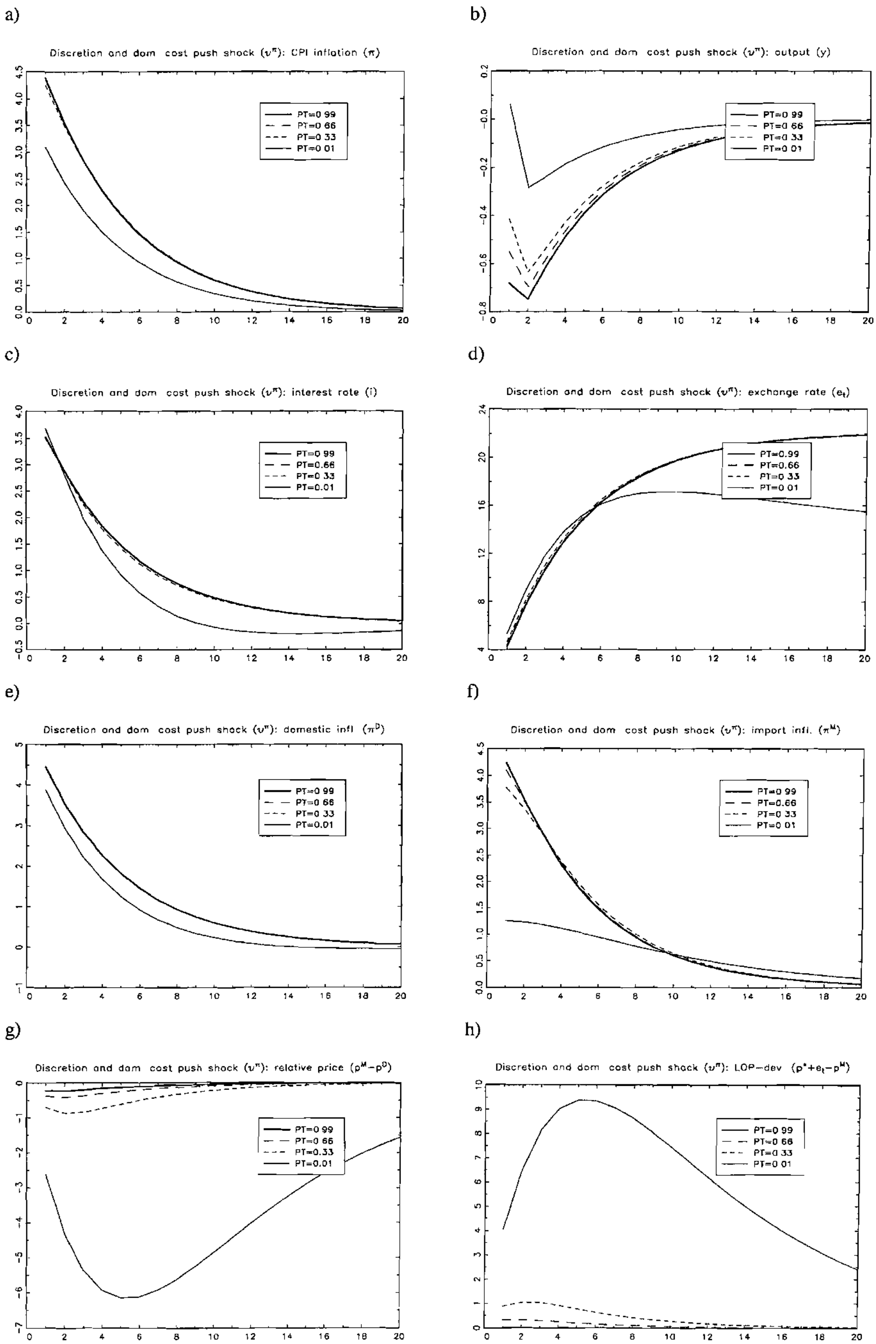
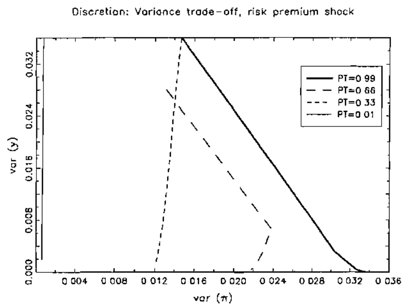
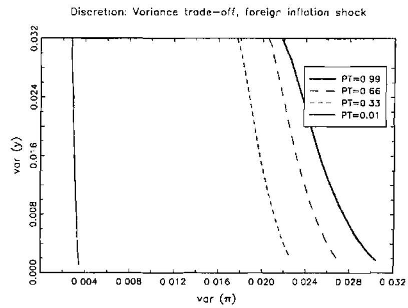


Figure 7: Inflation–output variability trade-off under different degrees of pass-through, individual shocks

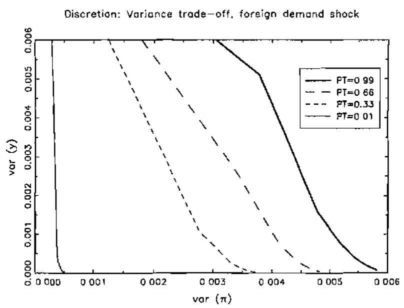
a) Risk premium shock (υ_t^{ϕ})



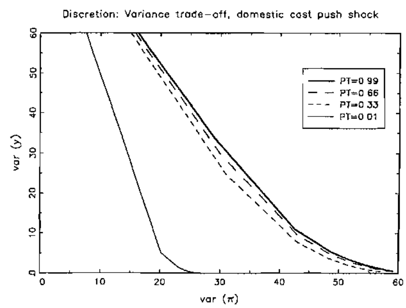
b) Foreign inflation shock ($u_t^{\pi^*}$)



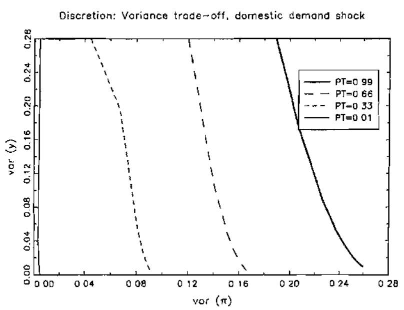
c) Foreign demand shock ($u_t^{y^*}$)



d) Domestic cost-push shock (υ_t^{π})

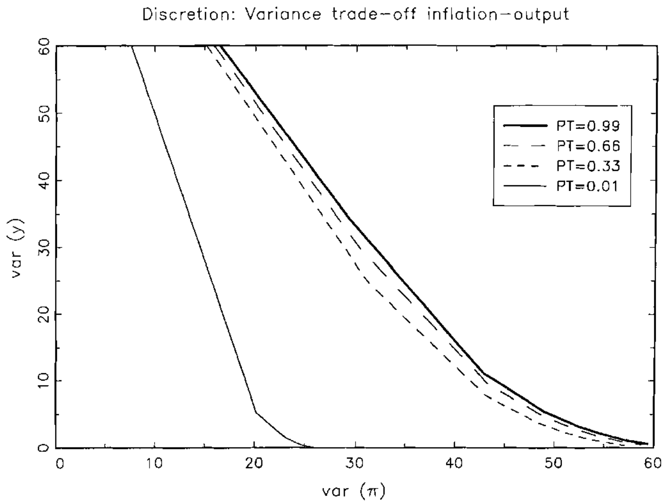


e) Domestic demand shock (υ_t^{y})



Note: The degree of output stabilization is altered such that $\lambda = [0,1]$, step 0.1. The y-axis is truncated to circumvent the extreme case of $\lambda = 0$, which makes the trade-off frontier skewed.

Figure 8: Inflation–output variability trade-off under different degrees of pass-through



Note: The degree of output stabilization is altered such that $\lambda = [0,1]$, step 0.1. The y-axis is truncated to circumvent the extreme case of $\lambda = 0$, which makes the trade-off frontier skewed.

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CHAPTER 3

OPTIMAL MONETARY POLICY DELEGATION UNDER INCOMPLETE EXCHANGE RATE PASS-THROUGH

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3

Abstract

The central bank's optimal objective function is analyzed in a small open economy model allowing for incomplete exchange rate pass-through. The results indicate that social welfare can only be marginally improved by including an explicit exchange-rate term in the delegated objective function, irrespective of the degree of pass-through. An implicit response to the exchange rate, through Consumer Price Index (CPI) inflation targeting is, however, beneficial. Welfare can, moreover, be enhanced by appointing a central banker with a greater preference for interest rate smoothing than that of the society, as a result of surpassing some of the stabilization bias arising under a discretionary policy. Consequently, there are welfare gains from monetary policy inertia. The optimal degree of interest rate smoothing is increasing in the degree of pass-through.

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1. Introduction

In an open economy, exchange rate movements affect inflation through direct changes in import prices as well as via aggregate demand, which is influenced by alterations in the relative price between foreign and domestic goods. In the presence of exchange rate disturbances, the policy maker can not stabilize demand without creating fluctuations in inflation, because the exchange rate has this twofold effect on both the demand and supply relations. The policy maker thus faces a trade-off between inflation and output variability. In contrast to the closed economy setting, this trade-off occurs for all types of shocks that enter the economy, since all adjustments of the policy controlled interest rate also generate movements in the exchange rate. The exchange rate works as an additional transmission mechanism of monetary policy, besides the traditional interest rate channel. Consider, for example, a positive demand shock. In a closed economy, this demand shock can be completely countered, without affecting inflation, by simply raising the interest rate.[1] In an open economy framework, the increase in the interest rate increase also affects the exchange rate, which appreciates and, in turn, feeds into both inflation and output. This implies that the central bank is forced to trade off reduced output variability for inflation variability (see e.g. Walsh (1999)).

Movements in the terms of trade can consequently affect the trade-off between monetary policy objectives. Accordingly, because of the exposure to exchange rate fluctuations, there have been some suggestions that the design of the optimal policy differs between closed and open economies (see e.g. Sutherland (2000)).[2, 3] Is it possible to ease the goal conflict, and diminish the trade-off, by assigning a different objective function to the open economy-policy maker? Should the policy maker use a different inflation measure, or perhaps explicitly respond to exchange rate fluctuations? By strictly targeting consumer price (CPI) inflation, the policy maker may induce large interest rate variability, since such a policy aims at neutralizing the price effect of every exchange rate fluctuation. On the other hand, by only focusing on domestic

[1] Note that this is contingent upon a central bank loss function that does not penalize interest rate changes, as well as on a forward-looking model without transmission lags of monetary policy.

[2] On the other hand, Clarida et al. (2001) advocate that the closed and open economy policy objectives are isomorphic as long as the terms of trade are proportional to the output gap.

[3] For a related discussion about relative price changes and the appropriate goal variables for the central bank in a closed economy, see Aoki (2001). Aoki suggests that his results can be applied to a small open economy, where accordingly domestic inflation should be completely stabilized. However, Aoki assumes import prices to be fully flexible, and that the law of one price holds. On the contrary, when the degree of price stickiness differs across sectors, Benigno (2001) finds that the optimal monetary policy in a currency area implies that a larger policy weight should be given to the inflation rate with a higher degree of nominal rigidity.

conditions, the policy maker can create excessive exchange rate volatility, which may be a sub-optimal outcome (Svensson (2000)).[4]

However, because of deliberate price discrimination or nominal rigidities, an exchange rate movement need not necessarily generate a one-to-one change in import prices (i.e. there may be an incomplete exchange rate pass-through), which is why the impact on the economy might be quite limited. If the degree of pass-through is small, the effect of exchange rate changes is minor and there is less need for the policy maker to adjust the interest rate to such disturbances. In the face of, for example, demand shocks and exchange rate disturbances, this implies that the conflict between inflation and output objectives is reduced, which shifts the policy frontier towards the closed economy outcome (see Adolfson (2001)). Consequently, also the (optimal) open-economy policy objective may be dependent on the degree of pass-through.

The purpose of this paper is to analyze the optimal objective, in terms of social welfare, that should be pursued by a discretionary policy maker of an open economy with incomplete exchange rate pass-through. What are the effects of exchange rate fluctuations on the optimized loss function, and is the optimal policy objective contingent upon the degree of pass-through? In particular, is it relevant to augment the delegated objective function with an exchange-rate stabilization term that may improve the policy maker's control over the inflation-output variability trade-off? This paper also deals with other ways of correctly specifying the policy objective to mitigate the 'stabilization bias', or less inertial policy responses, that arises under a discretionary policy (see e.g. Woodford (1999)). Are there any gains from assigning a different objective to the policy maker as compared to society, for example in terms of the degree of interest rate smoothing? Moreover, how does incomplete pass-through affect this stabilization bias?

The analysis is performed within an aggregate supply–aggregate demand model adjusted for incomplete exchange rate pass-through. The results indicate that the social welfare improvements of including an exchange-rate term among the policy objectives are small. Consequently, a direct, and explicit, stabilization of nominal or real exchange rates appears to be redundant, both when pass-through is limited and when it is complete. However, an indirect response to the exchange rate, through targeting CPI inflation rather than domestic inflation, is

[4] Nevertheless, rather than changing the inflation measure to target, high interest rate and exchange rate volatility might be avoided if the policy maker is more concerned about the real effects of the policy (i.e. flexible inflation targeting with some concern for output stabilization), which makes the policy more gradual.

welfare enhancing. The paper also points out that, although the incomplete exchange rate pass-through induces persistent policy responses to certain shocks, there are gains from appointing a central banker with a greater preference for interest rate smoothing than the social objective, as proposed by Woodford (1999). However, the results here show that the optimal degree of explicit interest rate smoothing decreases as pass-through decreases. The reason is that low pass-through as such generates more inertial interest rate reactions.

In Section 2, the model economy, and the central bank objectives, are outlined and parameterized. Section 3 contains the optimized central bank objectives, evaluated from a social loss rationale, and the resulting policy trade-offs under different types of disturbances. Robustness issues are discussed in Section 4, while some conclusions are presented in Section 5.

2. Model

The theoretical setting is a forward-looking open economy aggregate supply-aggregate demand model allowing for incomplete exchange rate pass-through. Most prior developments of open economy models have assumed the law of one price to hold, such that the exchange rate pass-through is complete (see, for example, Svensson (2000), and McCallum and Nelson (1999)). In contrast, in the model used here, the foreign producer can not fully adjust her domestic currency (import) price in the face of exchange rate changes because of nominal price adjustment costs (à la Rotemberg (1982)). This implies a limited exchange rate pass-through and consequently, a modified supply relation, where the degree of pass-through can be altered by simply changing the level of import price stickiness.[5]

2.1. Inflation, output, and interest rate relations

Consider an open economy with consumption of both domestically produced goods and imported foreign goods. The economy consists of an aggregate supply relation, an aggregate demand relation, and an interest rate parity condition pinning down expected exchange rate changes. The nominal interest rate is determined from an explicit central bank objective function. This economy (called domestic) is assumed to be small compared to the rest of the world (called foreign), such that foreign inflation, foreign output and foreign monetary policy are exogenously given.

The domestic aggregate supply equation is derived from the producers' optimal price setting relations assuming nominal (Rotemberg) price stickiness, and using the underlying constant elastic substitution (CES) function for the households' aggregate consumption. Aggregate inflation in the domestic economy (π_t), i.e. consumer price index (CPI) inflation, is composed by inflation of domestically produced goods ($\pi_t^D = p_t^D - p_{t-1}^D$) and import goods inflation denoted in the domestic currency ($\pi_t^M = p_t^M - p_{t-1}^M$), according to the following (see equations (A1) and (A2) in the Appendix):[6]

$$\begin{aligned} \pi_t &= (1-\kappa_M)\pi_t^D + \kappa_M \pi_t^M = \\ &= \alpha_\pi \mathrm{E}_t \pi_{t+1} + \alpha_y y_t + \alpha_q (p_t^M - p_t^D) + \alpha_p (p_t^* + e_t - p_t^M) + \varepsilon_t^\pi , \end{aligned} \tag{1}$$

where κ_M denotes the (steady-state) import share of domestic consumption, $0 < \alpha_\pi < 1$ is a discount factor, and α_y, α_q, and α_p are positive constants. y_t is domestic output, p_t^D is the price of domestically produced goods, p_t^M is the price of import goods denoted in the domestic currency, p_t^* is the foreign currency price of import goods, and e_t is the nominal exchange rate (domestic currency per unit of foreign currency). CPI inflation is a function of expected future inflation, aggregate output (or demand), the relative price of imports (which can be interpreted as a real exchange rate[7]), and the deviation between the optimal price of import goods in the absence of any nominal rigidities and the price actually charged (i.e., $p_t^* + e_t - p_t^M$).[8] This wedge term is what makes the pass-through adjusted supply relation different from a standard Phillips curve with complete exchange rate pass-through. The price stickiness implies that the domestic currency price can not be fully adjusted to alterations in, for example, the exchange rate. This creates a wedge between marginal cost (captured by the price charged in the foreign market adjusted for the exchange rate; $p_t^* + e_t$) and the price actually charged (p_t^M). This implies incomplete pass-through and short-run deviations from the law of one price.[9] The

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[5] For a more thorough discussion of the model, see Adolfson (2001).

