Exchange Rate Pass-through in General Equilibrium*

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Abstract

The existing literature estimates exchange rate pass-through into prices using a single-equation, partial equilibrium approach. This method can be susceptible to misspecification and omitted variable bias problems and precludes an understanding of deviation from law of one price conditional on underlying shocks. In this paper, I take a general equilibrium approach to understanding exchange rate pass-through. I fit a small open economy model with nominal and real rigidities to data on Australia, Canada, and New Zealand using Bayesian methods. I then assess the extent of incomplete exchange rate pass-through to export, import, and consumer prices conditional on various structural shocks. The effects are heterogenous across shocks and I find that law of one price deviation in export and import prices is driven mostly by an aggregate preference shock while deviation from purchasing power parity is driven mostly by a foreign consumption shock.

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1 Introduction

The extent to which exchange rate fluctuations are passed through to prices has substantial implications for both macroeconomic dynamics and policy prescriptions in standard open economy models. With high exchange rate pass-through, a currency depreciation is highly inflationary and shocks get transmitted substantially across borders. Moreover, with complete pass-through, exchange rate changes alter relative prices, thereby enabling expenditure switching across domestic and foreign goods. Incomplete pass-through, on the other hand, leads to law of one price deviation among traded goods, and dampens changes in relative prices following an exchange rate movement.

In addition, in standard monetary models, exchange rate pass-through has implications for optimal monetary and exchange rate policy. For example, Devereux and Engel (2003) show in a model where prices are set one period in advance that while flexible exchange rates are optimal under complete exchange rate pass-through, fixed exchange rates are optimal under incomplete pass-through. Moreover, Clarida, Gali, and Gertler (2002) show in a standard dynamic sticky price model that under complete pass-through, optimal monetary policy entails minimizing variation in output gap and domestic inflation. Engel (2009) however shows that in the same set-up under incomplete pass-through, it also needs to take exchange rate misalignments into account.

Due to its crucial role in open economy models, a voluminous empirical literature has attempted to estimate exchange rate pass-through into consumer, import, or export prices. The standard single equation, partial equilibrium approach in the literature estimates:

$$\pi_t = \omega + \sum_{s=0}^{j} \lambda_s \Delta S_{t-s} + \gamma' X_t + \epsilon_t. \tag{1}$$

where π_t is consumer, import, or export inflation, S_t is the nominal exchange rate, and X_t is the vector of controls. λ_0 is referred to as short-run pass-through and $\sum_{s=0}^{j} \lambda_s$ is the measure of long-run pass-through. The most comprehensive crosscountry estimation of pass-through using this approach is in Campa and Goldberg (2005) and Goldberg and Campa (2010). Tables 1 and 2 present their results. Table 1 shows that pass-through into import prices is quite incomplete even in the long run, with an average of around 0.4 across countries. Table 2 shows that pass-through into consumer prices is extremely small across many countries, and is typically lower than pass-through into import prices.

The implications of these empirical findings for open economy models and whether one can interpret incomplete pass-through as evidence for deviation from law of one price depends on several factors. First, we need to make sure that the estimation strategy does not suffer from potential misspecification and omitted variables bias issues. This is particularly relevant if one does not have proper controls for marginal costs and/or domestic prices for the goods.[1] In that case, an estimate of pass-through less than 1 does not imply that there is deviation from law of one price and price discrimination across countries by firms. Second, the finding that CPI pass-through tends to be quite low is hard to interpret if due to endogenous monetary policy, the central bank dampens CPI movements in the face of shocks that move the exchange rate. Third, even if the estimation strategy does not suffer from these potential confounding issues, this partial equilibrium approach precludes an understanding of pass-through conditional on underlying shocks. Therefore, we do not have an understanding of whether pass-through of nominal shocks is different from real shocks or demand shocks from supply shocks etc.

In this paper, in contrast to the literature, I take a model based general equilibrium approach, both in theory and estimation. This approach allows me to respond to the aforementioned challenges faced by the single equation strategy. I use a small open economy model with sticky prices and intermediate inputs to model incomplete exchange rate pass-through. I then estimate the model with Bayesian methods using data on output, prices, and nominal exchange rate for Australia, Canada, and New Zealand. This allows me to provide estimates of pass-through conditional on a structural shock. In particular, using impulse response analysis, I study how devi-

[1] I discuss this issue in more detail later in the paper using simulated data from a simple model.

ations from the law of one price in export, import, and consumer prices respond to various shocks. I also provide variance decomposition results to assess the relative importance of these shocks in explaining variation in the deviations from the law of one price. I am not aware of other work in the literature that take an approach similar to this paper.

I stick close to the existing open economy macroeconomics literature in my modelling and choice of various structural shocks. I extend the prototypical small open economy model where firms adjust nominal prices infrequently, for example the one in Monacelli (2005), by allowing for intermediate inputs in production, both domestic and imported. Then, following Stockman and Tesar (1995), for example, I allow for shocks to tastes and technology in the domestic country and following Chari, Kehoe, and McGrattan (2002), a nominal shock that affects aggregate demand. Consistent with the small open economy assumption, I model variables related to the rest of the world, such as foreign inflation and consumption, as following exogenous processes.

Using Bayesian methods to estimate the model parameters, I then compute the effect of the various shocks on deviations from the law of one price in export, import, and consumer prices. To that end I use impulse response and variance decomposition analysis. I find the effects to be quite heterogenous across the various shocks regarding both the induced persistence and the initial impact of the shocks. Moreover, I find that while law of one price deviation in export and import prices are mostly driven by the aggregate preference shock, deviation in purchasing power parity is driven mostly by the foreign consumption shock.[2]

In addition to the papers discussed above, this paper is related to broadly two other strands in the literature. First, a recent literature pioneered by Gopinath and Rigobon (2008) and Gopinath, Itskhoki, and Rigobon (2009) has focussed on estimating exchange rate pass-through at the goods level using U.S. micro-data underlying aggregate export and import price indices. These papers however do not focus on the underlying shocks driving the exchange rate, the focus of this paper. Second, this paper is an addition to the list of papers that fit small open economy

[2] I use the terms "deviation from the law of one price for consumer prices" and "deviation from purchasing power parity" interchangeably in the paper.

models to the data using Bayesian methods. Prominent examples are Justiniano and Preston (2010a) and Justiniano and Preston (2010b). These papers study the effects of foreign shocks and optimal monetary policy in small open economy models and do not investigate the determinants of exchange rate pass-through.

The rest of the paper is organized as follows. In sec 2, I introduce the small open economy model with nominal rigidities and intermediate inputs. In sec 3, I use variations of the model to understand theoretically potential issues facing standard pass-through regressions and then present the estimation strategy and empirical findings on exchange rate pass-through. In sec 4, I conclude with a summary of findings and a discussion of avenues for future research.

2 Model

The model features a small open economy, which is the home country, and the rest of the world. A representative consumer in the home country supplies labor to firms, consumes a final good that is a composite of the domestic and imported good, and invests in a complete set of state-contingent securities.

A continuum of monopolistically competitive firms in the home country produce differentiated varieties of the traded domestic good using labor and intermediate inputs, both domestic and imported. At the border, a continuum of monopolistically importing firms buy the foreign good at a world price they take as given and then combine it with intermediate inputs, both domestic and imported, to sell at home. The intermediate input is a composite of the differentiated varieties of final goods, and so the model features a round-about production structure. The home country's good has a negligible weight in the rest of the world's consumption basket. Final goods prices are sticky and are set in the currency of the importing country.[3]

In terms of notation, H (F) define the production location, whether the good is home (foreign) produced.[4] Then for prices, $*$ denotes that the price is in terms

[3] Thus, I assume local currency pricing to be exogenously given.

[4] Because this is a model of a small open economy, I use foreign and rest of the world interchangeably in the paper.

of foreign currency, while for goods, it denotes that the consumer is foreign. For example, $P_{H,t}$ ($P^*_{F,t}$) is the price level of the home (foreign) produced good in the home (foreign) country in the home (foreign) currency.