[6] The notation is as follows; lower case letters denote logarithmic values (i.e. deviations from steady-state), a superscript indicates whether domestic or import goods are considered, and foreign variables are represented by an asterisk. A price denoted in foreign currency is thus characterized by an asterisk. Finally, E_t denotes rational expectations as of period *t*.

[7] This is, in effect, the inverse of the terms of trade, and only one particular definition of the real exchange rate.

[8] Given equal demand elasticities in the two destinations to which the foreign producer sells, there are no incentives to deviate from the law of one price in the absence of nominal rigidities, because of the constant elastic substitution function. The optimal domestic flex price is just the price charged in the foreign market corrected for the exchange rate.

[9] In the long run, the producer expects to charge the optimal flexible price such that $(p^M - e - p^*) \sim I(0)$.

degree of pass-through is controlled by α_p, which is a function of the structural parameter determining the import price stickiness and the import share of total consumption. By imposing a larger nominal rigidity on the foreign producer, indicated by a lower α_p, a smaller exchange rate pass-through is generated. A higher cost of adjusting prices implies that less of an exchange rate movement will affect the current price. Furthermore, these adjustment costs lead to gradual changes in the price, implying that the producer alters the price charged in this period in the direction of the expected future optimal price.[10] Lastly, ε_t^{π} is a supply disturbance (i.e. a domestic cost-push shock) that is assumed to follow the autoregressive process, $\varepsilon_{t+1}^{\pi} = \tau_{\pi}\varepsilon_t^{\pi} + u_{t+1}^{\pi}$, where u_{t+1}^{π} is an iid disturbance with zero mean and variance σ_{π}^2.

The aggregate demand relation is obtained using a standard Euler equation for the (representative) household's intertemporal choice of consumption, and the CES function:

$$\begin{aligned} y_t = {} & \mathrm{E}_t y_{t+1} - \beta_q \mathrm{E}_t(\pi_{t+1}^M - \pi_{t+1}^D) - \beta_i(i_t - \mathrm{E}_t\pi_{t+1}) + \beta_e(\mathrm{E}_t\pi_{t+1}^D - (\mathrm{E}_t e_{t+1} - e_t) - \mathrm{E}_t\pi_{t+1}^*) \\ & - \beta_y^*(\mathrm{E}_t y_{t+1}^* - y_t^*) + \varepsilon_t^y, \end{aligned} \tag{2}$$

where i_t is the domestic interest rate, π_t^* is foreign inflation, and y_t^* is foreign output. ε_t^y is a demand shock (e.g. to preferences) that follows, $\varepsilon_{t+1}^y = \tau_y \varepsilon_t^y + u_{t+1}^y$, where u_{t+1}^y is an iid disturbance with zero mean and variance σ_y^2. Domestic output is a function of expected future output, the change in the expected future relative price of imports, $\mathrm{E}_t\Delta(p_{t+1}^M - p_{t+1}^D)$, the real interest rate, the change in the expected future relative price of exports, $\mathrm{E}_t\Delta(p_{t+1}^D - e_{t+1} - p_{t+1}^*)$, and the change in expected future foreign output.[11] The (change in the) relative price of imports appears through its effect on domestic demand for domestic goods, while the (change in the) relative price of exports and the (change in) foreign output show up due to their influence on foreign demand for domestic goods. The difference between the demand relation in equation (2) and a full pass-through demand curve lies in the deviation from the law of one price

[10] Roberts (1995) shows that the behaviour of the aggregate price is similar using the Rotemberg (1982) approach for introducing price stickiness, as when using the Calvo (1983) formulation (which, in contrast, renders staggeredness in the individual prices).

[11] Note that the relative price *level* affects the intratemporal allocation between consumption of imports and domestic goods, while the *change* in the relative price affects the intertemporal consumption decision. However, observe additionally that all difference terms disappear when solving equation (2) forward;

$$y_t = \beta_q(p_t^M - p_t^D) - \beta_i \sum_{s=0}^{\infty} \mathrm{E}_t(i_{t+s} - \pi_{t+s+1}) - \beta_e(p_t^D - e_t - p_t^*) + \beta_y^* y_t^* + \sum_{s=0}^{\infty} \mathrm{E}_t \varepsilon_{t+s}^y,$$

using the appropriate transversality conditions.

(i.e. $p_t^M \neq p_t^* + e_t$), which makes the relative price of imports ($p_t^M - p_t^D$) and the (inverse of the) relative price of exports ($p_t^D - e_t - p_t^*$) diverge. The limited pass-through is thus implicitly incorporated, also in the aggregate demand relation, through the import price (p_t^M).

The exchange rate fulfills a modified uncovered interest rate parity condition, linking the expected exchange rate change to the difference in domestic and foreign interest rates:

(3) $\quad i_t - i_t^* = \mathrm{E}_t e_{t+1} - e_t + \varepsilon_t^{\phi}$,

where i_t is the domestic interest rate, i_t^* is the foreign interest rate, and ε_t^{ϕ} is a risk premium following, $\varepsilon_{t+1}^{\phi} = \tau_{\phi}\varepsilon_t^{\phi} + u_{t+1}^{\phi}$, where u_{t+1}^{ϕ} is an iid disturbance with zero mean and variance σ_{ϕ}^2. Anything affecting this interest rate differential will also affect the exchange rate (such as foreign, and domestic, inflation or output shocks that generate some policy response) which is why 'independent' exchange rate shocks can be hard to distinguish. However, since risk premium shocks have the same (short-run) effects as autonomous disturbances to expectations about the future exchange rate, the risk premium shocks can be interpreted as 'pure' exchange rate disturbances.

The foreign economy consists of exogenous AR(1) processes for inflation and output, and a simple Taylor rule with some persistence added, determining the foreign interest rate (see e.g. Clarida et al. (2000)):

(4) $\quad y_{t+1}^* = \rho_y^* y_t^* + u_{t+1}^{y*}$,

(5) $\quad \pi_{t+1}^* = \rho_{\pi}^* \pi_t^* + u_{t+1}^{\pi*}$,

(6) $\quad i_t^* = (1-\rho_i^*)(b_{\pi}^* \pi_t^* + b_y^* y_t^*) + \rho_i^* i_{t-1}^* + u_t^{i*}$,

where ρ_y^*, ρ_{π}^*, ρ_i^* are non-negative coefficients less than unity, and u_{t+1}^{y*}, $u_{t+1}^{\pi*}$, u_{t+1}^{i*} are iid disturbances with zero mean and variance σ_{y*}^2, $\sigma_{\pi*}^2$, and σ_{i*}^2 , respectively.

2.2. Social preferences and policy implementation

To evaluate the central bank's alternative objectives, and performance, the following social loss function is assumed to prevail in the economy:

$$
(7) \qquad \begin{array}{ll} \min & E_t \sum_{j=0}^{\infty} \beta^j L_{t+j}^S \\ \text{where} & L_t^S = \left[\pi_t^2 + \lambda^S y_t^2 \right], \end{array}
$$

such that the social loss consists of quadratic deviations of CPI inflation and output from their (constant and zero) targets, and λ^S is the relative weight society puts on output stabilization. The output target is assumed to be equal to the natural output level so that there is no inflation bias in the model.[12]

That society cares about inflation stems from the fact that the nominal rigidities in the model cause a relative price dispersion between goods. Such price dispersion is detrimental for social welfare, since it induces differences in output across otherwise identical producers.[13] Woodford (2001) suggests that the *general* price level should be stabilized in economies with nominal rigidities, in order to reduce this price dispersion between flexible and fixed price producers. Stabilization of (CPI) inflation can reduce the price dispersion and hence, uncertainty about future real consumption, which is welfare improving for the risk averse consumers. In a closed economy, CPI inflation and domestic inflation are equivalent. However, this is not the case in an open economy, and some argue that domestic inflation, rather than CPI inflation, determines the open economy-welfare criterion.[14] On the other hand, CPI inflation targeting might better mitigate the two distortions that arise in the model used here, namely that domestic *and* import prices are both sticky (given incomplete exchange rate pass-through).[15] When the open economy-policy maker seeks to stabilize the economy around the flexible price outcome, the consequences of high interest rate variability must be considered, since this induces exchange rate fluctuations and terms of trade distortions.[16]

[12] The theoretical underpinnings of this objective function are characterized by a second-order Taylor approximation of the expected utility of a representative household (see Woodford (2001) for a closed economy derivation).

[13] Note, however, that foreign and domestic producers are not identical in this model. For instance, they use somewhat different inputs in production.

[14] Benigno and Benigno (2000) show that the open economy welfare criterion can be characterized by a loss function based on stabilization of consumption and domestic inflation, assuming producer currency pricing and full pass-through. Given incomplete exchange rate pass-through, Sutherland (2001) derives the welfare function in terms of the variances of domestic prices and the nominal exchange rate. However, Corsetti and Pesenti (2001) show that the open economy monetary policy objective can be represented as (equivalent) functions of either, *i*) expected markups, *ii*) the consumer price index, or *iii*) the output gap and deviations from the law of one price. As a result, they conclude that the use of appropriate policy trade-offs is important (i.e. that optimal policies trade off a larger output gap for lower import prices).

[15] Benigno (2001) shows that a weighted average of two regional inflation rates should be targeted in an optimal currency area, given nominal rigidities in both regions.

[16] Moreover, the consumption bundle, consisting of domestic and foreign goods, is priced in terms of aggregate prices, which is why agents intuitively care about CPI inflation.

As the discount factor, β, approaches unity, the intertemporal loss function becomes proportional to the unconditional mean of the period loss function, implying that the following relation can be used to quantify the social preferences (see e.g. Svensson (2000)):

$$(8) \qquad \mathrm{E}\left[L_t^S\right] = \mathrm{var}(\pi_t) + \lambda^S \ \mathrm{var}(y_t).$$

The monetary policy, in turn, is assumed to be implemented through a policy objective function, from which an explicit reaction function for the policy instrument can be obtained. The policy maker is lacking (certain) commitment technologies so that she, by assumption, solves her optimization problem under discretion and re-optimizes every period, treating the agents' expectations as given and independent of the current policy choice. The central bank adjusts its policy instrument, i.e. the nominal interest rate, to minimize the intertemporal loss function:

$$(9) \qquad \min_{\{i_{t+j}\}_{j=0}^{\infty}} \qquad \mathrm{E}_t \sum_{j=0}^{\infty} \beta^j L_{t+j}^{CB},$$

where β is a discount factor, and L_t^{CB} is the central bank period loss function. The question at hand is whether the central bank should pursue a different objective than that of the social preferences. Because of the stabilization bias occuring under a discretionary policy, the objective that is delegated to the policy maker (L_t^{CB}) need not necessarily be identical to the social loss function (L_t^S).

2.3. Policy delegation

Two issues are studied in this paper; *i)* how are the prior findings of (discretionary) optimal policy inertia affected by open economy aspects and incomplete exchange rate pass-through? *ii)* Is there a role for an explicit exchange rate objective in the policy maker's loss function? The stabilization bias may be reduced, and social welfare improved, by delegating a policy objective incorporating, for example, some interest rate smoothing, low output stabilization, or the stabilization of nominal or real exchange rates.

Consider, for example, that the policy maker (in contrast to the assumption made above) can commit to repeatedly raising interest rates. In this case, a smaller interest rate adjustment renders the same effect as a discretionary policy. The reason is that expectations about the future are affected by the current monetary policy choice under commitment. Since agents are forward-looking, the policy maker can, in this case, exploit the private agents' expectations about inflation and output, when implementing the monetary policy, although there is no inflation bias in this model. By just looking at equation (1), one sees that a smaller contraction in aggregate demand yields the adequate drop in inflation if expectations about future inflation can be lowered by, for example, committing to some policy choice. A commitment policy could then diminish the interest rate variance, reduce the loss and thereby make the trade-off between inflation and output variability more efficient.[17] Given that the commitment response is more inertial than the discretionary policy, the latter might possibly be improved upon by making it more persistent. Accordingly, Woodford (1999) suggests that by assigning a different objective function to the policy maker, with larger weight on interest rate smoothing than that of the society's objective, the discretionary outcome can be brought closer to the commitment solution.[18] This results from exploiting the agents' forward-looking behaviour, and the role of expectations. Woodford argues that interest rate persistence implies that expectations about future short interest rate changes yield a greater effect on *long* rates, and thereby also have a more substantial impact on aggregate demand.[19] Consequently, the larger weight on interest rate smoothing seems to be a way of simulating a 'commitment environment', which improves social welfare.

Walsh (1999) shows that there are gains from appointing a conservative banker in Rogoff's (1985) sense (i.e. with a lower degree of output stabilization than society) in an open economy with full pass-through when using a non-inertial rule (i.e. with no interest rate smoothing). As in Woodford's case of interest rate inertia, the reasoning builds on the possibility of exploiting the private agents' expectations. Consider a cost-push shock that raises inflation. If the policy maker is perceived to emphasize inflation objectives, expected future inflation will rise less (compared to if the output stabilization, in contrast, is larger). This implies that less of an output reduction is needed, which improves the inflation-output variability trade-off. In Rogoff's 'conservative banker' case as well as in Woodford's 'interest rate inertia' case, the policy maker is hence perceived to emphasize inflation objectives, either directly through lower output stabilization or, as in the latter case, indirectly through larger interest rate persistence.

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[17] A smaller initial *nominal* interest rate change is required to alter demand if inflation expectations can be lowered, since the induced *real* interest rate will be larger in this case (see equation (2)).

[18] Other examples of delegation schemes that make monetary policy more inertial are; nominal income growth targeting (Jensen (2001)), money growth targeting (Söderström (2001)), and price level targeting (Vestin (2000)). These schemes are not dealt with, in this paper, however.

[19] That future expected interest rates, i.e. the *long* interest rate, are of importance for output can be seen by solving equation (2) forward (see Footnote 11).

The reason why nominal or real exchange rate stabilization might be beneficial for social welfare, or to be more precise, might reduce the discretionary stabilization bias, is the exchange rate's role of transmitting monetary policy. By alleviating fluctuations in, for example, the nominal exchange rate, the policy maker gets a better chance of controlling the inflation-output variability trade-off in the face of certain shocks, such as domestic demand shocks, as mentioned in the Introduction. Since every interest rate adjustment also implies a change in the exchange rate, such an additional exchange rate stabilization-objective could internalize the actual impact caused by an interest rate response, which as well feeds into the economy through the exchange rate. Hence, this suggests that the total effect of monetary policy is taken into account, and that considerable variation in the exchange rate might be avoided.[20] However, recall that if the policy maker puts some weight on interest smoothing, the volatility in the nominal exchange rate is probably already kept small. Alternatively, by directly stabilizing the real exchange rate (i.e. either the relative price of imports or the relative consumer price) the central bank might, straight off, achieve a more stable inflation rate. The welfare improvement will, consequently arise from a more efficient stabilization of consumption, which is affected by relative price distortions that might possibly be mitigated by an exchange rate objective. However, note that the exchange-rate augmented policies might, indirectly, reduce the stabilization bias, since they imply a more inertial reaction function.

The central bank period objective function is quadratic in deviations of CPI inflation and output from their constant targets (normalized to zero), and quadratic in variations of the interest rate. This objective function is augmented with different exchange-rate terms according to the following:

(10a) $$L_t^{\Delta i} = \pi_t^2 + \lambda^{CB} y_t^2 + \nu_i (i_t - i_{t-1})^2,$$

(10b) $$L_t^{\Delta e} = \pi_t^2 + \lambda^{CB} y_t^2 + \nu_i (i_t - i_{t-1})^2 + \mu_{\Delta e}(e_t - e_{t-1})^2,$$

(10c) $$L_t^{TOT} = \pi_t^2 + \lambda^{CB} y_t^2 + \nu_i (i_t - i_{t-1})^2 + \mu_{(p^M - p^D)}(p_t^M - p_t^D)^2,$$

(10d) $$L_t^{PPP} = \pi_t^2 + \lambda^{CB} y_t^2 + \nu_i (i_t - i_{t-1})^2 + \mu_{(p^* + e - p)}(p_t^* + e_t - p_t)^2,$$

where λ^{CB} is the relative weight on output stabilization, ν_i is the parameter determining the rate of interest rate smoothing, and $\mu_{\Delta e}$, $\mu_{(p^M - p^D)}$ and $\mu_{(p^* + e - p)}$ are the relative weights on

[20] For a somewhat related discussion of incorporating the exchange rate into simple policy rules, see, e.g., Ball (1999), and Taylor (2001).

exchange rate stabilization. The central bank's *benchmark* objective is to directly implement the social preferences, which is accomplished by assigning equation (10a) with $\lambda^{CB} = \lambda^{S}$ and v_i = 0. Appointing a policy maker with preferences for interest rate smoothing and low output stabilization implies $v_i > 0$ and $\lambda^{CB} < \lambda^{S}$, respectively. The exchange rate is incorporated into the policy objective through quadratic deviations (from zero targets) of either; b) the nominal exchange rate difference, c) the relative import price (i.e. the inverse of the terms of trade), or d) the relative price between foreign and domestic CPIs (hereafter called deviations from Purchasing Power Parity (PPP)).[21]

Given incomplete exchange rate pass-through, the two real exchange rate definitions in equations (10c) and (10d) are not equivalent. The first exchange rate characterization is, in fact, a sub-set of the latter real exchange rate definition. That is, deviations from PPP in equation (10d) consist of two parts; the relative price of imports, as in equation (10c), as well as an explicit term capturing deviations from the Law of One Price.[22]

Policy adjustments of the nominal interest rate will feed into the economy via the real interest rate and the exchange rate. The real interest rate and the exchange rate both affect aggregate demand which, in turn, affects inflation, but the exchange rate also has a direct effect on inflation through changes in import prices. The two components in CPI inflation, that is, inflation of domestic goods (π_t^D) and inflation of import goods (π_t^M), are linked differently to the transmission channels of monetary policy. The inflation of import goods only responds to exchange rate alterations, while the inflation of domestic goods is affected by real interest rate changes (i.e. via aggregate demand changes) as well as by exchange rate changes. Since the degree of pass-through affects the extent to which exchange rate movements have an impact on the economy, it will influence the monetary policy transmission as well as the degree of exposure to foreign shocks, such as exchange rate disturbances.

[21] A possible extension is to include stabilization of the nominal exchange rate *level* in the delegated policy. However, this requires a different state-space representation where the (possibly non-stationary) level of the exchange rate is introduced. When the state vector contains non-stationary variables, it is though unclear whether the numerical algorithm captures the solution to the policy maker's problem. However, a feasible alternative (keeping the state vector stationary) is to expand the state-space representation with several lagged changes in the nominal exchange rate. In the limit, targeting the sum of these terms will approximate exchange rate level targeting. Note, however, that such an approach does not seem to change the main results obtained in the paper.

[22] That is, $(p_t^* + e_t - p_t) = (1-\kappa_M)(p_t^M - p_t^D) + (p_t^* + e_t - p_t^M)$.

The model (i.e. equations (1)-(6)) can be represented in state-space form, implying that the central bank's optimization problem can be expressed as a linear-quadratic problem (see the Appendix). The central bank's objective function, equations (9) and (10), closes the model. In the discretionary case, the central bank's reaction function will relate the interest rate to the predetermined variables of the model, and these reaction coefficients are unraveled by iterating on the value function.[23] The model is solved by numerical methods, described in e.g. Söderlind (1999), and therefore requires some parameterization.

2.4. Parameterization

To illustrate the monetary policy trade-off under different policy objectives, and varying degrees of exchange rate pass-through, the social loss is calculated using the choice of model parameters and shock variances shown in Table 1. These are chosen along the lines of e.g. Svensson (2000).[24]

Table 1: Parameter values

Social preferences	Supply relation	Demand relation	Foreign economy	Shock persistence	Shock variance
$\beta = 0.99$	$\kappa_M = 0.3$	$\beta_q = 1.26$	$\rho_y^* = 0.8$	$\tau_\pi = 0.8$	$\sigma_\pi^2 = 0.4$
$\lambda^S = 0.5$	$\alpha_\pi = 0.99$	$\beta_i = 0.35$	$\rho_\pi^* = 0.8$	$\tau_y = 0.8$	$\sigma_y^2 = 0.6$
	$\alpha_y = 0.056$	$\beta_e = 1.8$	$\rho_i^* = 0.8$	$\tau_\phi = 0.8$	$\sigma_\phi^2 = 0.8$
	$\alpha_q = 0.007$	$\beta_y^* = 0.27$	$b_y^* = 0.5$		$\sigma_{\pi*}^2 = 0.05$
	$\alpha_p = \{30, 0.6, 0.15, 0.03\}$		$b_\pi^* = 1.5$		$\sigma_{y*}^2 = 0.1$
					$\sigma_{i*}^2 = 0$

Since the degree of exchange rate pass-through in this model is generated by the nominal rigidity imposed on the foreign producer, pass-through is highly dependent on the exogenously given degree of import price stickiness. The level of adjustment costs (i.e. the level of nominal rigidity captured in parameter α_p) is chosen such that the degree of partial exchange rate pass-

[23] In the commitment case, the current behaviour of monetary policy additionally affects the private agents' expectations, which is why the optimal commitment policy also depends on the shadow prices of the forward-looking variables.

[24] The parameters are based on underlying deep model parameters that imply the following; a discount factor yielding an annual interest rate of 4% (assuming quarterly periods), a price elasticity of demand generating a 20 % markup over marginal cost, an import share consisting of 30 % of total consumption, an export share of 30 % of aggregate demand, an intertemporal elasticity of substitution of 0.5, and a parameter linking output to marginal costs such that the steady-state output elasticity of marginal costs is 0.8. Disturbance variances are more or less taken from Leitemo and Røisland (2000).

through is 0.99, 0.66, 0.33, and 0.09, respectively. In the first case, an exchange rate movement, consequently, immediately alters the import price by 99 % of the exchange rate movement. Hence, this set of values captures the standard open economy case of almost full pass-through, and three intermediate cases of incomplete pass-through. The empirical evidence seems to suggest that also small open economies lie in one of the intermediate categories. Adolfson (1997) reports 21 % immediate, partial, exchange rate pass-through, and another 12 % within a month, to aggregate Swedish import prices, whereas Naug and Nymoen (1996) obtain something like a 20% pass-through per quarter for data on aggregate Norwegian imports.

3. Optimal policy objectives - results

The model is numerically solved, resulting in an explicit reaction function for the central bank, as well as the transition matrix for the state variables (see the Appendix). The transition matrix is subsequently used to calculate the asymptotic variances of, for example, inflation and output which, in turn, determine the policy trade-off and the social loss (see equation (8)), under the various policy objectives.

3.1. Optimal interest rate inertia and optimal output stabilization

Figures 1 and 2 illustrate that social loss can be reduced by appointing a discretionary policy maker with a larger degree of interest rate smoothing or with a lower degree of output stabilization, compared to the preferences of the society.[25] This implies that the open-economy policy maker can exploit expectations about inflation and output as in the commitment case, which consequently produces a better trade-off between inflation and output stabilization. It seems that such a reduction in the loss can be achieved irrespective of whether pass-through is complete or incomplete.

Figure 1 shows that the inflation-output trade-off frontier is situated closer to the origin as the policy maker puts more weight on interest rate stabilization (i.e. larger v_i). In some sense, the policy maker 'commits' to continuously fighting inflation, thereby implying that current inflation can be lowered with a smaller output reduction. Further, the optimal rate of interest

[25] The economy is hit by a combination of all disturbances, with variances specified in Table 1 (see the Appendix for the variance-covariance matrix). Recall that only the social welfare and the inflation-output trade-off are affected by the size of the shocks. The policy maker's reaction function is certainty equivalent and thus independent of the disturbances' covariance matrix.

rate smoothing appears to be smaller in the cases with more limited pass-through (cf. Figures 1a and 1d).

Figure 2a shows that appointing a 'Rogoff-conservative' policy maker reduces the social loss. Note, however, that the adverse effects of driving output stabilization entirely to zero are fairly large. Moreover, the optimal degree of output stabilization does not seem to be dependent on the degree of pass-through.

Hence, although the policy maker's reaction function is already based on lagged variables, such as the prior relative price, some additional policy inertia seems to be reducing the social loss.[26] The reason for this is that additional policy inertia, for instance generated by an interest rate smoothing objective, implies that the agents' expectations about future policy are affected. This is especially apparent in the model used here, where the persistence comes from exogenous disturbances. The nominal price rigidity per se only renders forward-looking behaviour of the agents, and does not imply any backward-looking components in the equilibrium relations. Both the supply and the demand relations thus lack explicit backward-looking terms, so that their dependence on past values of the endogenous variables only comes from the policy rule (see equations (1) and (2)).[27]

Table 2 displays the optimal policy weights, and the resulting social loss, when delegating equation (10a) to the policy maker. Neither the reduction in social loss nor the optimal weight on output stabilization are dependent on the degree of pass-through, but the optimal degree of interest rate smoothing is increasing in the degree of pass-through (see Table 2).[28,29] The optimal weight on interest rate stabilization is thus larger in the full pass-through case, compared to if pass-through is low.

The reason for the interrelation between the interest rate smoothing and the exchange rate pass-through is that incomplete pass-through induces some inherent persistence into the policy reaction function. This might be explained by considering an exchange rate disturbance. A low

[26] Details on the reaction function are found in Table A1 in the Appendix.

[27] Note that even if the demand and supply relations were more backward-looking, changes in the policy rule would alter the agents' expectations. However, some forward-looking components are necessary for inertial policy-making to be optimal.

[28] Comparing the absolute loss *level* across different pass-through cases is of limited interest, since these cases represent different structural economies.

[29] The optimal interest rate inertia is also increasing in the degree of pass-through for $\lambda^{CB} = 0.5$, when narrowing the grid (not shown).

pass-through implies that the exchange rate movement is only incorporated into the import price to a small extent. Because of this low pass-through, the move towards the long-run steady-state (with complete pass-through) is gradual, which implies that the exchange rate disturbance has a prolonged effect on inflation. Hence, when pass-through is low, the policy maker will require a smaller, but more persistent, response to an exchange rate disturbance (i.e. a risk premium shock).

Table 2: Social loss (L^S) and optimized policy parameters ($\hat{\lambda}^{CB}$, $\hat{v}_i$), equation (10a)

	Benchmark	Optimizing the policy weights concerning:						
	$v_i = 0$	interest rate		output		output and interest rate jointly		
	$\lambda^{CB} = 0.5$	$\lambda^{CB} = 0.5$		$v_i = 0$				
Pass-through	$L^{CB} = L^S$	$\hat{v}_i$	Rel. L^S	$\hat{\lambda}^{CB}$	Rel. L^S	$\hat{\lambda}^{CB}$	$\hat{v}_i$	Rel. L^S
0.99	22.368	0.3	0.996	0.1	0.857	0.1	1.0	0.781
0.66	22.214	0.3	0.995	0.1	0.847	0.1	0.9	0.773
0.33	21.648	0.3	0.994	0.1	0.842	0.1	0.7	0.771
0.09	19.156	0.2	0.995	0.1	0.849	0.1	0.4	0.787

Note: The optimized policy weights are established by a grid search, with step 0.1, over the values 0-1.

Such a response can also be seen from the policy reaction function. Compared to the full pass-through case, the policy maker responds less to a risk premium shock (ε_t^{ϕ}) when pass-through is small, while concurrently adjusting its interest rate more to the lagged interest rate (i_{t-1}) (see Table A1b in the Appendix). The reaction coefficient on i_{t-1} is thus decreasing in the degree of pass-through. Consequently, also the optimal interest rate inertia (v_i) will be dependent on the degree of pass-through. Since the degree of actual interest rate persistence (measured as the reaction coefficient on the lagged interest rate) is larger when pass-through is small, it is not necessary to induce as large interest rate smoothing (i.e. increasing v_i) as in the full pass-through case.

The gains from appointing a 'Rogoff banker' appears to be larger than the gains from optimizing the degree of interest rate smoothing, i.e. appointing a 'Woodford banker' (see Table 2). Although the driving mechanism of both welfare improvements works through the expectation channel, the direct emphasis on inflation objectives (i.e. lower λ^{CB}) appears to have a greater influence on agents' expectations than the interest rate smoothing objective. The amount of optimal inertia, or persistence in the policy responses, is though dependent on the degree of output stabilization. Larger weights on output stabilization and on interest rate smoothing *both* imply that inflation is more gradually brought back to the targeted level of inflation. This similar role thus implies that less *additional* interest rate persistence, in the form of an interest rate smoothing objective, is required when the weight on output stabilization is large. Consequently, the additive value of optimizing the degree of interest rate smoothing becomes larger, the lower is the degree of output stabilization (λ^{CB}).

3.2. Optimal exchange rate stabilization

Now, consider the question of whether the exchange rate should be incorporated in the policy objective in order to enhance social welfare. Could some form of exchange rate stabilization capture the same type of favourable policy inertia, as induced by an interest rate smoothing objective, and reduce the discretionary stabilization bias? Figures 3a-3c illustrate the social loss under the three exchange-rate augmented loss functions (i.e. equations (10b) – (10d)). The welfare gains from delegating an exchange rate objective, if any, appear to be minor. Table 3 confirms this outcome, displaying the social loss and the optimized exchange rate parameters for a given level of (separately optimized) output and interest rate stabilization.[30]

The policy maker does not seem to be able to improve social welfare through equation (10b) by limiting fluctuations in the nominal exchange rate. The optimized weight on the exchange rate difference, $\hat{\mu}_{\Delta e}$, is zero in all pass-through cases (see Table 3).[31] Hence, trying to smooth out changes in the nominal exchange rate does not create the same kind of policy inertia that was found to be beneficial for the social loss above.[32] In contrast, a positive weight on nominal exchange rate stabilization appears to create excessive variability in output and relative prices (not shown). In fact, unrestrained exchange rate adjustments might be helpful in alleviating disturbances requiring relative price adjustments, which then make this kind of policy persistence detrimental.

[30] Recall that the coefficients placed on each objective are *relative* weights, implying that it is difficult to compare the size of specific policy weights between the benchmark case and cases incorporating additional variables.
[31] Note that Sutherland (2000) finds that CPI inflation targeting creates too little volatility in the nominal exchange rate, and that social welfare improves if the exchange rate level is included in the central bank objective function. Consequently, the optimal weight on the nominal exchange level rate turns out to be negative in Sutherland's full pass-through model (while the optimal output stabilization is zero). This effectively replicates domestic inflation targeting, which is the first-best outcome in that particular model, implying that the exchange rate element of CPI inflation should optimally be offset. On the other hand, in the model used here, targeting CPI inflation is welfare enhancing (see the discussion below).
[32] Note, however, that there seems to be some role for exchange rate stabilization (i.e. $\mu_{\Delta e} > 0$) if the stabilization bias is worse or, in other words, if the policy maker uses a more gradual policy (see Section 4.1. below).