2.1 Consumer

A representative consumer at home maximizes:

$$E_t \sum_{s=0}^{\infty} \beta^s \chi_{t+s} \left[\frac{C_{t+s}^{1-\sigma}}{1-\sigma} - \frac{N_{t+s}^{1+\phi}}{1+\phi} \right]$$

subject to the flow budget constraint:

$$P_t C_t + E_t\{\rho_{t,t+1} B_{t+1}\} \leq W_t N_t + \Gamma_t + B_t$$

where C_t is the consumption of the composite final good, N_t is labor, P_t is the price of the composite final good, W_t is nominal wage, and Γ_t is profits from firms. B_{t+1} is the value of the complete set of state-contingent securities at the beginning of period $t+1$, denominated in home currency for simplicity, and $\rho_{t,t+1}$ is the stochastic discount factor. Finally, β is the discount factor, χ_t is the aggregate preference shock, σ^{-1} is the intertemporal elasticity of substitution, and ϕ^{-1} is the Frisch elasticity of labor supply.[5]

The composite final good is an aggregate of the home, $C_{H,t}$, and imported, $C_{F,t}$, final good:

$$C_t = \left[(\gamma)^{\frac{1}{\eta}} C_{H,t}^{\frac{\eta-1}{\eta}} + (1-\gamma)^{\frac{1}{\eta}} C_{F,t}^{\frac{\eta-1}{\eta}} \right]^{\frac{\eta}{\eta-1}}$$

where the goods are an aggregate of a continuum of varieties, indexed by $i(j)$ for the home (foreign) good:

$$C_{H,t} = \left[\int_0^1 c_{H,t}(i)^{\frac{\varepsilon-1}{\varepsilon}} di \right]^{\frac{\varepsilon}{\varepsilon-1}} \quad C_{F,t} = \left[\int_0^1 c_{F,t}(j)^{\frac{\varepsilon-1}{\varepsilon}} dj \right]^{\frac{\varepsilon}{\varepsilon-1}}.$$

[5] A standard no-Ponzi scheme condition also applies. Moreover, to keep the presentation uncluttered, I do not specifically refer to different states of nature.

Here, $\eta > 0$ is the elasticity of substitution between the goods while $\varepsilon > 1$ is the elasticity of substitution among the varieties. γ is the preference parameter that determines the consumer's relative preference towards home good. $\gamma > \frac{1}{2}$ therefore, implies home bias in preferences for the domestic good.

The optimal price index P_t, as is well known, then takes the form:

$$P_t = \left[\gamma \left(P_{H,t}\right)^{1-\eta} + (1-\gamma)\left(P_{F,t}\right)^{1-\eta}\right]^{\frac{1}{1-\eta}}$$

where $P_{H,t}$ is the price in home currency of the home good, while $P_{F,t}$ is the price in home currency of the foreign good. These price indices are in turn aggregates of the prices of the varieties:

$$P_{H,t} = \left[\int_0^1 p_{H,t}(i)^{1-\varepsilon} di\right]^{\frac{1}{1-\varepsilon}} \quad P_{F,t} = \left[\int_0^1 p_{F,t}(j)^{1-\varepsilon} dj\right]^{\frac{1}{1-\varepsilon}}.$$

Given these definitions, the demand for the home and foreign good are given by:

$$\frac{C_{H,t}}{C_t} = \gamma \left(\frac{P_{H,t}}{P_t}\right)^{-\eta} \quad \frac{C_{F,t}}{C_t} = (1-\gamma)\left(\frac{P_{F,t}}{P_t}\right)^{-\eta}$$

while those for the varieties by:

$$\frac{c_{H,t}(i)}{C_{H,t}} = \left(\frac{p_{H,t}(i)}{P_{H,t}}\right)^{-\varepsilon} \quad \frac{c_{F,t}(j)}{C_{F,t}} = \left(\frac{p_{F,t}(j)}{P_{F,t}}\right)^{-\varepsilon}.$$

The maximization problem of the consumer yields the first-order conditions:

$$\frac{N_t^{\phi}}{C_t^{-\sigma}} = \frac{W_t}{P_t}$$

$$\rho_{t,t+s} = \left(\frac{\chi_{t+s}}{\chi_t}\right)\beta^s \left(\frac{C_{t+s}}{C_t}\right)^{-\sigma}\left(\frac{P_t}{P_{t+s}}\right) \tag{2}$$

where eqn.(2) holds for each state of nature.[6] The assumption of a complete set of state-contingent securities implies a unique stochastic discount factor. This property and eqn.(2) together with its foreign counterpart give:

[6] Optimality conditions also include a standard transversality condition.

$$Q_t = Q_0 \left(\frac{C_0^*}{\chi_0 C_0} \right)^{\sigma} \left(\frac{\chi_t C_t}{C_t^*} \right)^{\sigma}$$

where $Q_t = S_t \frac{P_t^*}{P_t}$ is the real exchange rate, S_t the nominal exchange rate, C_t^* the foreign consumption, and P_t^* the foreign price level. The constant term $Q_0 \left(\frac{C_0^*}{C_0} \right)^{\sigma}$ disappears in the log linear approximation of the model.[7]

2.2 Domestic firms

Home firm i produces output $y_{H,t}(i)$ using a constant returns to scale technology:

$$y_{H,t}(i) = A_t l_t(i)^{1-\alpha} M_t(i)^{\alpha}$$

where $l_t(i)$ is the labor input, $M_t(i)$ is the intermediate input, and α is the share of intermediate input. A_t is the aggregate, country-specific technology shock that is assumed to follow an exogenous process over time. When $\alpha = 0,$ the set-up becomes identical to the one used in many sticky price models, such as Monacelli (2005).[8]

The intermediate input is an aggregate of the domestic, $M_{H,t}(i)$, and imported, $M_{F,t}(i)$, final good, defined for simplicity in an analogous way to that of the consumer:

$$M_t(i) = \left[(\gamma)^{\frac{1}{\eta}} M_{H,t}(i)^{\frac{\eta-1}{\eta}} + (1-\gamma)^{\frac{1}{\eta}} M_{F,t}(i)^{\frac{\eta-1}{\eta}} \right]^{\frac{\eta}{\eta-1}}.$$

Again, these final goods are aggregates of the continuum of varieties:

$$M_{H,t}(i) = \left[\int_0^1 m_{H,t}\ (i,i')^{\frac{\varepsilon-1}{\varepsilon}} di' \right]^{\frac{\varepsilon}{\varepsilon-1}} \quad M_{F,t}(i) = \left[\int_0^1 m_{F,t}\ (i,j')^{\frac{\varepsilon-1}{\varepsilon}} dj' \right]^{\frac{\varepsilon}{\varepsilon-1}}$$

where $m\ (i,i')$ denotes the quantity of the i' intermediate input used by firm i.

The model therefore features a round-about production structure, introduced by Basu (1995). Notice that this set-up is distinct from an alternate specification also

[7]In terms of notation, an increase in S_t is a depreciation of the exchange rate for the home country.

[8]Also note that labor is supplied in an economy-wide market.

used in the literature, where production occurs in a chain. Basu (1995) argues in favor of the round-about specification by noting that input-output tables, even those that are quite detailed, have very few zeros. Recently, Midrigan (2008) and Nakamura and Steinsson (2008) have used this structure in closed economy models to introduce strategic complementarities in price setting without implying inconsistent behavior with regards to evidence on pricing from micro-data.[9] Here, I use this set-up for the same purpose, in an small open economy model.