Neither targeting the relative price of imports in equation (10c), (i.e. stabilizing the (inverse of the) terms of trade), nor alleviating deviations from PPP through equation (10d), seems to considerably improve social welfare. The optimized policy weights on the different real exchange rate definitions are zero, or close to zero, in most pass-through cases (see Table 3).[33] Neither the full pass-through case, nor the two intermediate pass-through cases, indicates that any of the exchange-rate terms should be incorporated into the policy maker's objective function. It is only for the case with the smallest pass-through that some real exchange rate stabilization is welfare improving to any noticeable extent. This is somewhat surprising, given that the expenditure switching effects (or the relative price distortions) caused by exchange rate movements ought to be small in this case, at least in the face of risk premium shocks. However, note that the volatility of the endogenously determined exchange rate increases as pass-through decreases (see Table A2 in the Appendix). When pass-through is low, a country-specific shock can not be absorbed by the (exogenously) sticky import price, and the required relative price adjustments are therefore generated through lager movements in the endogenously determined exchange rate. This implies that the unconditional variance of the relative price of imports is, in fact, larger when pass-through is low than when pass-through is complete, which induces a policy response to the real exchange rate in the former case.[34]

Table 3: Social loss (L^S) and optimized exchange rate policy parameters

Pass-through	equation (10a)			equation (10b)		equation (10c)		equation (10d)	
	$\hat{\lambda}^{CB}$	$\hat{v}_i$	L^S	$\hat{\mu}_{\Delta e}$	Rel. L^S	$\hat{\mu}_{(p^M-p^D)}$	Rel. L^S	$\hat{\mu}_{(p^*+e-p)}$	Rel. L^S
0.99	0.1	1.0	17.461	0	1.0	0	1.0	0	1.0
0.66	0.1	0.9	17.176	0	1.0	0	1.0	0	1.0
0.33	0.1	0.7	16.683	0	1.0	-0.1	0.998	0	1.0
0.09	0.1	0.4	15.082	0	1.0	0.4	0.979	0.1	0.983

Note: The output and interest rate stabilization is separately optimized to reflect the marginal advantage of incorporating an exchange-rate term. The optimized exchange rate weights are established by a grid search, with step 0.1, over the values -1 to 1. However, some negative parameters do not yield a solution to the system.

[33] The results do not seem to be affected by the degree of policy inertia (v_i). Even without any interest rate smoothing, the optimal exchange rate weights are low in most cases (see Table A3 in the Appendix).

[34] Note that Devereux and Engel (2000) show that with zero pass-through, the optimal policy objective in their model is independent of the exchange rate volatility. When pass-through is zero, the optimal policy is therefore consistent with fixed exchange rates in response to real shocks. In the full pass-through case, the exchange rate is, in contrast, employed for stabilizing consumption, although there is now a welfare cost of exchange rate volatility. However, this volatility is traded off for the benefits of exchange rate adjustments in reducing consumption variance.

3.3. Domestic inflation targeting

It might be argued that the low optimized weights on the different exchange rate objectives above originate from the fact that the exchange rate is already *indirectly* incorporated in the policy maker's objective function through targeting CPI inflation and output, which is why a *direct* aim is redundant. Since inflation and output are both affected by exchange rate fluctuations, and agents are forward-looking, future exchange rate expectations are already incorporated into the realized outcomes of inflation and output (see e.g. equation (1)). If this is the case, it suggests that the exchange rate should be given a different emphasis if the policy maker, in contrast, targets domestic inflation. Since the direct exchange rate component that enters CPI inflation through import prices, is filtered out from domestic inflation, certain effects of an exchange rate movement are removed.[35,36] Consequently, if stabilizing the exchange rate is truly important, the optimized weight must be larger if the policy maker targets domestic inflation.

Comparing the social loss under CPI inflation targeting and domestic inflation targeting indicates that the former scheme provides larger welfare (cf. Tables 2 and 4). The difference between the two targeting schemes is about 3% for the full pass-through case, but becomes smaller as the degree of pass-through decreases. This suggests that the indirect exchange rate component of CPI inflation is, in fact, beneficial for the policy outcome. Note also that the nominal exchange rate volatility is slightly lower when targeting CPI inflation (see Table A2 in the Appendix). However, although it appears to be better for the policy maker to target CPI inflation, the welfare improvement of including an exchange-rate term is not larger under domestic inflation targeting (see Table 4b). The direct exchange rate responses do not seem to be given higher emphasis and overall, the optimized exchange rate coefficients appear to be quite similar to the ones under CPI targeting. Consequently, *explicit* exchange rate stabilization does not play a welfare enhancing role, irrespective of whether the policy maker targets CPI inflation or domestic inflation, while an *implicit* exchange rate response through CPI inflation targeting is beneficial.

[35] Despite this, the exchange rate still influences domestic inflation both via expenditure switching effects in aggregate demand, as well as via imported input intermediates.

[36] Recall that there are no transmission lags of the monetary policy in this model, which implies that the policy maker will react to all disturbances, permanent as well as temporary. If, in contrast, the policy maker faces transmission lags in the effect of monetary policy, interest rate adjustments to temporary fluctuations in the real exchange rate (i.e. deviations from purchasing power parity) might produce excessive variations in both inflation and output, which is clearly undesirable for the policy maker (see e.g. Taylor (2001)). In that case, the policy maker would aspire to exactly filter out temporary inflationary impulses (stemming from short-run departures from the law of one price), from the inflation measure she is targeting.

Table 4a: Social loss (L^S), and optimized output and interest rate stabilization ($\hat{\lambda}^{CB}$, $\hat{v}_i$), under domestic inflation targeting

	equation (10a), π^D - targeting							
		Optimizing the policy weights concerning:						
	$v_i = 0$	interest rate		output		output and interest rate jointly		
	$\lambda^{CB} = 0.5$	$\lambda^{CB} = 0.5$		$v_i = 0$				
Pass-through	L^S	$\hat{v}_i$	Rel. L^S	$\hat{\lambda}^{CB}$	Rel. L^S	$\hat{\lambda}^{CB}$	$\hat{v}_i$	Rel. L^S
0.99	22.951	0.2	0.997	0.1	0.839	0.1	0.6	0.777
0.66	22.614	0.2	0.996	0.1	0.842	0.1	0.7	0.770
0.33	21.856	0.2	0.994	0.1	0.849	0.1	0.7	0.772
0.09	19.175	0.2	0.994	0.1	0.878	0.1	0.6	0.800

Table 4b: Social loss (L^S), and optimized exchange rate stabilization ($\hat{\mu}_{\Delta e}, \hat{\mu}_{(p^M-p^D)}, \hat{\mu}_{(p^*+e-p)}$), under domestic inflation targeting

	π^D - targeting								
Pass-	equation (10a)			equation (10b)		equation (10c)		equation (10d)	
through	$\hat{\lambda}^{CB}$	$\hat{v}_i$	L^S	$\hat{\mu}_{\Delta e}$	Rel. L^S	$\hat{\mu}_{(p^M-p^D)}$	Rel. L^S	$\hat{\mu}_{(p^*+e-p)}$	Rel. L^S
0.99	0.1	0.6	17.827	0.1	0.988	0	1.0	0	1.0
0.66	0.1	0.7	17.421	0.1	0.993	0	1.0	0	1.0
0.33	0.1	0.7	16.879	0	1.0	-0.1	0.997	0	1.0
0.09	0.1	0.7	15.346	0	1.0	0.3	0.985	0.1	0.982

As discussed in Section 2.2., it seems as if society should be concerned about CPI inflation when pass-through is incomplete. Note, however, that the results are qualitatively robust to changing the social preferences, such that society values stable *domestic* inflation (i.e. evaluating the delegated policies from a social loss function of the form; $L^D = \text{var}(\pi^D) + \lambda^S \text{var}(y)$). In particular, the results suggest that the policy maker should target CPI inflation, even if domestic inflation is an argument in the social loss function (cf. Tables 5a and 5b). The reason is that exchange rate fluctuations indirectly also influence domestic inflation. Movements in the exchange rate affect the domestic producer's marginal cost through intermediate imports and through relative price changes in aggregate demand. By targeting CPI inflation, the policy maker achieves an implicit response to the exchange rate, which also reduces the domestic inflation variability. Since CPI inflation targeting generates lower exchange rate volatility, which improves the variance trade-off between domestic inflation and output, this is helpful for stabilizing domestic inflation.

Table 5a: Social loss ($L^D = \text{var}(\pi^D) + \lambda^S \text{var}(y)$), and optimized policy parameters, delegating CPI inflation targeting

Pass-through	π - targeting								
	equation (10a)			equation (10b)		equation (10c)		equation (10d)	
	$\hat{\lambda}^{CB}$	$\hat{v}_i$	L^D	$\hat{\mu}_{\Delta e}$	Rel. L^D	$\hat{\mu}_{(p^M-p^D)}$	Rel. L^D	$\hat{\mu}_{(p^*+e-p)}$	Rel. L^D
0.99	0.1	1.2	17.643	0	1.0	0	1.0	0	1.0
0.66	0.1	1.0	17.522	0	1.0	0	1.0	0	1.0
0.33	0.1	0.7	17.277	0	1.0	-0.1	0.997	0	1.0
0.09	0.1	0.4	16.345	0	1.0	0.5	0.972	0.1	0.982

Table 5b: Social loss ($L^D = \text{var}(\pi^D) + \lambda^S \text{var}(y)$), and optimized policy parameters, delegating domestic inflation targeting

Pass-through	π^D - targeting								
	equation (10a)			equation (10b)		equation (10c)		equation (10d)	
	$\hat{\lambda}^{CB}$	$\hat{v}_i$	L^D	$\hat{\mu}_{\Delta e}$	Rel. L^D	$\hat{\mu}_{(p^M-p^D)}$	Rel. L^D	$\hat{\mu}_{(p^*+e-p)}$	Rel. L^D
0.99	0.1	0.7	17.942	0.1	0.991	0	1.0	0	1.0
0.66	0.1	0.7	17.735	0.1	0.997	0	1.0	0	1.0
0.33	0.1	0.7	17.468	0	1.0	0	1.0	0	1.0
0.09	0.1	0.5	16.581	0	1.0	0.4	0.98	0.1	0.98

4. Robustness

4.1. Increased stabilization bias and exchange-rate augmented policies

How do the exchange-rate augmented policy functions perform when the discretionary stabilization bias is worse? That is, although the explicit exchange rate stabilization is not welfare improving compared to delegating a policy optimized with respect to output and interest rate stabilization, the exchange rate may play a role if, for some reason, a conservative 'Rogoff-banker' can not be appointed.

A larger weight on output stabilization implies that the delegated policy is more gradual, compared to the case when a 'Rogoff-conservative' banker, with lower output weight, is appointed. This, in turn, has consequences for the exchange-rate augmented policy functions. Gradual interest rate responses imply that risk premium shocks yield prolonged departures of the exchange rate from its long-run level, for example. Note also that exchange rate volatility is higher when output stabilization is larger (not shown). Consequently, there seems to be more reason to stabilize the exchange rate in this case.

As a result, when the policy weight on output stabilization is kept at the same level as the social preferences (i.e. $\lambda^{CB} = \lambda^{S} = 0.5$), the optimized weight on the nominal exchange rate change, in equation (10b), turns out positively in every pass-through case. Moreover, this reduces social loss by up to 15% (see Table A4 in the Appendix). On the other hand, the results regarding the real exchange-rate augmented policy functions are somewhat more ambiguous. As is the case when output stabilization is optimized, stabilization of the terms of trade, or of the departures from PPP, can not reduce social loss in the full pass-through case, but improves welfare when pass-through is low.

4.2. Other parameterizations

Can an exchange rate objective play a welfare improving role if the economy becomes more open, where openness is measured in terms of import and export shares? A more open economy implies that the exposure to foreign disturbances increases, and that the impact on both demand and supply relations is greater, thereby requiring larger interest rate responses. However, although the real exchange rate affects inflation and output more significantly in this case, the exchange rate per se is less influenced. Since the domestic sector is already affected, there is less need for exchange rate induced relative price adjustments, which lower the exchange rate volatility (not shown). Therefore, neither nominal, nor real, exchange rate stabilization yields any substantial welfare enhancement, compared to delegating a policy function with optimal output and interest rate stabilization (see Table A5a in the Appendix). Consequently, the results appear to be qualitatively robust to changing the degree of openness.

The importance of the exchange rate channel also increases if the risk premium becomes more persistent, or if the relative variances of risk premium disturbances and other foreign shocks increase. Persistent shocks warrant more prolonged interest rate responses, which is why the optimal interest rate inertia is slightly larger in this case (see Table A5b in the Appendix).

However, there are still no welfare improvements from explicitly stabilizing the exchange rate, as long as the delegated policy is optimized with respect to output and interest rate stabilization. Larger variances of the foreign disturbances, in turn, imply that the optimal policy must be somewhat more aggressive to offset these shocks. Since this is reflected by a lower degree of interest rate smoothing, welfare is not improved by adding an explicit exchange-rate term to the policy maker's other (optimized) objectives (see Table A5c in the Appendix).

5. Conclusions

The optimal discretionary policy objective is analyzed within a forward-looking aggregate supply-aggregate demand model, adjusted for incomplete exchange rate pass-through. The monetary policy trade-off between inflation and output variability is eased as the degree of pass-through decreases, since the exchange rate channel then transmits monetary policy, and foreign disturbances, to a smaller extent. This implies that also the delegated policy objective function is dependent on the degree of pass-through in the economy.

However, there are only small welfare improvements, if any, of incorporating an explicit nominal, or real, exchange-rate term in the policy maker's optimized objective function. Neither the stabilization of nominal exchange rate changes, nor of real exchange rates (i.e. either the relative price of imports, or deviations from Purchasing Power Parity), does improve the policy maker's performance in terms of social welfare. However, an indirect exchange rate response, achieved by targeting CPI inflation, appears to be sufficient for reducing the social loss somewhat, compared to if the policy maker targets domestic inflation. The reason is that expectations about future exchange rates affect both inflation and output, and that CPI inflation targeting generates lower exchange rate volatility. Moreover, CPI inflation targeting seems to do better than domestic inflation targeting, irrespective of whether the exchange rate pass-through is limited or complete. This result is neither dependent on the society's preferences for CPI inflation stabilization or domestic inflation stabilization.

Still, there are other aspects than the relative price distortions above that can be altered, such that a different objective than that of the society is delegated to the policy maker. The results indicate that some of the stabilization bias that occurs under a discretionary policy can be mitigated through appointing a 'Rogoff-conservative banker' with lower weight on output stabilization or through appointing an interest rate smoothing policy maker ('Woodford banker'). By exploiting the agents' expectations about future policy, the inflation-output trade-off is made more favourable which, in turn, reduces social loss. The welfare improvement of 'pure' interest rate smoothing appears to be low, while combining a low weight on output stabilization with interest rate smoothing gives a sizeable effect.

The optimized weight on output stabilization appears, in principle, to be independent of the degree of pass-through. In contrast, the policy weight on the optimized interest rate inertia is increasing in the degree of pass-through. The reason is that incomplete, and gradual, pass-though requires a prolonged interest rate response when, for example, a risk premium disturbance hits the economy. This inherent interest rate persistence consequently implies that less additional interest rate inertia, in the form of an interest rate smoothing objective, is needed when pass-through is incomplete.