Given these definitions, the demand for the home and foreign intermediate input is given by:

$$\frac{M_{H,t}(i)}{M_t(i)} = \gamma \left(\frac{P_{H,t}}{P_t}\right)^{-\eta} \quad \frac{M_{F,t}(i)}{M_t(i)} = (1-\gamma)\left(\frac{P_{F,t}}{P_t}\right)^{-\eta}$$

while those for the varieties by:

$$\frac{m_{H,t}\ (i,i')}{M_{H,t}(i)} = \left(\frac{p_{H,t}(i')}{P_{H,t}}\right)^{-\varepsilon} \quad \frac{m_{F,t}\ (i,j')}{M_{F,t}(i)} = \left(\frac{p_{F,t}(j')}{P_{F,t}}\right)^{-\varepsilon}$$

Moreover, as is well known, cost minimization by the home firm leads to the following condition for the optimal choice of input:

$$\frac{W_t}{P_t} = \frac{1-\alpha}{\alpha}\left[\frac{M_t(i)}{l_t(i)}\right].$$

The marginal cost for the home firm, MC_t, is given by:

$$MC_t \ = \left((1-\alpha)^{1-\alpha}\,\alpha^{\alpha}\right)^{-1}\frac{W_t^{1-\alpha}P_t^{\alpha}}{A_t}$$

[9]Many recent studies using micro-data have documented the prevalence of large price changes. Other popular ways of introducing strategic complementarities, such as a fixed factor or non-isoelastic demand, damp down price changes in response to both idiosyncratic and aggregate shocks. Therefore, in such models, unrealistic size of idiosyncratic shocks or menu costs is needed to match the large price changes. The intermediate input channel on the other hand, damps down price changes in response to only aggregate shocks, and so models using this mechanism are not subject to the same critique.

which depends only on the aggregate variables and is not firm-specific due to the assumptions of constant returns to scale and economy-wide factor markets. Nevertheless, there still are strategic complementarities in price-setting since the marginal cost depends on P_t, which in turn, depends on the pricing decisions of all firms.

Final goods prices are sticky. For analytical tractability, I use the Calvo (1983) assumption where monopolistically competitive firms do not change prices with a constant probability, regardless of the history of price changes.[10] I discuss the firms' pricing problem for domestic sales and exports separately below.

2.2.1 Domestic sales price-setting

I assume that for domestic sales, home firms set prices in the home currency. At home, firm i sells variety i to the the home consumer and home firms. Since the firm does not get to update prices with probability θ_H, it chooses price $p_{H,t}(i)$ by maximizing expected discounted profits:

$$E_t \sum_{s=0}^{\infty} \rho_{t,t+s} \left(\theta_H\right)^s \left(p_{H,t}(i) - MC_{t+s}\right) X_{t+s}(i)$$

where $X_{t+s}(i)$ is the domestic demand for variety i. The first-order condition for this problem is given by:

$$E_t \sum_{s=0}^{\infty} \rho_{t,t+s} \left(\theta_H\right)^s \left(p_{H,t}(i) - \mu MC_{t+s}\right) X_{t+s}(i) = 0$$

where as usual, $\mu = \frac{\varepsilon}{\varepsilon - 1}$ is the constant markup.

2.2.2 Exports price-setting

Now, I consider the problem of the home firm i exporting its variety i to the rest of the world. It sets prices in the foreign currency. Thus, I assume local currency pricing for exports. Therefore, the model features incomplete exchange rate pass-through into export prices from two sources: nominal rigidities combined with local currency

[10] For a textbook treatment of models with this feature, see Woodford (2003).

pricing, and real rigidities due to intermediate inputs in production. The probability with which the firm updates exports prices can be different from the probability with which it updates domestic prices.

Since the firm does not get to update prices with probability θ_H^*, it chooses price $p_{H,t}^{*LCP}(i)$ by maximizing expected discounted profits:

$$E_t \sum_{s=0}^{\infty} \rho_{t,t+s} \left(\theta_H^*\right)^s \left(p_{H,t}^{*LCP}(i) S_{t+s} - MC_{t+s}\right) X_{t+s}^*(i)$$

where $X_{t+s}^*(i)$ is the foreign demand for variety i. The first-order condition for this problem is given by:

$$E_t \sum_{s=0}^{\infty} \rho_{t,t+s} \left(\theta_H^*\right)^s \left(p_{H,t}^{*LCP}(i) S_{t+s} - \mu MC_{t+s}\right) X_{t+s}^*(i) = 0.$$

2.3 Importing firms

Importing firm j, situated at the border, produces imported final good $y_{F,t}(j)$ using a constant returns to scale technology:

$$y_{F,t}(j) = y_{F,t}^{\text{Im}}(j)^{1-\zeta} M_t^{\text{Im}}(j)^{\zeta}$$

where $y_{F,t}^{\text{Im}}(j)$ is the foreign good, $M_t^{\text{Im}}(j)$ is the intermediate input, and ζ is the share of intermediate input. I allow ζ to be different from α. When $\zeta = 0$, the set-up becomes identical to the one used in other small open economy models, such as Monacelli (2005).

Again, like with domestic firms, the intermediate input is an aggregate of the domestic, $M_{H,t}^{\text{Im}}(j)$, and imported, $M_{F,t}^{\text{Im}}(j)$, final good, defined for simplicity in an analogous way to that of the consumer:

$$M_t^{\text{Im}}(j) = \left[(\gamma)^{\frac{1}{\eta}} M_{H,t}^{\text{Im}}(j)^{\frac{\eta-1}{\eta}} + (1-\gamma)^{\frac{1}{\eta}} M_{F,t}^{\text{Im}}(j)^{\frac{\eta-1}{\eta}}\right]^{\frac{\eta}{\eta-1}}.$$

These final goods are aggregates of the continuum of varieties:

$$M_{H,t}^{\mathrm{Im}}(j) = \left[\int_0^1 m_{H,t}^{\mathrm{Im}} \ (j, i')^{\frac{\varepsilon - 1}{\varepsilon}} di' \right]^{\frac{\varepsilon}{\varepsilon - 1}} \quad M_{F,t}^{\mathrm{Im}}(j) = \left[\int_0^1 m_{F,t}^{\mathrm{Im}} \ (j, j')^{\frac{\varepsilon - 1}{\varepsilon}} dj' \right]^{\frac{\varepsilon}{\varepsilon - 1}}$$

where $m \ (j, i')$ denotes the quantity of the i' intermediate input used by firm j. The demand for the intermediate inputs and the varieties are defined in the same way as for the domestic firms.

Moreover, as is well known, cost minimization by the home firm leads to the following condition for the optimal choice of input:

$$\frac{P_{Ft}^{\mathrm{Im}}(j)}{P_t} = \frac{1 - \zeta}{\zeta} \left[\frac{M_t(j)}{y_{F,t}^{\mathrm{Im}}(j)} \right].$$

where $P_{Ft}^{\mathrm{Im}}(j)$ is the price in home currency of the foreign good faced by the importing firms. The marginal cost for the importing firm, MC_t^{Im}, is then given by:

$$MC_t^{\mathrm{Im}} = \left((1 - \zeta)^{1 - \zeta} \zeta^{\zeta} \right)^{-1} \left(P_{Ft}^{\mathrm{Im}}(j) \right)^{1 - \zeta} P_t^{\zeta}.$$

Again, there are strategic complementarities in price-setting since the marginal cost depends on $P_t,$ which in turn, depends on the pricing decisions of all firms.

2.3.1 Imports price-setting

I assume that the importing firm, at the border, buys the foreign good at a world price, $P_{Ft}^{*}(j)$, it takes as given. Thus:

$$P_{Ft}^{\mathrm{Im}}(j) = S_t P_{Ft}^{*}(j).$$

In this model, therefore, at the border, law of one price holds for the foreign good. Then, after combining with intermediate input, the firm sells the differentiated imported variety j under sticky prices set in the home currency. Thus, I assume local currency pricing for imports. Again, the model features incomplete exchange rate pass-through into import prices from two sources: nominal rigidities combined with local currency pricing, and real rigidities due to intermediate inputs in production.