Appendix

A.1. The central bank's optimization problem

The two components in aggregate (CPI) inflation, that is inflation of import goods and inflation of domestic goods, follow:

(A1) $$\pi_t^M = \beta \, \mathrm{E}_t \pi_{t+1}^M + \frac{\alpha_p}{\kappa_M}\left(p_t^* + e_t - p_t^M\right),$$

(A2) $$\pi_t^D = \beta \, \mathrm{E}_t \pi_{t+1}^D + \frac{1}{(1-\kappa_M)}\left(\alpha_y y_t + \alpha_q (p_t^M - p_t^D) + \varepsilon_t^\pi\right).$$

To formulate the state-space representation of the model, the following identities are additionally used:

(A3) $$(p_t^M - p_t^D) = (p_{t-1}^M - p_{t-1}^D) + \pi_t^M - \pi_t^D,$$

(A4) $$(p_t^* + e_t - p_t^M) = (p_{t-1}^* + e_{t-1} - p_{t-1}^M) + \pi_t^* + \Delta e_t - \pi_t^M.$$

This implies that the complete model, i.e. the system of equations (1)-(6), the three shock processes[37], plus (A1)-(A4), can be rewritten in state-space form:

(A5) $$\tilde{A}_0 \begin{bmatrix} x_{1,t+1} \\ \mathrm{E}_t x_{2,t+1} \end{bmatrix} = \tilde{A} \begin{bmatrix} x_{1,t} \\ x_{2,t} \end{bmatrix} + \tilde{B} i_t + \tilde{\upsilon}_{t+1},$$

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

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

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

where $x_{1,t}$ is a 9×1 vector of predetermined state variables, $x_{2,t}$ is a 4×1 vector of forward-looking variables, and $\tilde{\upsilon}_{t+1}$ is a 13×1 vector of disturbances,

[37] That is, $\varepsilon_{t+1}^\pi = \tau_\pi \varepsilon_t^\pi + u_{t+1}^\pi$, $\varepsilon_{t+1}^y = \tau_y \varepsilon_t^y + u_{t+1}^y$, and $\varepsilon_{t+1}^\phi = \tau_\phi \varepsilon_t^\phi + u_{t+1}^\phi$.

$$\tilde{A}_0 = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -b_y^*(1-\rho_i^*) & 1 & -b_\pi^*(1-\rho_i^*) & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & (1-\kappa_M)\beta_i+\beta_q+\beta_e & \kappa_M\beta_i-\beta_q & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{\kappa_{a_q}}{(1-\kappa_M)} & 0 & 0 & \beta_\pi & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{a_p}{\kappa_M} & 0 & 0 & \beta_\pi & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix},$$

$$\tilde{A} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \rho_y^* & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \rho_i^* & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \rho_\pi^* & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \tau_\pi & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \tau_\phi & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \tau_y & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & -1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & -1 & 1 \\ 0 & -\beta_y^*(1-\rho_y^*) & -\beta_e & \rho_\pi^*\beta_e & 0 & -\beta_e & -1 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & -\frac{a_y}{(1-\kappa_M)} & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & -1 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix},$$

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

The policy maker's control problem is a standard stochastic linear-quadratic problem:

(A6)
$$\begin{aligned} J(x_t) &= \min_{i_t}\left\{x_t'\tilde{Q}x_t + \beta\,\mathrm{E}_t J(x_{t+1})\right\} = \min_{i_t}\left\{\begin{bmatrix} x_t' & i_t' \end{bmatrix}\begin{bmatrix} Q & U \\ U' & R \end{bmatrix}\begin{bmatrix} x_t \\ i_t \end{bmatrix} + \beta\,\mathrm{E}_t J(x_{t+1})\right\} = \\ &= \min_{i_t}\left\{x_t'Qx_t + 2x_t'Ui_t + i_t'Ri_t\right\} + \beta\,\mathrm{E}_t J(x_{t+1}), \end{aligned}$$

where Q, U and R are matrices mapping the goal variables (i.e. π_t, y_t, $(i_t - i_{t-1})$) to the state variables. In the discretionary case, the value function will be quadratic in the predetermined state variables, $J(x_t) = x_{1,t}V_t x_{1,t} + \omega_t$, and the forward-looking variables will be a linear function of the predetermined variables, $x_{2,t} = H^d x_{1,t}$ (see e.g. Söderlind (1999)). V is a matrix and ω is a scalar, both to be determined by iterating on the value function. The first order condition of this problem relates the interest rate to the predetermined variables, $i_t = F^d x_{1,t}$. This also implies that the predetermined variables can be written as, $x_{1,t+1} = M^d x_{1,t} + \upsilon_{t+1}$, where M^d is a matrix depending on F^d, H^d and the structural parameters in the state-space representation. The dynamics of the system under discretion is thus the following:

(A7a) $x_{1,t+1} = M^d x_{1,t} + \upsilon_{t+1}$,

(A7b) $x_{2,t} = H^d x_{1,t}$,

(A7c) $i_t = F^d x_{1,t}$.

This system has a stable solution if the number of stable eigenvalues in M^d equals the number of predetermined variables. The numerical algorithm then captures the solution, that is, unravels the coefficients in the reaction function, F^d, and in H^d (see Adolfson (2001) for more details).

A.2. Variance-covariance matrices

The unconditional variance-covariance matrix of the disturbance vector, υ_{t+1}, is given by $\Sigma_\upsilon = \begin{bmatrix}\Sigma_{\upsilon 1} & 0_{9\times 4}\end{bmatrix}$, where $\Sigma_{\upsilon 1}$ is defined as:

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

Given that the dynamics of the system can be written as (A7), the asymptotic unconditional variance-covariance matrix of the predetermined variables is given by:

(A8) $\Sigma_{x1} = M^d \Sigma_{x1} M^{d'} + \Sigma_{\upsilon 1}$,

(A9) $\text{vec}(\Sigma_{x1}) = \left[I_{n1^2} - (M^d \otimes M^d)\right]^{-1} \text{vec}(\Sigma_{\upsilon 1})$, using $\text{vec}(A+B)=\text{vec}(A)+\text{vec}(B)$, and $\text{vec}(ABC)=(C^{'}\otimes A)\text{vec}(B)$ (see Rudebusch and Svensson (1999)). The variables of interest can be written as a function of the predetermined variables,

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

implying that the variance-covariance matrix of the interest variables is

(A10) $\Sigma_z = T^d \Sigma_{x1} T^{d'}$.

Table A1a: Reaction function, coefficients in $-F^d$ ($i_t = -F^d x_{1,t}$), benchmark case

	Equation (10a), $\lambda^{CB} = 0.5$, $v_i = 0$								
Pass-through	i_{t-1}	y_t^*	i_t^*	π_t^*	ε_t^π	ε_t^ϕ	ε_t^y	$(p_{t-1}^M - p_{t-1}^D)$	$(p_{t-1}^* + e_{t-1} - p_{t-1}^M)$
0.99	0	0.033	0.932	-0.679	3.596	0.932	0.195	-0.0248	0
0.66	0	0.023	0.868	-0.686	3.627	0.868	0.377	0.072	0
0.33	0	0.018	0.83	-0.688	3.697	0.83	0.487	0.128	0
0.09	0	0.021	0.824	-0.678	3.859	0.824	0.503	0.132	0

Table A1b: Reaction function, coefficients in $-F^d$ ($i_t = -F^d x_{1,t}$), with interest rate smoothing

	Equation (10a), $\lambda^{CB} = 0.5$, $v_i = 0.1$								
Pass-through	i_{t-1}	y_t^*	i_t^*	π_t^*	ε_t^π	ε_t^ϕ	ε_t^y	$(p_{t-1}^M - p_{t-1}^D)$	$(p_{t-1}^* + e_{t-1} - p_{t-1}^M)$
0.99	0.015	0.034	0.913	-0.66	3.523	0.913	0.192	-0.024	0
0.66	0.025	0.025	0.842	-0.655	3.503	0.842	0.36	0.067	0
0.33	0.033	0.022	0.797	-0.647	3.529	0.797	0.46	0.12	0
0.09	0.037	0.024	0.786	-0.634	3.66	0.786	0.477	0.125	0

Table A1c: Reaction function, coefficients in $-F^d$ ($i_t = -F^d x_{1,t}$), with optimized policy weights

	Equation (10a), optimized policy weights								
Pass-through	i_{t-1}	y_t^*	i_t^*	π_t^*	ε_t^π	ε_t^ϕ	ε_t^y	$(p_{t-1}^M - p_{t-1}^D)$	$(p_{t-1}^* + e_{t-1} - p_{t-1}^M)$
0.99	0.18	0.05	0.734	-0.448	2.005	0.734	0.076	-0.054	0
0.66	0.237	0.048	0.631	-0.389	1.892	0.631	0.17	0.005	0
0.33	0.264	0.044	0.573	-0.367	1.898	0.573	0.249	0.051	0
0.09	0.239	0.039	0.579	-0.399	2.175	0.579	0.327	0.085	0

Note: The optimized policy weights are $\lambda^{CB} = \{0.1, 0.1, 0.1, 0.1\}$, $v_i = \{1.0, 0.9, 0.7, 0.4\}$ for pass-through = {0.99, 0.66, 0.33, 0.09}, respectively.

Table A2a: Unconditional variance and social loss (L^S); non-optimized policy weights

	Equation (10a), $\lambda^{CB} = 0.5$, $v_i = 0$							
Pass-through	L^S	var (π)	var (y)	var (p^M-	var (Δe)	var (i)	var (π^D)	var (π^M)
0.99	22.368	21.891	0.954	4.501	23.196	16.470	21.892	23.053
0.66	22.214	21.806	0.815	4.010	24.136	16.41	21.995	22.104
0.33	21.648	21.318	0.660	4.198	25.403	16.303	21.889	20.48
0.09	19.156	18.94	0.433	14.634	27.174	16.035	20.593	15.957

Table A2b: Unconditional variance and social loss (L^S); optimized policy weights

	Equation (10a), $\lambda^{CB} = 0.1$, $v_i = \{1.0, 0.9, 0.7, 0.4\}$							
Pass-through	L^S	var (π)	var (y)	var (p^M-	var (Δe)	var (i)	var (π^D)	var (π^M)
0.99	17.461	11.468	11.987	5.36	12.409	8.070	11.667	12.254
0.66	17.176	11.478	11.395	4.953	13.349	7.699	11.825	11.44
0.33	16.683	11.556	10.253	5.226	14.738	7.643	12.151	10.707
0.09	15.082	11.455	7.254	12.675	17.583	8.254	12.718	9.302

Table A2c: Unconditional variance and social loss (L^S); domestic inflation targeting

	Equation (10a), π^D - targeting, $\lambda^{CB} = 0.1$, $v_i = \{0.6, 0.7, 0.7, 0.6\}$							
Pass-through	L^S	var (π)	var (y)	var (p^M-	var (Δe)	var (i)	var (π^D)	var (π^M)
0.99	17.827	13.415	8.822	5.322	14.73	9.353	13.539	14.563
0.66	17.421	12.820	9.201	4.847	15.066	8.547	13.134	12.903
0.33	16.879	12.23	9.298	5.158	15.767	8.035	12.819	11.397
0.09	15.346	11.163	8.366	12.551	17.435	7.863	12.399	9.067

Table A3: Social loss (L^S) and optimized exchange rate parameters; without interest rate smoothing

Pass-through	equation (10a) $\hat{\lambda}^{CB}$	equation (10a) $\hat{v}_i$	equation (10a) L^S	equation (10b) $\hat{\mu}_{\Delta e}$	equation (10b) Rel. L^S	equation (10c) $\hat{\mu}_{(p^M-p^D)}$	equation (10c) Rel. L^S	equation (10d) $\hat{\mu}_{(p^*+e-p)}$	equation (10d) Rel. L^S
0.99	0.1	0	19.173	-0.1	0.999	0	1.0	0.1	0.999
0.66	0.1	0	18.818	0	1.0	0	1.0	0	1.0
0.33	0.1	0	18.22	0	1.0	-0.1	0.999	0.1	0.996
0.09	0.1	0	16.266	0	1.0	0.6	0.970	0.1	0.949

Table A4: Social loss (L^S) and optimized exchange rate policy parameters, under a more gradual policy (i.e. $\lambda^{CB} = 0.5$)

	Policy weights, $\lambda^{CB} = 0.5$, $v_i = 0$						
	Benchmark equation (10a)	equation (10b)		equation (10c)		equation (10d)	
Pass-through	L^S	$\hat{\mu}_{\Delta e}$	L^S	$\hat{\mu}_{(p^M-p^D)}$	L^S	$\hat{\mu}_{(p^*+e-p)}$	L^S
0.99	22.368	2.0	0.848	0	1.0	0	1.0
0.66	22.214	1.8	0.854	0	1.0	0.3	0.998
0.33	21.648	1.5	0.867	0	1.0	0.9	0.963
0.09	19.156	1.0	0.907	6.4	0.778	1.0	0.808

Table A5a: Social loss (L^S) and optimized exchange rate parameters; increased openness

Pass-through	equation (10a)			equation (10b)		equation (10c)		equation (10d)	
	$\hat{\lambda}^{CB}$	$\hat{v}_i$	L^S	$\hat{\mu}_{\Delta e}$	Rel. L^S	$\hat{\mu}_{(p^M-p^D)}$	Rel. L^S	$\hat{\mu}_{(p^*+e-p)}$	Rel. L^S
0.99	0.1	1.3	17.477	0	1.0	0	1.0	0	1.0
0.66	0.1	0.8	16.992	0	1.0	0	1.0	0	1.0
0.33	0.1	0.5	16.007	0	1.0	0	1.0	0.2	0.995
0.09	0.1	0.3	12.70	0	1.0	0.3	0.964	0.1	0.953

Note: Twice the openness compared to the benchmark parameterization. That is, the export and import shares are both 60% of aggregate demand and consumption, respectively, and the share of imported intermediates in production is 20%.

Table A5b: Social loss (L^S) and optimized exchange rate parameters; more persistent risk premium

Pass-through	equation (10a)			equation (10b)		equation (10c)		equation (10d)	
	$\hat{\lambda}^{CB}$	$\hat{v}_i$	L^S	$\hat{\mu}_{\Delta e}$	Rel. L^S	$\hat{\mu}_{(p^M-p^D)}$	Rel. L^S	$\hat{\mu}_{(p^*+e-p)}$	Rel. L^S
0.99	0.1	1.2	17.828	0	1.0	0	1.0	0.1	0.994
0.66	0.1	1.1	17.40	0	1.0	0	1.0	0	1.0
0.33	0.1	1.0	16.832	0	1.0	0.1	0.999	0	1.0
0.09	0.1	0.5	15.199	0	1.0	0	1.0	0	1.0

Note: The risk premium persistence is $\tau_\phi = 0.95$.

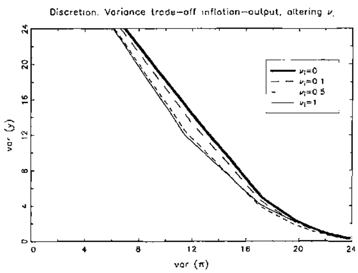
Table A5c: Social loss (L^S) and optimized exchange rate parameters; larger foreign disturbances

Pass-through	equation (10a)			equation (10b)		equation (10c)		equation (10d)	
	$\hat{\lambda}^{CB}$	$\hat{v}_i$	L^S	$\hat{\mu}_{\Delta e}$	Rel. L^S	$\hat{\mu}_{(p^M-p^D)}$	Rel. L^S	$\hat{\mu}_{(p^*+e-p)}$	Rel. L^S
0.99	0.1	0.7	17.78	0	1.0	0	1.0	0.1	0.999
0.66	0.1	0.6	17.476	0	1.0	0	1.0	0	1.0
0.33	0.1	0.5	16.397	0	1.0	0	1.0	0	1.0
0.09	0.1	0.3	15.246	0	1.0	0.4	0.982	0.1	0.977

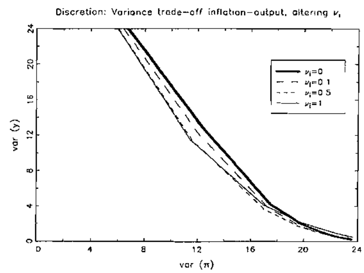
Note: Twice the variance of the foreign disturbance terms compared to the benchmark parameterization (i.e. $\sigma_\phi^2 = 1.6$, $\sigma_{\pi^*}^2 = 0.1$, $\sigma_{y^*}^2 = 0.2$).