Since the firm does not get to update prices with probability θ_F, it chooses price $p_{F,t}(j)$ by maximizing expected discounted profits:

$$E_t \sum_{s=0}^{\infty} \rho_{t,t+s} \left(\theta_F\right)^s \left(p_{F,t}(j) - MC_{t+s}^{\text{Im}}\right) X_{t+s}^{\text{Im}}(j) \tag{3}$$

where $X_{t+s}^{\text{Im}}(j)$ is the demand for variety j. The first-order condition for this problem is given by:

$$E_t \sum_{s=0}^{\infty} \rho_{t,t+s} \left(\theta_F\right)^s \left(p_{F,t}(j) - \mu MC_{t+s}^{\text{Im}}\right) X_{t+s}^{\text{Im}}(j) = 0. \tag{4}$$

2.4 Aggregate demand

I assume a simple aggregate demand side to ensure the existence and uniqueness of the price level. I specify that the nominal expenditure in the home country follows an exogenous process:

$$Z_t = P_t C_t.$$

Monetary policy is therefore not explicitly modeled, but this specification can be rationalized through a monetary policy rule for nominal expenditure, or through a cash-in-advance constraint.[11]

2.5 Rest of the world

I close this model of a small open economy by assuming that the home country's good has a negligible weight in the rest of the world's consumption basket. This implies that:

$$C_t^* = C_{F,t}^* \qquad P_t^* = P_{F,t}^*.$$

[11]For a recent use of such a modeling device, see Carvalho and Nechio (2008).

The dynamics of C_t^* and P_t^* are taken exogenously as given.[12] Finally, the demand for the home good by the rest of the world is given by:

$$\frac{C_{H,t}^*}{C_t^*} = \left(\frac{P_{H,t}^{*LCP}}{P_t^*}\right)^{-\eta}.$$

2.6 Market clearing

Markets clear for goods and labor in equilibrium. For the home variety i, total output should equal consumption by the home and foreign consumers and use as intermediate inputs by home and importing firms:

$$y_{H,t}(i) = c_{H,t}\ (i) + c_{H,t}^*\ (i) + \int_0^1 m_{H,t}\ (i', i)di' + \int_0^1 m_{H,t}^{\text{Im}}\ (j', i)dj'$$

where $m\ (i', i)$ is the amount of intermediate input of variety i used by firm i'. For the imported variety j, total output should equal consumption by home consumers and use as intermediate inputs by home and importing firms:

$$y_{F,t}(j) = c_{F,t}\ (j) + \int_0^1 m_{F,t}\ (i', j)di' + \int_0^1 m_{F,t}^{\text{Im}}\ (j', j)dj'.$$

Finally, labor markets clear in the home country:

$$\int_0^1 l_t(i)di = N_t.$$

3 Results

In this section, I first illustrate the possibility of bias in standard pass-through regressions by using simulated data from a variant of the model presented in sec 2. Then, I estimate the model in sec 2 using Bayesian methods and present results on structural estimates of exchange rate pass-through.

[12]In estimation, I posit that the foreign consumption and inflation follow independent AR(1) processes.

3.1 Standard pass-through regressions

For reference, I first, estimate standard pass-through regressions for Canada as given by eqn.(1).[13] I present results on pass-through coefficients for CPI, import, and export inflation in table 3. I do not use any controls in these regressions. The results are very similar to those in the literature, with incomplete pass-through for import and export inflation, and extremely low pass-through for CPI inflation.

Next, I use simulated data from a simple variation of the model presented in sec 2 to assess how such standard pass-through regressions can yield biased estimates. For illustrative purposes, I make the following simplifications. First, I set $\alpha = \zeta = 0$ so that there are no intermediate inputs in production. For import prices, I then simplify to allow for law of one price to hold at all instances. Finally, instead of the local currency assumption on export prices, I consider producer currency pricing. That is, now prices of domestic exports are set in the domestic currency. This means that all fluctuations in exchange rates are transmitted one-for-one to export prices:

$$\hat{p}^*_{H,t} = \hat{p}_{H,t} - \hat{S}_t.$$

The structural exchange rate pass-through into export prices coefficient in this context is then 1.[14]

Now consider the standard exchange rate pass-through into export prices regression given by eqn. (1):

$$\pi^*_{H,t} = \omega - \sum_{s=0}^{j} \lambda_s \Delta S_{t-s} + \gamma' X_t + \epsilon_t.$$

If in this regression proper controls for domestic prices, $\hat{p}_{H,t}$, or marginal costs are not included, then the estimates of λ will be biased away from the true estimate of 1. The direction of the bias depends on the shock hitting the economy and how it affects marginal costs and exchange rates.

[13] I desribe the data sources in detail later in the paper.

[14] Through out this paper, $\hat{x}$ represents log-linearized version of variable x.

For example, consider a nominal shock at home. It depreciates the home currency. At the same time, it increases marginal costs, as nominal wages increase, and thereby, the nominal price of the good at home. This therefore, leads to an downward bias in the estimate of λ. Next, consider a technology shock at home. If $\sigma > 1,$ the shock depreciates the home currency. At the same time, it decreases marginal costs, and thereby, the nominal price of the good at home. Thus, if $\sigma > 1,$ there will be an upward bias in the estimate of λ and vice-versa.

To illustrate this possibility of misspecification, I solve the model by log-linearizing around a non-stochastic steady state. I then simulate the model and run this standard regression without any controls on the simulated data. For the simulation, while later I estimate all the parameters, I use an extremely standard calibration.[15] I present the results in table 4. As expected, with nominal shocks, we get the pass-through estimate to be less than 1, while for technology shocks, if $\sigma > 1$, it is greater than 1 and vice-versa.

3.2 Estimation

Now, I fit the log-linearized version of the model presented in sec 2 to data from three countries. With the estimates at hand, I then present results on structural measures of exchange rate pass-through, conditional on different underlying shocks.

3.2.1 Bayesian framework

I use a Bayesian approach for estimation. The first-order approximation to the equilibrium conditions of the model takes the form:

$$\Gamma_0 (\theta) s_t = \Gamma_1 (\theta) s_{t-1} + \Gamma_\varepsilon(\theta)\varepsilon_t + \Gamma_\eta(\theta)\pi_t$$

where s_t is a vector of model variables and ε_t is a vector of shocks to the exogenous processes. π_t is a vector of rational expectations forecast errors, which implies

[15]The parameter values that I use for the stochastic simulation are: $\beta = 0.99, \theta = 0.7, \sigma = 0.5,\ 2,\ \phi = 2.5,\ \gamma = 0.5,\ \eta = 1,$ and random walk processes for the nominal aggregate expenditure and aggregate technology.

$E_{t-1}\pi_t = 0$ for all t, and θ contains the structural model parameters. The solution to this system takes the form:

$$s_t = \Omega_1(\theta)s_{t-1} + \Omega_\varepsilon(\theta)\varepsilon_t.$$

The solution can be obtained using standard methods, for example, Sims (2000). Finally, the model variables are related to the observables by the measurement equation:

$$y_t = Bs_t$$

where y_t is the vector of observables.

Let $Y = \{y\}_{t=1}^{T}$ be the data. In a Bayesian framework, the likelihood function $L(Y \mid \theta)$ is combined with a prior density $p(\theta)$ to obtain the posterior density:

$$p(\theta \mid Y) \quad \propto \quad p(\theta)L(Y \mid \theta).$$

Assuming Gaussian shocks, I evaluate the likelihood function using the Kalman filter. A numerical optimization routine is used to maximize $p(\theta \mid Y)$ and find the posterior mode. Then, I generate draws from $p(\theta \mid Y)$ using the Metropolis-Hastings algorithm. I use a Gaussian proposal density in the algorithm, using a inverse of a scaled Hessian computed at the posterior mode as the covariance matrix. The computation details are in the appendix. The results I report below are based on 1.5 million draws in the Metropolis-Hastings algorithm. I conduct convergence diagnostics using trace plots and multiple chains. I burn-in $1/3^{rd}$ of the draws.

To settle on a particular model specification, I do Bayesian model comparison using the marginal data densities of the models. The marginal data density of a model is given by:

$$p(Y) = \int p(\theta)L(Y \mid \theta)\ d\theta.$$

Note that this measure penalizes over parameterization of the model.[16] The mar-

[16]In comparing models A and B I am interested in the relative posterior probabilities

ginal data density is approximated by the Geweke (1999) modified harmonic-mean estimator. The computation details are in the appendix.

3.2.2 Data

I use quarterly Australian data from 1984 : I to 2007 : IV, Canadian data from 1982 : I to 2007 : IV, and New Zealand data from 1988 : III to 2007 : IV. The time period chosen is dictated by when the countries decided to adopt a floating exchange rate regime. All the data, except on population which is available from the U.S. Census Bureau, is obtained from the International Financial Statistics database maintained by the International Monetary Fund. Annual population data is converted to quarterly frequency using quarterly interpolation in order to calculate output per capita.[17]

I use de-meaned data from three countries on CPI inflation, import inflation, export inflation, rate of nominal exchange rate depreciation, and real output per capita growth rates, which constitute the elements in the vector y_t. Thus, the observables constitute of only domestic variables. I allow for five exogenous processes:

$$\Delta\hat{Z}_t = \rho_Z \Delta\hat{Z}_{t-1} + \epsilon_{Z,t} \qquad \hat{A}_t = \rho_A \hat{A}_{t-1} + \epsilon_{A,t} \qquad \hat{\chi}_t = \rho_\gamma \hat{\chi}_{t-1} + \epsilon_{\chi,t}$$

$$\hat{C}_t^* = \rho_c^* \hat{C}_{t-1}^* + \epsilon_{C,t}^* \qquad \pi_t^* = \rho_\pi^* \pi_{t-1}^* + \epsilon_{\pi,t}^*$$

This means that the vector ε_t is given by $\left[\epsilon_{Z,t},\ \epsilon_{A,t},\ \epsilon_{\chi,t},\ \epsilon_{C,t}^*,\ \epsilon_{\pi,t}^*\right]$.

Most of the variables that I choose and the exogenous processes that I allow for in the estimation have a quite natural justification. Given the need to identify nominal and technology shocks, using data on CPI inflation and output per capita is an obvious choice. Moreover, since the objective of the paper is to estimate exchange rate pass-through, it is imperative to use data on import and export inflation and

of the models given the data. That is, $\frac{p(A|Y)}{p(B|Y)} = \frac{p(A)}{p(B)}\frac{p(Y|A)}{p(Y|B)}$ where $p(A)$ and $p(B)$ are the prior probabilities of the models A and B. Since I am not specifying different prior probabilities over the models, I simply compare the marginal data densities given by $p(Y \mid A)$ and $p(Y \mid B)$.

[17]The series obtained from IFS are real GDP, CPI, Imports price index, Exports price index, and Nominal effective exchange rate.

exchange rates. I also allow for preference shocks to help account for the dynamics of the exchange rate. In accordance with the home country being a small open economy, I then consider the dynamics of foreign consumption and inflation to be exogenous to the home country.

3.2.3 Results

I discuss below the priors that I choose for the estimation, the corresponding posterior estimates, and impulse response and variance decomposition analysis of exchange rate pass-through.

Priors I describe in table 5 the prior distributions that I use. I impose the same priors across the three countries. All parameter are assumed a priori to be independent. I use the beta distribution for parameters that are between 0 and 1. I use the inverse gamma distribution for the standard deviation of shocks and the gamma distribution for the rest of the parameters. The data is quarterly, and hence I set a high value for β with a tight prior. I use only one measure of price stickiness across all sectors, and the prior mean is roughly in line with evidence from micro studies such as Dhyne et al (2006). The implied prior mean duration is 2.5 quarters.[18]

Given that imports do not constitute a substantial fraction of production and consumption in these countries, the prior mean for γ is high. The cost share of intermediate inputs in domestic production, α, is set to have a prior mean of 0.7. Nakamura and Steinsson (2008) argue that a value around 0.75 is reasonable for the U.S. in a closed-economy context, while Midrigan (2008) uses a value of 0.66. Their estimates are certainly within the 90% interval of the prior density. I use the same prior for the share of intermediate inputs in imports. The prior mean of inverse of the markup, μ^{-1}, is set at 0.7, and is reasonably tight.

The prior mean for the inverse of the intertemporal elasticity of substitution, σ, allows for a moderate amount of risk aversion, with a fairly large standard deviation. The mean for η is set between the high estimates found in micro studies and the

[18] In future extensions of this work, it would be interesting to allow for different degrees of nominal rigidities across domestic, export, and import prices.

low values obtained in the macro literature. The mean for the inverse of the Frisch elasticity of substitution, ϕ, is set to be fairly high, but with a reasonably wide prior to account for the uncertainty in the literature.

The shocks are assumed to be uncorrelated with each other. I set the prior mean for the AR (1) parameter for the growth rate of nominal expenditure to be 0.4. This is in line with estimates in the literature, such as Mankiw and Reis (2002). As is standard, I allow for persistent technology, preference, and foreign shocks. For the standard deviation of the technology and nominal shocks, I use relatively loose priors with a mean of 1%. For the preference shock, because of the need to account for volatile nominal exchange rates, I allow for a much higher variance and greater uncertainty. Similarly, for the two foreign shocks as well, I allow for a much higher variance, with a mean of 4%, and more uncertainty.

Posterior estimates While estimating the model in sec 2, the posterior estimate for ζ, the share of intermediate inputs in imports, is very close to 0. Since this suggests the lack of importance of this parameter in fitting the data, I do a Bayesian model comparison exercise where I compare the marginal data densities of two model specifications for each country: one with $\zeta \neq 0$ and the other with $\zeta = 0$. The results are in table 6. It is clear that imposing $\zeta = 0$ leads to a higher marginal data density and therefore I focus on this specification for the rest of the paper. This results suggest that with the high estimate of home bias in preferences for the domestic good, it is not necessary to have a substantial intermediate input component in imports to account for the extremely low pass-through of CPI to exchange rates.

In tables $7-9$ I report posterior estimates of the model parameters for Australia, Canada, and New Zealand respectively. While there is some heterogeneity across the three countries in the posterior estimates of the various parameters, there clearly are broad similarities. In terms of the extent of nominal rigidities, the implied durations are in line with recent estimates from micro-data. The estimates also point to moderately high risk aversion, a fairly low Frisch elasticity of labor supply, and a quite low elasticity of substitution between the domestic and foreign goods. The low estimate of the elasticity of substitution between domestic and foreign goods is a common feature of macro studies of this parameter. In addition, the estimation yields a high degree of preference bias for the home good. This is a reasonable estimate for small open economies. The estimates yield a substantial share of intermediate inputs in domestic production. The inverse of the markup is also estimated in the range widely used for calibration purposes.

In line with the literature, the AR (1) parameter for the growth rate of nominal expenditure is not high. The persistence of the preference shock and the foreign inflation shock is also fairly low. On the other hand, the posterior means imply a high degree of persistence for the technology shock and especially so for the foreign consumption shock. Moreover, the standard deviations of the preference and the foreign consumption and inflation shocks are estimated to be particularly high.

Impulse responses With the estimates of the parameters at hand, I next analyze how law of one price deviations, which arise due to the various sources of incomplete exchange rate pass-through in the model, respond to underlying shocks. In particular, I am interested in the behavior law of one price deviation for imports, $\hat{L}_t$, exports, $\hat{L}_t^*$, and consumer prices, $\hat{Q}_t$, which are defined as:

$$\hat{L}_t = \hat{S}_t + \hat{P}^*_{F,t} - \hat{P}_{F,t} \qquad \hat{L}^*_t = \hat{P}_{H,t} - \hat{S}_t - \hat{P}^*_{H,t} \qquad \hat{Q}_t = \hat{S}_t + \hat{P}^*_t - \hat{P}_t.$$

These definitions imply, for example, that incomplete exchange rate pass-through into imports leads to a positive $\hat{L}_t$. If exchange rate pas-through to imports and exports was complete, then both $\hat{L}_t$ and $\hat{L}_t^*$ would be 0.

Figs.$1-9$ show the impulse response of $\hat{L}_t$, $\hat{L}_t^*$, and $\hat{Q}_t$ to a one standard deviation nominal, technology, and the preference shock respectively. I plot the posterior mean and the 90% probability intervals of the impulse responses. For brevity, I do not report the impulse responses to the two foreign shocks. Again, while there is some heterogeneity in the results across countries, there clearly are broad similarities.