Figure 1: Inflation-output variability trade-off under different degrees of interest rate smoothing (v_i)

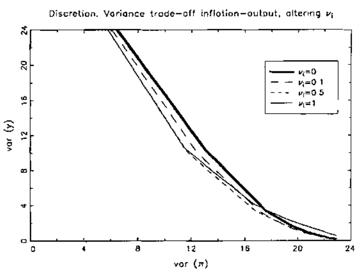
a) Pass-through = 0.99



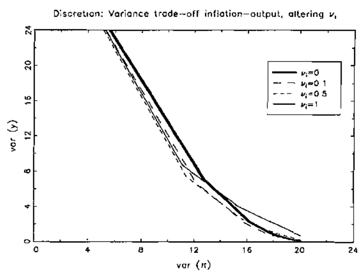
b) Pass-through = 0.66



c) Pass-through = 0.33



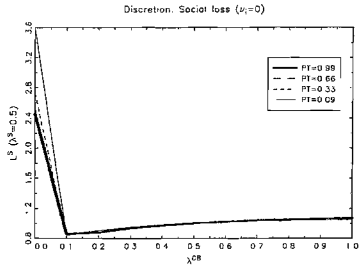
c) Pass-through = 0.09



Note: The degree of output stabilization is altered in equation (10a) such that $\lambda^{CB} = [0,1]$, step 0.1. The y-axis is truncated to circumvent the extreme case of $\lambda^{CB} = 0$, which makes the trade-off frontier skewed.

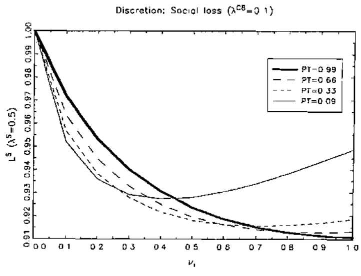
Figure 2: Social loss, varying the different policy weights

a) Output stabilization, λ^{CB}



Note: Relative loss compared to the *benchmark* policy that delegates the social preferences

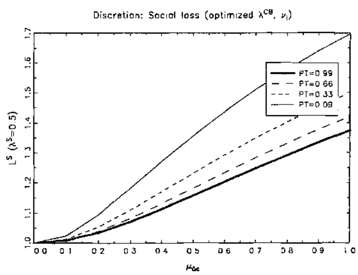
b) Interest rate smoothing, ν_i



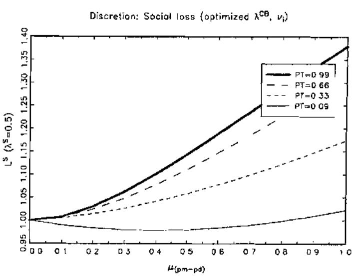
Note: Relative loss compared to an objective *without* interest rate smoothing

Figure 3: Social loss, varying the weights on the exchange-rate terms, equations (10b)–(10d)

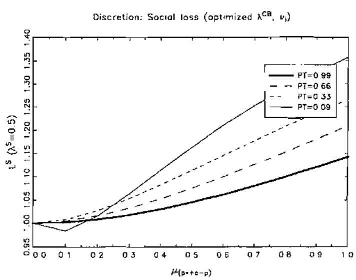
a) Nominal exchange rate change stabilization, $\mu_{\Delta e}$



b) Relative import price stabilization, $\mu_{(p^M-p^D)}$



c) Real exchange rate stabilization, $\mu_{(p^*+e-p)}$



Note: Relative loss compared to the loss resulting from an objective *without* the exchange rate.

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CHAPTER 4

INCOMPLETE EXCHANGE RATE PASS-THROUGH AND SIMPLE MONETARY POLICY RULES

Malin Adolfson*

4

Abstract

The performance of various monetary rules is investigated 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. However, an indirect exchange rate response, through a policy reaction to Consumer Price Index (CPI) inflation rather than to domestic inflation, is welfare enhancing in all pass-through cases. This result is moreover independent of whether society values domestic or CPI inflation stabilization. The only case where a direct real exchange rate response is slightly welfare improving occurs when the other reaction coefficients, on inflation and output, are sub-optimal.

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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 also 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 (in the conduct of monetary policy) by extending her simple policy rule to include a direct feedback from 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 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, by including a lagged exchange-rate term in the policy rule, the central banker could possibly filter out transitory effects of exchange rate fluctuations on inflation, when adjusting the interest rate (Ball (2000)). In this case, a purchasing power parity-adjusted measure of inflation will be targeted, which might imply less volatility in the interest rate. This, in turn, circumvents excessive variations in output. Third, a policy rule including the exchange rate might be less restrictive in that it incorporates a direct reaction to the inflationary impulse, or shock, rather than only responding to the result of the exchange rate movement (i.e. changes in inflation and output). Consequently, this implies a possibility to directly adjust the interest rate and offset the exchange rate effects on, for example, spending.

Prior literature analyzing open economies and simple policy rules has explored a broad set of exchange-rate augmented policy rules, without attaining a complete consensus of whether it is beneficial (or not) 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 the optimal policy rule, where optimality is measured in terms of social welfare, in an open economy with

[1] Among the previously evaluated policies are, for example, rules incorporating the real exchange rate, the current and lagged real exchange rate, or the change in the nominal exchange rate. Ball (1999) and Ball (2000) use a backward-looking model, concluding that the optimal simple rule should encompass a real exchange-rate term and that 'long-run' inflation should be targeted (i.e. excluding transitory effects of the exchange rate). For the use of the exchange rate-augmented policy rules in forward-looking models, see e.g. Batini et al. (2001), Leitemo and Söderström (2001), McCallum and Nelson (1999), and Taylor (2001). The majority of these authors find that, in terms of welfare, the performance of different simple rules is only marginally (if at all) improved by including a direct feedback from some exchange-rate term. In contrast, Monacelli (1999), and Weerapana (2000) both show that the welfare improvement of using a policy rule incorporating an exchange-rate term is somewhat more substantial, at least when the exchange rate pass-through is incomplete or, as in the latter case, when the volatility of exchange rate shocks is large. In addition, Cecchetti et al. (2000) find that a response to the real exchange rate is beneficial, also when using inflation forecast based rules for implementing policy.

incomplete exchange rate pass-through. In particular, the importance of the degree of pass-through is investigated. If the policy maker implements inflation targeting 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? 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 that; *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 response to the *non-optimized* Taylor rule does enhance social welfare somewhat, since it reduces the sub-optimality of the overall policy response (i.e. the resulting interest rate adjustment). *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, and it is not contingent upon society's preferences for either 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 described 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 the agents' optimizing behaviour. 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 some Rotemberg (1982) price stickiness.[2]

[2] For a more thorough discussion of the model and its underlying microfoundations, see Adolfson (2001a).

The economy of primary interest (called domestic) consists of three (log-linearized) equations determining inflation, output, and expected exchange rate changes:[3]

$$\begin{aligned} \text{(1)} \quad \pi_t &= (1-\kappa_M)\pi_t^D + \kappa_M \pi_t^M \\ &= \alpha_\pi \mathrm{E}_t \pi_{t+1} + \alpha_y y_t + \alpha_q (p_t^M - p_t^D) + \alpha_p (p_t^* + e_t - p_t^M) + \varepsilon_t^\pi , \end{aligned}$$

$$\begin{aligned} \text{(2)} \quad y_t &= \mathrm{E}_t y_{t+1} - \beta_q \mathrm{E}_t (\pi_{t+1}^M - \pi_{t+1}^D) - \beta_i (i_t - \mathrm{E}_t \pi_{t+1}) + \beta_e (\mathrm{E}_t \pi_{t+1}^D - (\mathrm{E}_t e_{t+1} - e_t) - \mathrm{E}_t \pi_{t+1}^*) \\ &\quad - \beta_y^* (\mathrm{E}_t y_{t+1}^* - y_t^*) + \varepsilon_t^y , \end{aligned}$$

$$\text{(3)} \quad i_t - i_t^* = \mathrm{E}_t e_{t+1} - e_t + \varepsilon_t^\phi .$$

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 (π_t^D) and imported inflation (π_t^M). 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 (i.e. a particular real exchange rate measure), which turns up because of imported intermediate inputs, and e_t is the nominal exchange rate (domestic currency per unit of foreign currency). Deviations from the law of one price arise due to the nominal import price stickiness and are captured by the term ($p_t^* + e_t - p_t^M$), where the price stickiness parameter α_p governs the degree of exchange rate pass-through. A less complete, or smaller, short-run pass-through occurs in the model by assigning a greater price rigidity, that is, a smaller α_p. Finally, ε_t^π 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}^π is an iid disturbance with zero mean and variance σ_π^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 underlying CES aggregator. Domestic demand shocks (e.g. originating from preference shifts)

[3] 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, E_t denotes rational expectations as of period t.

are captured in ε_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 zero mean and variance σ_y^2. This output relation differs from its full pass-through equivalence because of the (short-run) deviations from the law of one price, which makes the relative price of imports ($p_t^M - p_t^D$) and the relative price of exports ($p_t^D - e_t - p_t^*$) diverge.[4] The internal relative price (of imports) appears through its effect on domestic consumers' demand, while the external relative price (of exports) shows up due to the foreign consumers' demand for domestic goods.

Equation (3) is a modified uncovered interest rate parity condition derived from the consumers' optimal holdings of domestic and foreign bonds, assuming an added risk premium (ε_t^ϕ) to the foreign bond prices. The risk premium is a 'pure' exchange rate disturbance capturing autonomous shocks to expectations about the future exchange rate.[5] The risk premium follows the AR(1) process, $\varepsilon_{t+1}^\phi = \tau_\phi \varepsilon_t^\phi + u_{t+1}^\phi$, where u_t^ϕ is an iid disturbance with zero mean and variance σ_ϕ^2.

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

(4) $$y_{t+1}^* = \rho_y^* y_t^* + u_{t+1}^{y*},$$

(5) $$\pi_{t+1}^* = \rho_\pi^* \pi_t^* + u_{t+1}^{\pi*},$$

(6) $$i_{t+1}^* = (1-\rho_i^*)(b_\pi^* \pi_{t+1}^* + b_y^* y_{t+1}^*) + \rho_i^* i_t^* + u_{t+1}^{i*},$$

[4] The relative price *change* turns up in equation (2) because it affects the intertemporal consumption decision, while the relative price *level* affects the intratemporal allocation between consumption of imports and domestic goods. Note, however, that the difference terms disappear when solving equation (2) forward.

[5] 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.

where ρ_y^*, ρ_π^*, ρ_i^* are non-negative coefficients less than unity, and u_{t+1}^{y*}, $u_{t+1}^{\pi*}$, u_{t+1}^{i*} are iid disturbances with zero mean and variance σ_{y*}^2, $\sigma_{\pi*}^2$ and σ_{i*}^2 , respectively.[6, 7]

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).[8] It might be easier for the central banker 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 directly derived from the policy maker's objective function are more complex and highly contingent upon the particular choice of model representation. 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. 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 following set of different policy rules is therefore simply postulated, and evaluated:

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[6] 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_{t+1}^{y*} and $u_{t+1}^{\pi*}$ are correlated.

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

[8] Adolfson (2001b) discusses the somewhat related issue of what the optimal discretionary policy should be in an open economy with incomplete exchange rate pass-through.

(7a) $i_t = (1-\rho)\left(b_\pi \pi_t + b_y y_t\right) + \rho\, i_{t-1}$,

(7b) $i_t = (1-\rho)\left(b_\pi \pi_t + b_y y_t + b_{\Delta e}(e_t - e_{t-1})\right) + \rho\, i_{t-1}$,

(7c) $i_t = (1-\rho)\left(b_\pi \pi_t + b_y y_t + b_{(pm-pd)}(p_t^M - p_t^D)\right) + \rho\, i_{t-1}$,

(7d) $i_t = (1-\rho)\left(b_\pi \pi_t + b_y y_t + b_{(p*+e-p)}(p_t^* + e_t - p_t)\right) + \rho\, i_{t-1}$,

where b_π, b_y, $b_{\Delta e}$, $b_{(pm-pd)}$ and $b_{(p*+e-p)}$ are the policy maker's reaction coefficients, and ρ is the degree of interest rate persistence. The policy maker sets the interest rate as a linear function of the lagged interest rate and the deviations of CPI inflation and output (and possibly the exchange rate) from their zero targets.[9] Equation (7a), setting $\rho = 0$, is the simple rule suggested by Taylor (1993), while Clarida et al. (2000) advocate that the persistence parameter, ρ, is typically 0.8-0.9 for this simple rule to be consistent with the empirical evidence. Three other rule specifications incorporate the exchange rate in some form. Equation (7b) 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 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. Consequently, equation (7c) incorporates the relative price of imports into the policy rule, while equation (7d) uses a different definition of the real exchange rate, namely the relative consumer price. Hence, the latter two rules both adjust the interest rate to a particular real exchange rate specification, but because of incomplete pass-through, the two characterizations of the real exchange rate are not equivalent. ($p^M - p^D$) in equation (7c) captures the terms of trade, while ($p^* + e - p$) in equation (7d) captures deviations from purchasing power parity (PPP) between the foreign and 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

[9] Note that equations (7a)-(7d) 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, that, in turn, relate the forward-looking variables to the predetermined variables. Moreover, note that the subsequent results are qualitatively robust to changing the policy rule so that, in contrast, the interest rate only depends on lagged variables.

[10] Note that there are no transmission lags of monetary policy here, why 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 probably wants to disregard transitory exchange rate movements.

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.

The above suggested policy rules are evaluated in terms of a social loss function. Social preferences are assumed to follow a standard objective function with quadratic deviations of CPI inflation and output from their constant target levels (here normalized to zero for simplicity):

$$(8) \qquad \min_{\{i_{t+j}\}_{j=0}^{\infty}} \quad E_t \sum_{j=0}^{\infty} \beta^j L_{t+j}^S$$
$$\text{where} \quad L_t^S = \left[\pi_t^2 + \lambda^S y_t^2\right],$$

where $0 < \beta < 1$ is a discount factor, and λ^S is the relative weight society puts on output stabilization.[11] To minimize the social loss function and find the optimal simple rule, the model (equations (1)-(6)) is expressed in state-space form (see Appendix A), implying that the minimization in equation (8) can be stated as a linear-quadratic problem. The policy maker is assumed to be able to commit to either of the simple policy rules in equation (7). As the discount factor, β, 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)):

$$(9) \qquad E\left[L_t^S\right] = \text{Var}(\pi_t) + \lambda^S \text{Var}(y_t).$$

The loss function in equation (9) is used to assess which rule in equation (7) provides a superior stabilization of the economy, as well as for optimizing the reaction coefficients in each policy rule. Equation (9) is estimated using asymptotic variances that can be obtained from the solution (or transition matrix) of the model, which are both described in Appendix A. The model is solved using numerical methods, for example described in Söderlind (1999), why it needs to be

[11] In a closed economy, Woodford (2001) shows that this objective function represents a second-order Taylor approximation of the expected utility for the representative household, making it a reasonable welfare measure for monetary policy. This loss function is also appropriate in an open economy with incomplete pass-through, since the relative price distortion that occurs due to sticky domestic prices *and* rigid import prices can be mitigated with stable CPI inflation. Stabilization of CPI inflation consequently reduces the uncertainty about future real consumption, which is welfare improving for the risk averse consumers. For a detailed discussion of the open economy-social objectives and their pass-through aspects, see Section 3.4. below.

parameterized. The parameter values shown in Table 1 are based on underlying deep parameters, which are chosen along the lines of prior literature.

Table 1: Parameterization

Social preferences	Benchmark policy rule	Supply relation	Demand relation	Foreign economy	Shock persistence	Shock variance
$\beta = 0.99$	$b_\pi = 1.5$	$\kappa_M = 0.3$	$\beta_q = 1.26$	$\rho_y^* = 0.8$	$\tau_\pi = 0.8$	$\sigma_\pi^2 = 0.4$
$\lambda^S = 0.5$	$b_y = 0.5$	$\alpha_\pi = 0.99$	$\beta_i = 0.35$	$\rho_\pi^* = 0.8$	$\tau_y = 0.8$	$\sigma_y^2 = 0.6$
	$\rho = 0.8$	$\alpha_y = 0.056$	$\beta_e = 1.8$	$\rho_i^* = 0.8$	$\tau_\phi = 0.8$	$\sigma_\phi^2 = 0.8$
		$\alpha_q = 0.007$	$\beta_y^* = 0.27$	$b_y^* = 0.5$		$\sigma_{\pi*}^2 = 0.05$
		$\alpha_p = \{30, 0.6, 0.15, 0.03\}$		$b_\pi^* = 1.5$		$\sigma_{y*}^2 = 0.1$
						$\sigma_{i*}^2 = 0.01$

The parameter of main interest for the twist of this paper, is the exchange rate pass-through related parameter (α_p) governing the level of adjustment costs, and thereby also the degree of pass-through. It is chosen in order to cover four different rates of exchange rate pass-through; a full-pass through case (99%), and three intermediate cases of incomplete pass-through (66%, 33%, and 9%).[12] 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.[13] Further, the variances of the disturbance terms are more or less taken from a structural vector auto-regression on Norwegian data (see Leitemo and Røisland (2000)). The benchmark 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; 0.8.