As is clear, while exchange rate pass-through is incomplete in the short-run, law of one price or purchasing power parity holds in the long run. The main result from the impulse responses is the heterogeneity in the effects on law on one price deviations across the various shocks. Technology shocks lead to a persistent and hump-shaped effect on $\hat{L}_t$, $\hat{L}_t^*$, and $\hat{Q}_t$, albeit with a fairly low effect on impact for $\hat{L}_t$ and $\hat{L}_t^*$.[19] The effects of nominal and preference shocks in converse die out quite fast, but the effects are quite substantial on impact.

Variance decompositions Another way to assess the different roles played by the underlying shocks in generating law of one price deviations is to compute the variance decomposition of In tables $10 - 12$, I report variance decomposition of $\hat{L}_t$, $\hat{L}_t^*$, and $\hat{Q}_t$ for Australia, Canada, and New Zealand respectively. These are unconditional variance decomposition measures computed at the posterior mean.

A quite striking result is that technology and nominal shocks play a negligible role in explaining movements in law of one price deviation. The aggregate preference shock is the main driver of law of one price deviation in import and export prices while the foreign shock plays the most important role in law of one price deviation in consumer prices. These results are thus suggestive of the well known "exchange rate disconnect" puzzle, the inability of fundamental shocks such as technology and nominal shocks to explain the dynamics of the exchange rate.

4 Conclusion

In this paper, in contrast to the literature, I study (incomplete) exchange rate pass-through in general equilibrium. Theoretically, I use a small open economy DSGE model to understand pass-through dynamics conditional on a shock. I also use simulated data from the model to study potential misspecification and omitted variable bias that can plague the standard single equation partial equilibrium estimation approach. Finally, I estimate a rich model using data on output, prices, and the nominal exchange rate from Australia, Canada, and New Zealand. Then using impulse response and variance decomposition analysis, I assess how exchange rate pass-through

[19] Steinsson (2008) emphasizes the hump-shaped response of the real exchange rate to a technology shock in a two-country model with nominal rigidities.

is affected by structural shocks. I find that incomplete pass-through to import and export prices is driven mostly by a preference shock while deviation from purchasing power parity is driven by the foreign consumption shock.

In future work, it would be interesting to consider several model extensions. It would be worthwhile to allow for features such habit formation in consumption and inflation indexation to generate persistence in the endogenous variables. It might also be important to allow for time varying desired markups along the lines of Atkeson and Burstein (2008), Dornbusch (1987), and Krugman (1987). Finally, another avenue for research would be to delve further into the inability of fundamental shocks such as technology, nominal, and preference shocks to explain the behavior of the real exchange rate.

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Table 1: Exchange rate pass-through into import prices

Country	Short-Run	Long-Run ($j = 4$)	Country	Short-Run	Long-Run ($j = 4$)
Australia	0.56	0.67	Japan	0.43	1.13
Austria	0.21	0.10	Netherlands	0.79	0.84
Belgium	0.21	0.68	New Zealand	0.22	0.22
Canada	0.75	0.65	Norway	0.40	0.63
Czech Republic	0.39	0.60	Poland	0.56	0.78
Denmark	0.43	0.82	Portugal	0.63	1.08
Finland	0.55	0.77	Spain	0.68	0.70
France	0.53	0.98	Sweden	0.48	0.38
Germany	0.55	0.80	Switzerland	0.68	0.93
Hungary	0.51	0.77	United Kingdom	0.36	0.46
Italy	0.35	0.35	United States	0.23	0.42

Source: Campa and Goldberg (2005)

Table 2: Exchange rate pass-through into consumer prices

Country	Long-Run ($j = 4$)	Country	Long-Run ($j = 4$)
Australia	0.09	Netherlands	0.38
Austria	-0.09	New Zealand	-0.10
Belgium	0.08	Norway	0.08
Denmark	0.16	Poland	0.59
Finland	-0.02	Portugal	0.60
France	0.48	Spain	0.36
Germany	0.07	Sweden	-0.11
Hungary	0.42	United Kingdom	-0.11
Italy	0.03	United States	0.01

Source: Goldberg and Campa (2010)

Table 3: Exchange rate pass-through into import, consumer, and export prices for Canada

	$j=0$	$j=1$	$j=2$	$j=3$	$j=4$
Imports	0.649	0.645	0.614	0.570	0.501
CPI	-0.008	0.018	0.004	-0.020	-0.015
Exports	0.372	0.355	0.330	0.208	0.148

Table 4: Exchange rate pass-through into export prices using simulated data

	$j=0$	$j=1$	$j=2$	$j=3$	$j=4$
Nominal Shock	0.353	0.201	0.111	0.068	0.042
Technology Shock, $\sigma=2$	2.598	2.649	2.690	2.719	2.741
Technology Shock, $\sigma=0.5$	-1.662	-1.618	-1.585	-1.557	-1.535

Table 5: Prior distributions

Parameters	Domain	Density	Prior Mean	Prior Stdev
β	[0,1)	Beta	0.95	0.03
θ	[0,1)	Beta	0.6	0.2
γ	[0,1)	Beta	0.7	0.05
σ	$\mathbb{R}^+$	Gamma	3	2
η	$\mathbb{R}^+$	Gamma	2	1.5
ϕ	$\mathbb{R}^+$	Gamma	3	2
α	[0,1)	Beta	0.7	0.2
μ^{-1}	[0,1)	Beta	0.7	0.1
ζ	[0,1)	Beta	0.7	0.2
ρ_z	[0,1)	Beta	0.4	0.15
ρ_a	[0,1)	Beta	0.7	0.15
ρ_χ	[0,1)	Beta	0.7	0.15
ρ_{c*}	[0,1)	Beta	0.7	0.15
ρ_{π^*}	[0,1)	Beta	0.7	0.15
σ_z	$\mathbb{R}^+$	InvG	1	0.5
σ_a	$\mathbb{R}^+$	InvG	1	0.5
σ_χ	$\mathbb{R}^+$	InvG	4	2
σ_{c*}	$\mathbb{R}^+$	InvG	4	2
σ_{π^*}	$\mathbb{R}^+$	InvG	4	2

Table 6: Bayesian model comparison

	Marginal data density		
	Australia	Canada	New Zealand
$\zeta \neq 0$	-1158	-1065	-943
$\zeta = 0$	-1150	-1055	-935

Table 7: Posterior estimates for Australia

Parameters	Prior Mean	Posterior Mean	Probability Interval 90%	
β	0.95	0.9856	[0.9734	0.9984]
θ	0.6	0.5182	[0.4760	0.5599]
γ	0.7	0.8980	[0.8712	0.9278]
σ	3	4.6503	[3.1503	6.1031]
η	2	0.2016	[0.0312	0.3590]
ϕ	3	2.2529	[0.1566	4.3437]
α	0.7	0.6689	[0.5397	0.7998]
μ^{-1}	0.7	0.6920	[0.5291	0.8564]
ρ_z	0.4	0.1714	[0.0686	0.2703]
ρ_a	0.7	0.8741	[0.8046	0.9464]
ρ_χ	0.7	0.4591	[0.3736	0.5462]
ρ_{c*}	0.7	0.9880	[0.9777	0.9987]
ρ_{π^*}	0.7	0.4578	[0.2785	0.6366]
σ_z	1	1.1327	[0.9953	1.2694]
σ_a	1	0.9563	[0.6337	1.2680]
σ_χ	4	4.3033	[3.0025	5.5966]
σ_{c*}	4	2.9704	[2.1983	3.7160]
σ_{π^*}	4	6.9529	[5.7784	8.1009]

Table 8: Posterior estimates for Canada

Parameters	Prior Mean	Posterior Mean	Probability Interval 90%	
β	0.95	0.9885	[0.9789	0.9988]
θ	0.6	0.6087	[0.5689	0.6492]
γ	0.7	0.9104	[0.8920	0.9327]
σ	3	3.3163	[2.4445	4.1854]
η	2	0.2303	[0.0315	0.4089]
ϕ	3	2.7012	[0.2158	5.1814]
α	0.7	0.7093	[0.5782	0.8446]
μ^{-1}	0.7	0.6935	[0.5329	0.8581]
ρ_z	0.4	0.4616	[0.3379	0.5860]
ρ_a	0.7	0.8854	[0.8136	0.9601]
ρ_χ	0.7	0.6051	[0.5372	0.6748]
ρ_{c*}	0.7	0.9882	[0.9781	0.9989]
ρ_{π^*}	0.7	0.4575	[0.3148	0.5968]
σ_z	1	0.7512	[0.6635	0.8390]
σ_a	1	0.9337	[0.6414	1.2157]
σ_χ	4	4.5096	[3.3316	5.6558]
σ_{c*}	4	2.6118	[2.0274	3.1786]
σ_{π^*}	4	4.7902	[3.9381	5.6380]

Table 9: Posterior estimates for New Zealand

Parameters	Prior Mean	Posterior Mean	Probability Interval 90%	
β	0.95	0.9816	[0.9657	0.9980]
θ	0.6	0.5649	[0.5238	0.6059]
γ	0.7	0.9105	[0.8924	0.9328]
σ	3	3.3246	[2.1504	4.4507]
η	2	0.2340	[0.0315	0.4182]
ϕ	3	2.2939	[0.1205	4.5837]
α	0.7	0.7901	[0.7001	0.8831]
μ^{-1}	0.7	0.6781	[0.5140	0.8422]
ρ_z	0.4	0.1853	[0.0806	0.2892]
ρ_a	0.7	0.9100	[0.8509	0.9723]
ρ_χ	0.7	0.4524	[0.3614	0.5457]
ρ_{c*}	0.7	0.9698	[0.9436	0.9972]
ρ_{π^*}	0.7	0.2752	[0.1541	0.3960]
σ_z	1	1.3317	[1.1579	1.5040]
σ_a	1	0.7200	[0.5134	0.9208]
σ_χ	1	5.3293	[3.5940	7.0223]
σ_{c*}	4	3.7210	[2.6880	4.7148]
σ_{π^*}	4	8.4845	[7.3338	9.8267]

Table 10: Variance decomposition for Australia

	$\epsilon_{Z,t}$	$\epsilon_{A,t}$	$\epsilon_{\chi,t}$	$\epsilon^*_{C,t}$	$\epsilon^*_{\pi,t}$
$\hat{L}_t$	1.65	0.58	73.63	24.14	0.00
$\hat{L}^*_t$	1.52	0.53	67.75	22.21	7.98
$\hat{Q}_t$	0.11	0.85	5.46	93.58	0.00

Table 11: Variance decomposition for Canada

	$\epsilon_{Z,t}$	$\epsilon_{A,t}$	$\epsilon_{\chi,t}$	$\epsilon^*_{C,t}$	$\epsilon^*_{\pi,t}$
$\hat{L}_t$	1.11	0.60	76.31	21.97	0.00
$\hat{L}^*_t$	1.01	0.54	69.17	19.92	9.36
$\hat{Q}_t$	0.16	1.90	8.99	88.95	0.00

Table 12: Variance decomposition for New Zealand

	$\epsilon_{Z,t}$	$\epsilon_{A,t}$	$\epsilon_{\chi,t}$	$\epsilon^*_{C,t}$	$\epsilon^*_{\pi,t}$
$\hat{L}_t$	2.52	0.28	70.94	26.26	0.00
$\hat{L}^*_t$	2.14	0.23	60.08	22.24	15.31
$\hat{Q}_t$	0.71	3.49	15.00	80.80	0.00