[12] For empirical basis of incomplete exchange rate pass-through in small open economies, see e.g. Adolfson (1997), and Naug and Nymoen (1999).

[13] See Adolfson (2001a) for an exact mapping between the parameters shown in Table 1 and these deep parameters.

3. Results

3.1. Standard (non-optimized) reaction coefficients

Figure 1 illustrates the social loss from implementing monetary policy through the three exchange-rate augmented policy rules, varying the degree of exchange rate reactions. The reaction coefficients on inflation, output and the lagged interest rate are the ones suggested by Taylor (1993), and Clarida et al. (2000), while the response coefficient on the respective exchange-rate term varies between -1 and 1. Inclusion of an exchange rate reaction, through any of the three rules, seems to reduce social loss somewhat. Moreover, the optimal degrees of exchange rate response appear to be dependent on the degree of pass-through (cf. Figures 1a and 1d).

This is also 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. 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. However, the results indicate that the welfare improvement of incorporating either the *nominal exchange rate change*, the *terms of trade*, or *deviations from PPP*, is moderate (i.e. 0-4% enhancement). Note though that the rules incorporating the real exchange rate perform somewhat better in terms of social welfare, than the rule including the nominal exchange rate change. The largest welfare gain appears to be occurring when the policy maker responds to deviations from PPP. One reason could be that this term better captures the distortion that occurs due to the price stickiness in the model, namely departures from the law of one price. Recall that low pass-through implies less influence of foreign disturbances. On the other hand, this lower pass-through is induced by larger nominal rigidity. Consequently, the policy maker faces a trade-off between the lower effects of exchange rate fluctuations and the larger deviations from the flexible price outcome.

Table 2: Social loss (L^S) and optimized exchange rate reaction coefficients ($\hat{b}_{\Delta e}, \hat{b}_{(pm-pd)}, \hat{b}_{(p^*+e-p)}$), using standard reaction coefficients on (b_π, b_y, ρ)

	$b_\pi = 1.5,\ b_y = 0.5,\ \rho = 0.8$						
	equation (7a)	equation (7b)		equation (7c)		equation (7d)	
Pass-through	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	1	0.3	0.98	0.4	0.964	0.6	0.963
0.66	1	0.2	0.992	0.3	0.982	0.6	0.96
0.33	1	0.1	0.997	0.2	0.994	0.6	0.96
0.09	1	0	1.0	0	1.0	0.4	0.971

Note: For some parameter values in the grid search (over −1 to 1 with step 0.1), the specified decision rule does not stabilize the system (i.e. there is no unique solution).

3.2. Optimized reaction coefficients

Note that the standard reaction coefficients (i.e. $b_\pi = 1.5$, $b_y = 0.5$, and $\rho = 0.8$) need not be optimal for the particular model used here, 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, the inclusion of any additional state variable will probably 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, optimizing the other reactions (on inflation, output, and the interest rate persistence) will reduce the sub-optimality of the simple rule, which partly mitigates this problem. Therefore all policy reactions are optimized, using a grid search over a range of values.

Table 3a displays the optimized reaction coefficients on inflation, output, and the interest rate persistence for the policy rule without the exchange rate (i.e. equation (7a)). Note that the optimal interest rate persistence is very high, for all pass-through cases, which is also consistent with the monetary policy conduct actually observed (see Clarida et al. (1998)). Moreover, the response coefficients for the optimized rule do not at all resemble the policy rule suggested by Taylor (1993). In contrast to Taylor's rule, the optimized responses to both inflation and output are much larger here, while their relative difference appears to be less sizeable, irrespective of the degree of pass-through. 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), and Rudebusch and

Svensson (1999)).[14] Note also that the inflation response appears to be slightly larger in the full pass-through case, compared to the two intermediate cases of incomplete pass-through. Since the exchange rate channel in the full pass-through case transmits shocks to a greater extent, this requires a more forceful policy reaction. The differences are rather small, however, and moreover, dependent on which disturbances enter the economy (see Figure 3 for impulse responses).

Figure 2 describes the social loss resulting from the optimized rule, adding different degrees of exchange rate reactions. The welfare enhancement of following these exchange-rate augmented rules is, if any, very small. As a result of optimizing all reaction coefficients, the role of the exchange rate in the policy rule thus appears to be less notable, compared to the findings above.

Table 3b shows the optimized response coefficients on the different exchange-rate terms, as well as the relative social loss. The responses on inflation, output, and the lagged interest rate are optimized separately, in order to scrutinize the marginal value of incorporating the exchange rate.[15] 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. Although small, the optimized reactions on the nominal exchange rate change and the terms of trade are increasing in the degree of pass-through, while the response to deviations from PPP does not appear to increase monotonically with larger pass-through. However, the welfare improvement of incorporating the nominal exchange rate change, or one of the two real exchange-rate terms, is practically zero in most pass-through cases (i.e. less than 0.1%).

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-

[14] 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.

[15] Another way of measuring the additive value of the exchange rate is to simultaneously optimize all reaction coefficients, and subsequently 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.

through.[16] 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 CPI inflation raises the interest rate.

Table 3a: Social loss (L^S) and optimized reaction coefficients ($\hat{b}_\pi, \hat{b}_y, \hat{\rho}$); equation (7a)

Pass-through	equation (7a) $\hat{\rho}$		
	$\hat{b}_\pi$	$\hat{b}_y$	$\hat{\rho}$
0.99	3.7	2.8	0.8
0.66	3.5	2.6	0.8
0.33	3.4	2.6	0.8
0.09	3.8	3.2	0.8

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

	$\hat{b}_\pi, \hat{b}_y, \hat{\rho}$ optimized (see Table 3a)						
	equation (7a)	equation (7b)		equation (7c)		equation (7d)	
Pass-through	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	1	0.1	0.9995	0.1	0.9998	0.2	0.9998
0.66	1	0.1	0.9999	0	1.0	0.1	0.9998
0.33	1	0	1.0	-0.2	0.999	0.2	0.9995
0.09	1	-0.1	0.999	-0.6	0.988	0.9	0.989

Note: b_π, b_y, ρ are optimized separately (see Table 3a) in order to reflect the marginal advantage of incorporating an exchange-rate term. The optimized exchange rate responses are established by a grid search over –1 to 1, with step 0.1.

Altogether, the results 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 other optimized responses. 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

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

positive exchange rate reaction) precisely implies a larger interest rate response to inflationary impulses reflected in the exchange rate, which thus results in an implicit development towards the optimized policy rule *without* the exchange rate.

3.3. Responding to domestic inflation

Another reason why the exchange-rate augmented rules are only marginally, if at all, welfare improving, might be that the instrument rule already contains an implicit reaction to the exchange rate, realized through the response to CPI inflation. Consequently, Taylor (2001) suggests that the CPI inflation-interest rate rule includes a sufficient exchange rate response. If, in contrast, the policy maker adjusts the interest rate to domestic inflation (π^D), most of the direct exchange rate impact is filtered out.[17] 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 therefore analyzed using domestic inflation as a reaction variable.

Table 4 presents the social loss and the optimized response coefficients, when the policy rule consists of domestic 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. Furthermore, the results in Tables 3 and 4 show that the inclusion of any exchange-rate term is *relatively* more welfare enhancing under the domestic inflation rule than under the CPI inflation rule, although the differences are very small. This reflects that some of the exchange rate reaction, in fact, is inherent in the CPI inflation response, as discussed above. Still, there is no strong indication that a *direct* exchange rate response should be added to the optimized policy rule.

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

Table 4: Relative social loss and optimized reaction coefficients, policy reaction to domestic inflation (π_t^D)

Pass-through	equation (7a)				equation (7b)		equation (7c)		equation (7d)	
	$\hat{b}_\pi$	$\hat{b}_y$	$\hat{\rho}$	L_d^S/L^S	$\hat{b}_{\Delta e}$	Rel. L_d^S	$\hat{b}_{(pm-pd)}$	Rel. L_d^S	$\hat{b}_{(p^*+e-p)}$	Rel. L_d^S
0.99	3.8	3.0	0.8	1.013	0.2	0.999	0.3	0.999	0.4	0.999
0.66	3.4	2.6	0.8	1.01	0.1	0.999	0.1	0.9998	0.4	0.999
0.33	5.5	4.6	0.9	1.0	0.2	0.9996	-0.1	0.9998	0.7	0.998
0.09	3.3	2.9	0.8	1.024	0	1.0	-0.7	0.982	1.0	0.98

Note: L_d^S/L^S denotes the relative loss compared to delegating equation (7a) based on CPI inflation. Rel. L_d^S represents the relative loss between the respective exchange-rate augmented rule and equation (7a), based on domestic inflation (i.e. the loss reduction from exchange rate stabilization under domestic inflation targeting). b_π, b_y, ρ are optimized separately in order to reflect the marginal advantage of incorporating an exchange-rate term.

3.4. Social preferences

As seen above, the question of whether to incorporate the exchange rate in the open economy-policy rule is related to the issue of what inflation measure the interest rate adjustment optimally is based on. This in turn might, however, be dependent on the society's particular welfare function. What is the correct objective function of an open economy? In a model with nominal rigidities, where prices do not adjust simultaneously, unnecessary variation in the relative price of goods (which, in turn, generates inflationary impulses) can be avoided by keeping the *general* price level stabilized (Woodford (2001)). The effects of nominal rigidities, that is the relative price distortions, can thereby be neutralized.

Some authors have argued that domestic inflation stabilization, rather than CPI inflation stabilization, characterizes the open economy-welfare criterion (see, for example, Sutherland (2001)). However, this reasoning builds on an assumption of full pass-through, such that import prices are in fact fully flexible. In this case, the distortion can be alleviated, and the flexible price outcome restored by stabilizing domestic inflation, to which the price stickiness pertains. On the other hand, in the model used here, both domestic and import prices are sticky, given incomplete pass-through. This implies that the distortion applies to both foreign and domestic producers, why *general* translates into the consumer price index to which the producers' relate their own price. Consequently, this suggests that CPI inflation should be stabilized when pass-through is incomplete.[18]

The results are in all pass-through cases, nonetheless, robust to evaluating the exchange-rate augmented rules from a social loss function including domestic inflation, that is $L_t^D = \mathrm{var}(\pi_t^D) + \lambda^S \mathrm{var}(y_t)$.[19] This is shown in Table 5, which displays the social loss (L_t^D), and the optimized policy reactions, from policy rules based on either CPI inflation or domestic 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. The reason is that exchange rate volatility is lower under a policy rule based on CPI inflation (see Table 1 in the Appendix). This, in turn, is helpful also for stabilizing domestic inflation, since the latter is affected by exchange rate fluctuations through imported intermediate inputs. The lower exchange rate volatility improves the variance trade-off between domestic inflation and output, which thus is less considerable if the policy maker responds to CPI inflation (see Figure 4). Consequently, interest rate rules based on CPI inflation will be more welfare enhancing than the rules reacting to domestic inflation.

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

Pass-through	equation (7a)				equation (7b)		equation (7c)		equation (7d)	
	$\hat{b}_\pi$	$\hat{b}_y$	$\hat{\rho}$	L^D	$\hat{b}_{\Delta e}$	Rel. L^D	$\hat{b}_{(pm-pd)}$	Rel. L^D	$\hat{b}_{(p^*+e-p)}$	Rel. L^D
0.99	3.5	2.7	0.8	1	0.1	0.9997	-0.1	0.9999	-0.1	0.9999
0.66	3.3	2.5	0.8	1	0.2	0.9999	-0.2	0.9997	0	1.0
0.33	3.4	2.6	0.8	1	0	1.0	-0.3	0.998	0.1	0.9999
0.09	3.9	3.1	0.8	1	-0.2	0.999	-0.7	0.988	0.8	0.991

[18] Benigno (2001) shows that a weighted average of the two inflation rates (in an optimal currency area) should be targeted, given equal nominal rigidities across the two sectors.
[19] Note also that the results are not (qualitatively) affected by whether an interest rate smoothing-objective is included in either of the two social loss functions.

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

Pass-	equation (7a)				equation (7b)		equation (7c)		equation (7d)	
through	$\hat{b}_\pi$	$\hat{b}_y$	$\hat{\rho}$	L_d^D/L^D	$\hat{b}_{\Delta e}$	Rel. L_d^D	$\hat{b}_{(pm-pd)}$	Rel. L_d^D	$\hat{b}_{(p^*+e-p)}$	Rel. L_d^D
0.99	3.5	2.8	0.8	1.01	0.2	0.998	0.1	0.9999	0.1	0.9999
0.66	3.3	2.6	0.8	1.009	0.2	0.999	-0.1	0.9999	0.3	0.986
0.33	5.5	4.6	0.9	0.9994	0.2	0.9996	-0.4	0.999	0.5	0.999
0.09	3.4	2.8	0.8	1.023	0	1.0	-0.7	0.984	1.0	0.983

Note: L_d^D/L^D denotes the relative loss compared to delegating equation (7a) based on CPI inflation. Rel. L_d^D represents the relative loss between the respective exchange-rate augmented rule and equation (7a), based on domestic inflation (i.e. the loss reduction from exchange rate stabilization under domestic inflation targeting). b_π, b_y, ρ are optimized separately in order to reflect the marginal advantage of incorporating an exchange-rate term.

4. Robustness issues

Does the exchange rate have an explicit role (in the monetary policy conduct) if the economy becomes more open in terms of larger import and export shares? In this case, foreign disturbances have a larger impact on the domestic economy, and one might think that this should also affect the policy rule. Nonetheless, adding an exchange-rate term to the (re)optimized policy rule does not notably improve welfare. The reaction coefficients on inflation and output do, however, appear to be increasing in the degree of openness (see Table A2 in the Appendix).

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. However, neither in this case do the exchange-rate augmented rules imply any greater welfare improvements compared to the fully optimized policy rule. Note though that the other reactions on inflation and output compensate for the lack of an explicit exchange-rate term, so that the resulting policy rule is anyhow a lot more vigorous (see Table A3 in the Appendix).

The same applies if the relative variances of the foreign disturbances are larger. 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 outperform the fully optimized rule (see Table A4 in the Appendix).

5. Conclusions

The performance of various open-economy policy rules is analyzed 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 do not outperform the optimized Taylor rule. Neither nominal, nor real, exchange rate responses do enhance the stabilization of the economy. There are no sizeable social welfare improvements from using exchange-rate augmented rules, irrespective of the degree of pass-through, given optimized reactions to inflation and output.