Australia

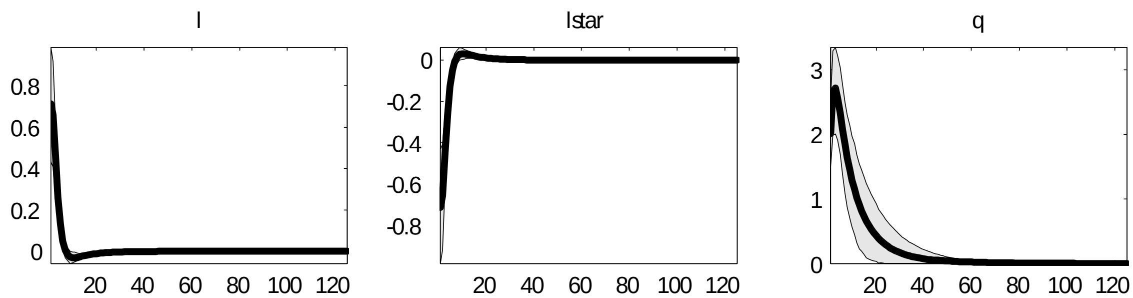

Fig 1: Mean and 90% probability intervals of the response to a technology shock

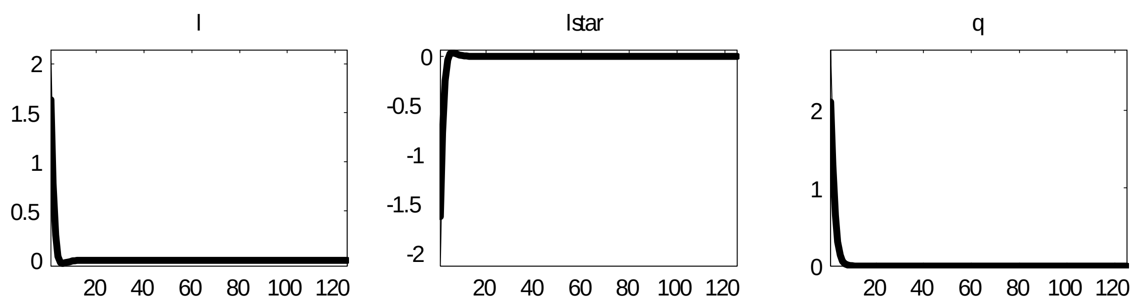

Fig 2: Mean and 90% probability intervals of the response to a nominal shock

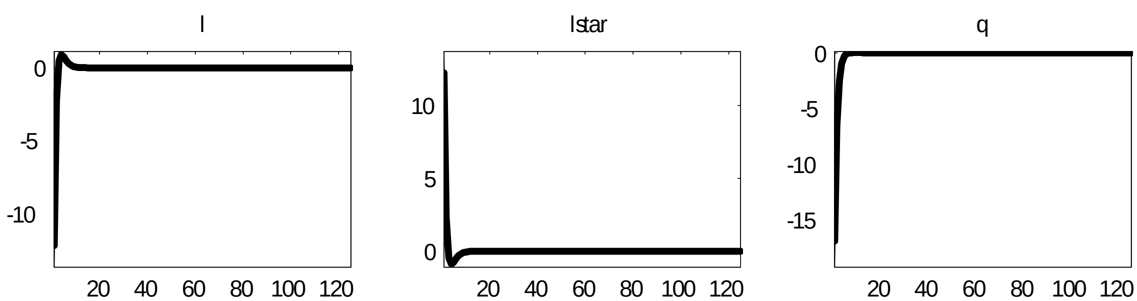

Fig 3: Mean and 90% probability intervals of the response to a preference shock

Canada

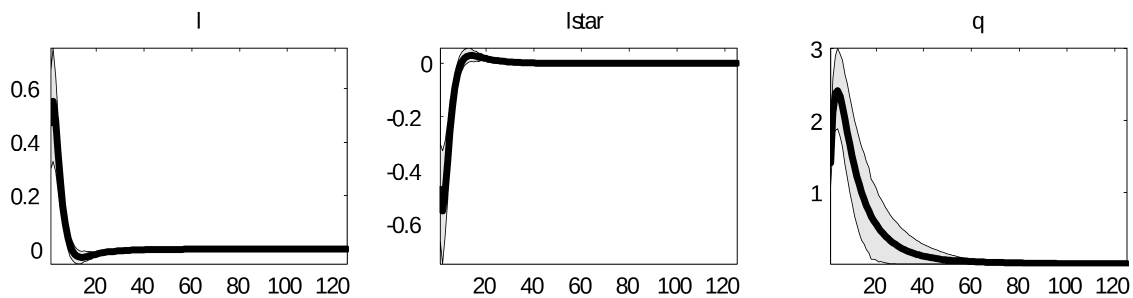

Fig 4: Mean and 90% probability intervals of the response to a technology shock

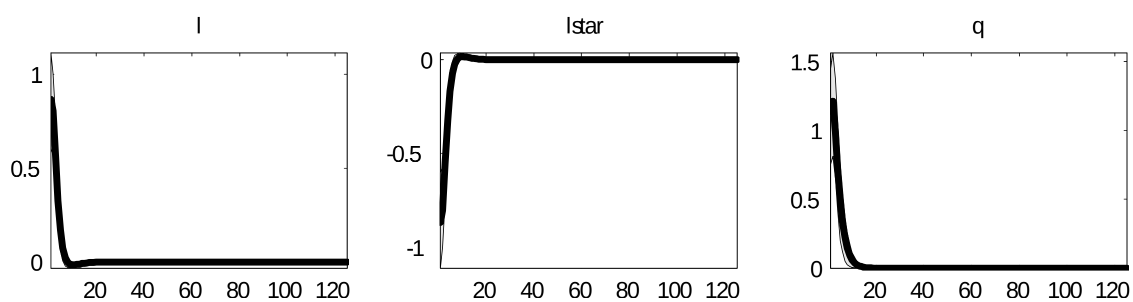

Fig 5: Mean and 90% probability intervals of the response to a nominal shock

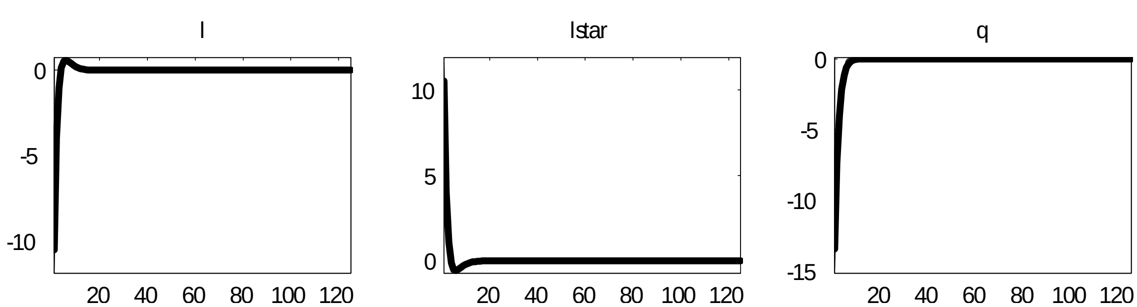

Fig 6: Mean and 90% probability intervals of the response to a preference shock

New Zealand

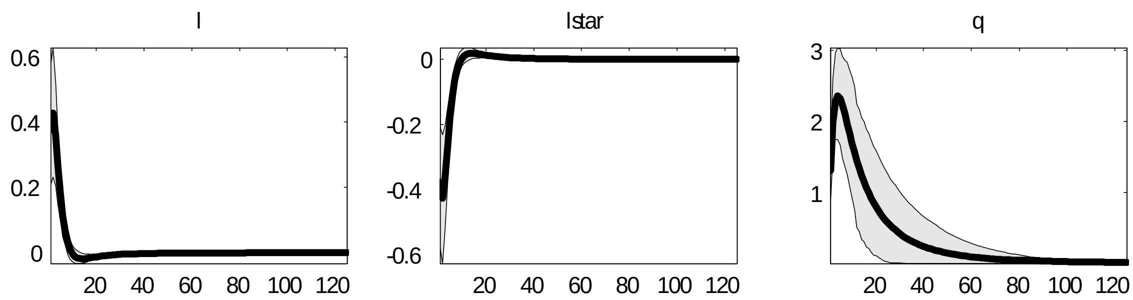

Fig 7: Mean and 90% probability intervals of the response to a technology shock

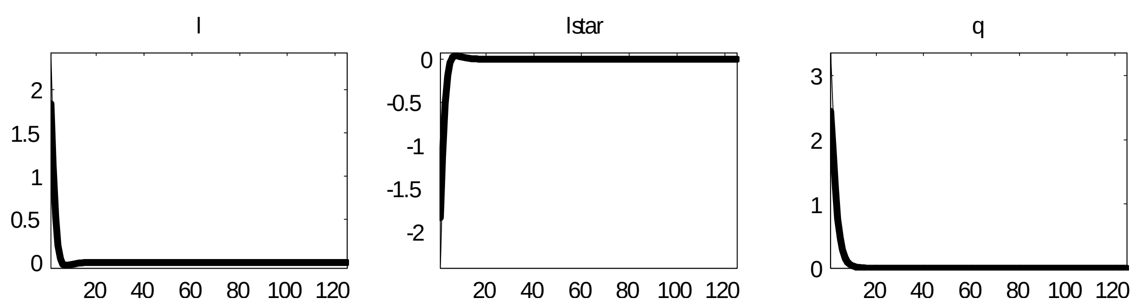

Fig 8: Mean and 90% probability intervals of the response to a nominal shock

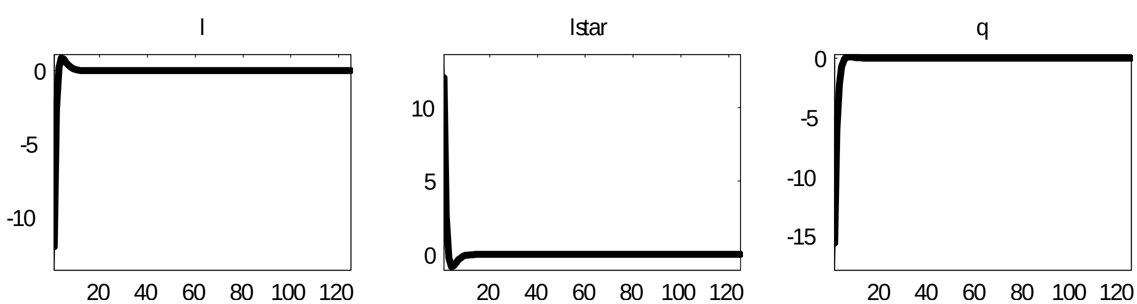

Fig 9: Mean and 90% probability intervals of the response to a preference shock

5 Appendix

5.1 Posterior simulation

The Metropolis-Hastings algorithm works as follows. Let the posterior mode computed from the numerical optimization routine be $\tilde{\theta}$. Let the inverse of the Hessian computed at $\tilde{\theta}$ be $\tilde{\Sigma}$.

(a) Choose a starting value θ^0. Then use a loop over the following steps (b)-(d).

(b) For $d = 1, ..., D,$ draw a θ^* from the proposal distribution $N(\theta^{d-1},\ c\tilde{\Sigma})$.

(c) Accept $\theta^*,$ that is $\theta^d = \theta^*,$ with probability $\min\{1, r(\theta^{d-1},\ \theta^*)\}$. Reject θ^*, that is $\theta^d = \theta^{d-1},$ otherwise.

(d) $r(\theta^{d-1},\ \theta^*)$ is given by:

$$r(\theta^{d-1},\ \theta^*) = \frac{p(\theta^*)L(Y \mid \theta^*)}{p(\theta^{d-1})L(Y \mid \theta^{d-1})}$$

The scale parameter c is chosen to lead to acceptance rates of around 30%.

5.2 Model comparison

The objective here is to compute the marginal data densities of the various model specifications:

$$p(Y) = \int p(\theta)L(Y \mid \theta)\ d\theta.$$

The draws from the posterior are used to simulate the marginal density and then an average of these simulated values is taken. First note that we can write:

$$\frac{1}{p(Y)} = \int \frac{f(\theta)d\theta}{p(\theta)L(Y \mid \theta)} d\theta$$

where f is a probability density function such that $\int f(\theta)d\theta = 1$. Then, we can use the following estimator:

$$\hat{p}(Y) = \left[\frac{1}{D} \sum_{d=1}^{D} \frac{f(\theta^d)}{p(\theta^d) L(Y \mid \theta^d)} \right]^{-1}$$

where d denotes the posterior draws obtained using the Metropolis Hastings algorithm. For f, Geweke (1999) proposed a truncated multivariate normal distribution.