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

Appendix

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

To formulate the model (i.e. equations (1)-(6)) in state-space form, the following components, shock processes, and identities are used:

(A1a) $\pi_t^M = \beta \, \mathrm{E}_t \pi_{t+1}^M + \frac{\alpha_p}{\kappa_M}\left(p_t^* + e_t - p_t^M\right),$

(A1b) $\pi_t^D = \beta \, \mathrm{E}_t \pi_{t+1}^D + \frac{1}{(1-\kappa_M)}\left(\alpha_y y_t + \alpha_q (p_t^M - p_t^D) + \varepsilon_t^\pi\right),$

(A2a) $\varepsilon_{t+1}^\pi = \tau_\pi \varepsilon_t^\pi + \upsilon_{t+1}^\pi,$

(A2b) $\varepsilon_{t+1}^y = \tau_y \varepsilon_t^y + \upsilon_{t+1}^y,$

(A2c) $\varepsilon_{t+1}^\phi = \tau_\phi \varepsilon_t^\phi + \upsilon_{t+1}^\phi,$

(A3a) $(p_t^M - p_t^D) = (p_{t-1}^M - p_{t-1}^D) + \pi_t^M - \pi_t^D,$

(A3b) $(p_t^* + e_t - p_t^M) = (p_{t-1}^* + e_{t-1} - p_{t-1}^M) + \pi_t^* + \Delta e_t - \pi_t^M.$

The state-space representation is

(A4) $$\tilde{A}_0 \begin{bmatrix} x_{1,t+1} \\ \mathrm{E}_t x_{2,t+1} \end{bmatrix} = \tilde{A} \begin{bmatrix} x_{1,t} \\ x_{2,t} \end{bmatrix} + \tilde{B}\, i_t + \tilde{\upsilon}_{t+1},$$

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

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

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

where $x_{1,t}$ is a 9×1 vector of predetermined state variables, $x_{2,t}$ is a 4×1 vector of forward-looking variables, and $\tilde{\upsilon}_{t+1}$ is a 13×1 vector of disturbances,

$$\tilde{A}_0 = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -b_y^*(1-\rho_i^*) & 1 & -b_\pi^*(1-\rho_i^*) & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & (1-\kappa_M)\beta_i + \beta_q + \beta_e & \kappa_M \beta_i - \beta_q & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{\kappa_{a_q}}{(1-\kappa_M)} & 0 & 0 & \beta_\pi & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{a_p}{\kappa_M} & 0 & 0 & \beta_\pi & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix},$$

$$\tilde{A} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \rho_y^* & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \rho_i^* & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \rho_\pi^* & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \tau_\pi & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \tau_\phi & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \tau_y & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & -1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & -1 & 1 \\ 0 & -\beta_y^*(1-\rho_y^*) & -\beta_e & \rho_\pi^* \beta_e & 0 & -\beta_e & -1 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & -\frac{a_y}{(1-\kappa_M)} & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & -1 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix},$$

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

Premultiplying (A4) with $\tilde{A}_0^{-1}$, and inserting the monetary policy reaction, $i_t = -F\begin{bmatrix} x_{1,t} & x_{2,t} \end{bmatrix}'$, yields

(A5) $$\begin{bmatrix} x_{1,t+1} \\ \mathrm{E}_t x_{2,t+1} \end{bmatrix} = (A - BF)\begin{bmatrix} x_{1,t} \\ x_{2,t} \end{bmatrix} + \begin{bmatrix} \upsilon_{1,t+1} \\ 0_{4\times1} \end{bmatrix},$$

where $A = \tilde{A}_0^{-1}\tilde{A}$, $B = \tilde{A}_0^{-1}\tilde{B}$, and $\begin{bmatrix} \upsilon_{1,t+1} & 0_{4\times1} \end{bmatrix}' = \tilde{A}_0^{-1}\tilde{\upsilon}_{t+1}$. Provided that the policy rule, F, implies a unique equilibrium, the dynamics of the model is given by

(A6a) $x_{1,t+1} = M^s x_{1,t} + \upsilon_{1,t+1}$,

(A6b) $x_{2,t+1} = H^s x_{1,t+1}$,

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

Given the system's dynamics in equation (A6), the variance-covariance matrix of the predetermined variables results from

$$\text{(A7a)} \quad \Sigma_{x1} = M^s \Sigma_{x1} M^{s'} + \Sigma_{\upsilon 1},$$

$$\text{(A7b)} \quad \text{vec}(\Sigma_{x1}) = \left[I_{n1^2} - (M^s \otimes M^s)\right]^{-1} \text{vec}(\Sigma_{\upsilon 1}),$$

where the unconditional variance-covariance matrix of the disturbance vector, υ_{t+1}, is given by $\Sigma_\upsilon = (\Sigma_{\upsilon 1} \quad 0_{9\times 4})$, where $\Sigma_{\upsilon 1}$ is defined as

$$\Sigma_{\upsilon 1} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \sigma^2_{y*} & (1-\rho_i^*)b_y^*\sigma^2_{y*} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & (1-\rho_i^*)b_y^*\sigma^2_{y*} & \sigma^2_{i*} + (1-\rho_i^*)^2(b_\pi^{*2}\sigma^2_{\pi*} + b_y^{*2}\sigma^2_{y*}) & (1-\rho_i^*)b_\pi^*\sigma^2_{\pi*} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & (1-\rho_i^*)b_\pi^*\sigma^2_{\pi*} & \sigma^2_{\pi*} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \sigma^2_\pi & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \sigma^2_\phi & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \sigma^2_y & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix},$$

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):

$$\text{(A12)} \quad \Sigma_z = T^s \Sigma_{x1} T^{s'}.$$

Table A1a: Unconditional variances and social loss, using standard reaction coefficients on (b_π, b_y, ρ)

	$b_\pi = 1.5,\ b_y = 0.5,\ \rho = 0.8$ equation (7a); $i_t = (1-\rho)(b_\pi \pi_t + b_y y_t) + \rho\, i_{t-1}$						
Pass-through	var (π)	var (y)	var (p^M-p^D)	var (Δe)	var (i)	var (π^D)	var (π^M)
0.99	9.037	27.180	7.162	12.191	4.325	8.759	12.061
0.66	8.533	25.576	5.984	12.930	4.10	8.67	9.259
0.33	7.938	24.756	5.865	13.925	3.764	8.448	7.308
0.09	6.688	24.678	11.315	15.575	3.106	7.754	4.979

Table A1b: Unconditional variances and social loss, using optimized reaction coefficients

	optimized reactions; see Table 3a equation (7a); $i_t = (1-\rho)(b_\pi \pi_t + b_y y_t) + \rho\, i_{t-1}$						
Pass-through	var (π)	var (y)	var (p^M-p^D)	var (Δe)	var (i)	var (π^D)	var (π^M)
0.99	11.852	11.443	5.426	12.853	8.458	12.034	12.726
0.66	11.555	11.461	5.04	13.398	8.031	11.902	11.542
0.33	11.36	10.831	5.314	14.501	7.754	11.948	10.539
0.09	10.508	9.113	12.37	16.295	7.735	11.708	8.487

Table A1c: Unconditional variances and social loss, responding to domestic inflation (π_t^D)

	optimized reactions; see Table 4 equation (7a); $i_t = (1-\rho)(b_\pi \pi_t^D + b_y y_t) + \rho\, i_{t-1}$						
Pass-through	var (π)	var (y)	var (p^M-p^D)	var (Δe)	var (i)	var (π^D)	var (π^M)
0.99	12.214	11.164	5.57	13.487	8.747	12.363	13.348
0.66	11.885	11.147	5.091	14.058	8.257	12.213	11.976
0.33	11.143	11.266	5.355	14.784	7.142	11.722	10.350
0.09	11.042	8.784	12.473	17.128	8.123	12.257	8.986

Table A2: Social loss (L^S) and optimized reaction coefficients, greater openness

Pass-through	equation (7a) $\hat{b}_\pi$	$\hat{b}_y$	$\hat{\rho}$	L^D	equation (7b) $\hat{b}_{\Delta e}$	Rel. L^D	equation (7c) $\hat{b}_{(pm-pd)}$	Rel. L^D	equation (7d) $\hat{b}_{(p^*+e-p)}$	Rel. L^D
0.99	4.5	3.6	0.8	1	0.1	0.9999	0.1	0.9999	0.3	0.9999
0.66	4.4	3.6	0.8	1	0.1	0.9999	-0.2	0.9999	0.7	0.9997
0.33	4.6	3.9	0.8	1	-0.1	0.9999	-0.5	0.999	1.3	0.998
0.09	3.9	3.7	0.7	1	-0.3	0.997	-0.7	0.987	1.0	0.984

Note: The size of the import and export shares, and the share of imported inputs are doubled (i.e. 60% and 20%, respectively, in contrast to the benchmark case; 30% and 10%). b_π, b_y, ρ are optimized separately in order to reflect the marginal advantage of incorporating an exchange-rate term.

Table A3: Social loss (L^S) and optimized reaction coefficients, larger risk premium persistence

Pass-through	equation (7a) $\hat{b}_\pi$	$\hat{b}_y$	$\hat{\rho}$	L^D	equation (7b) $\hat{b}_{\Delta e}$	Rel. L^D	equation (7c) $\hat{b}_{(pm-pd)}$	Rel. L^D	equation (7d) $\hat{b}_{(p^*+e-p)}$	Rel. L^D
0.99	7.5	5.9	0.9	1	0.4	0.999	0.9	0.982	1.2	0.982
0.66	6.7	5.2	0.9	1	0.3	0.999	0.7	0.981	1.1	0.98
0.33	6.5	5.1	0.9	1	0.2	0.9998	0.7	0.982	1.0	0.981
0.09	7.5	6.6	0.9	1	-0.1	0.9999	0.4	0.996	1.1	0.977

Note: The risk premium persistence is $\tau_\phi = 0.95$. b_π, b_y, ρ are optimized separately in order to reflect the marginal advantage of incorporating an exchange-rate term.

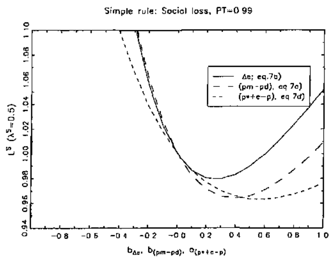
Table A4: Social loss (L^S) and optimized reaction coefficients, larger risk premium variance

Pass-through	equation (7a) $\hat{b}_\pi$	$\hat{b}_y$	$\hat{\rho}$	L^D	equation (7b) $\hat{b}_{\Delta e}$	Rel. L^D	equation (7c) $\hat{b}_{(pm-pd)}$	Rel. L^D	equation (7d) $\hat{b}_{(p^*+e-p)}$	Rel. L^D
0.99	7.3	6.8	0.8	1	0.5	0.998	1.1	0.996	1.5	0.996
0.66	6.8	6.3	0.8	1	0.4	0.999	0.8	0.998	1.5	0.995
0.33	6.5	6.1	0.8	1	0.3	0.999	0	1.0	1.7	0.991
0.09	7.0	7.2	0.8	1	-0.1	1.0	-1.8	0.981	2.6	0.9

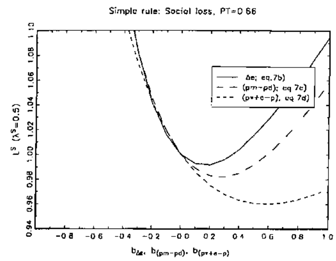
Note: The risk premium variance is five times larger than in the basecase parameterization; $\sigma_\phi^2 = 2.0$. b_π, b_y, ρ are optimized separately in order to reflect the marginal advantage of incorporating an exchange-rate term.

Figure 1: Social loss under varying degrees of exchange rate reactions added to the Taylor rule

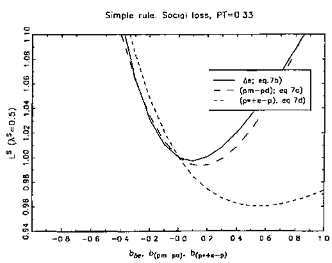
a) Pass-Through = 0.99



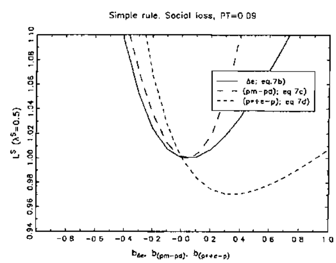
b) Pass-Through = 0.66



c) Pass-Through = 0.33



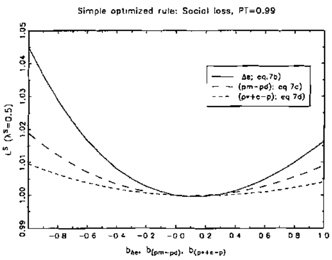
d) Pass-Through = 0.09



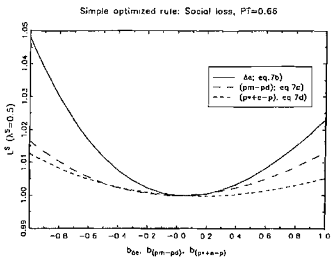
Note: Relative social loss compared to the social loss under the Taylor rule *without* the exchange rate. Truncated y-axis.

Figure 2: Social loss under varying degrees of exchange rate reactions added to the optimized rule

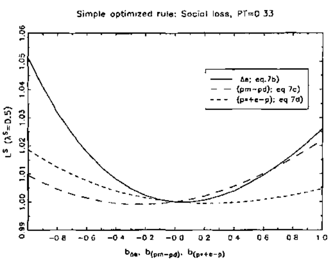
a) Pass-Through = 0.99



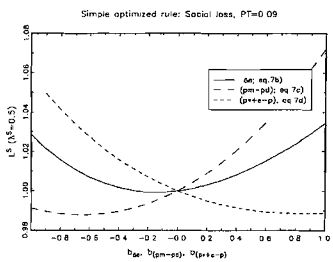
b) Pass-Through = 0.66



c) Pass-Through = 0.33



d) Pass-Through = 0.09



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

Figure 3: Impulse responses for the case with full pass-through (99%; solid) and with incomplete pass-through (33%; dashed), using optimized rules

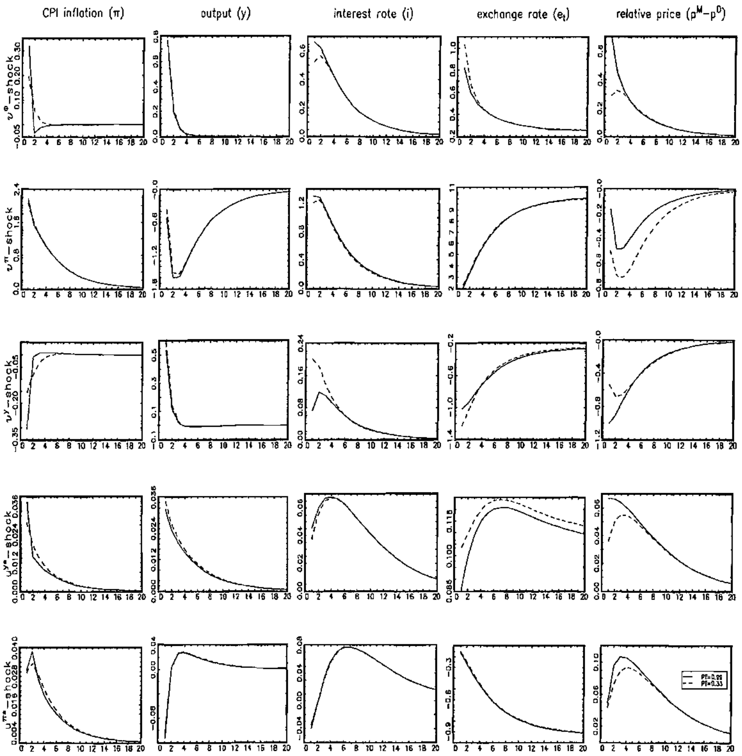
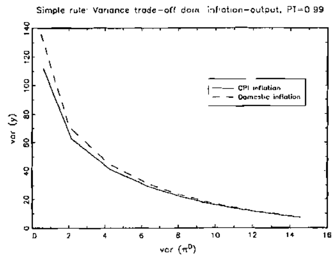
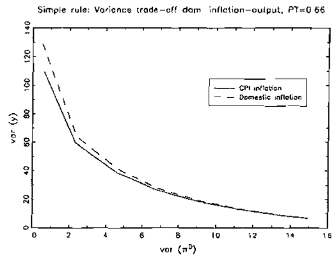


Figure 4: Domestic inflation-output variance trade-off, CPI inflation based rule vs. domestic inflation based rule

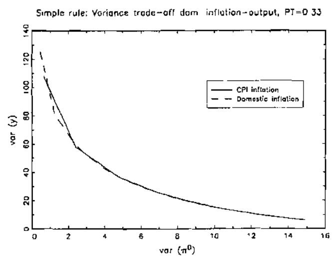
a) Pass-Through = 0.99



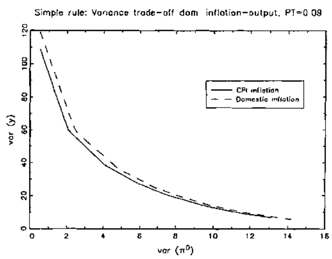
b) Pass-Through = 0.66



c) Pass-Through = 0.33



d) Pass-Through = 0.09



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.

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