Understanding the Cross Country Effects of US Technology Shocks[*][†]

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Abstract

Business cycles are substantially correlated across countries. Yet, most existing models are not able to generate substantial transmission through international trade. We show that the nature of such transmission depends fundamentally on the features determining the responsiveness of labor supply and labor demand to international relative prices. We augment a standard international macroeconomic model to incorporate three key features: a weak short run wealth effect on labor supply, variable capital utilization, and imported intermediate inputs for production. This model can generate large and significant endogenous transmission of technology shocks through international trade. We demonstrate this by estimating the model using data for Canada and the United States with quasi-Bayesian methods. We find that this model can account for the substantial transmission of permanent U.S. technology shocks to Canadian aggregate variables such as output and hours documented in a structural vector autoregression. Transmission through international trade is found to explain the majority of the business cycle comovement between the United States and Canada while exogenous correlation of technology shocks is not important.

JEL classification: F41, F44, F62, E30.

Keywords: International transmission of business cycles, international comovement, structural analysis, quasi-Bayesian.

1 Introduction

It is widely documented that business cycles comove substantially across countries. Knowledge of how shocks transmit across countries is important to understand business cycles in each country and to design external policies. One potential explanation for the observed comovements across countries is endogenous transmission, i.e. shocks propagate from one country to another country through international trade in goods and financial assets. Yet, most existing models in the international business cycle literature are not able to generate significant endogenous transmission. International real business cycle models starting from Backus et al. (1992, 1995) generate weak correlation of key aggregate variables such as output and hours[1]. In particular, Schmitt-Grohé (1998) demonstrates that a class of real business cycle models cannot explain the observed dynamic effects of shocks to U.S. output on the Canadian economy. Even in the more recent papers such as Engel and Wang (2011) and Johnson (2012), outputs across countries are only weakly correlated, suggesting that their models still do not generate substantial endogenous transmission. In the recent New Open Economy Macroeconomics (NOEM) literature, Justiniano and Preston (2010) find that estimated international business cycle models with nominal rigidities also fail to explain both the documented importance of U.S. shocks for Canadian business cycles and the comovements of macroeconomic variables between these two countries. Other papers using estimated NOEM models such as Adolfson et al. (2006, 2007) or Christiano et al. (2010) also report the similar result: namely that foreign shocks explain little of the domestic variables. These results suggest that models with or without nominal rigidities fail to explain the observed cross-country comovements, especially when one looks beyond the second moments often used in this literature to judge their performance.

In this paper, we argue that a standard real international business cycle model augmented with three key features can generate substantial endogenous transmission of technology shocks and help to explain the observed business cycle comovements. The three key features are: Jaimovich-Rebelo preferences allowing for a low wealth elasticity of labor supply, variable capital utilization and imported intermediate inputs for production. We show that this augmented model is capable of explaining over 90% of the observed transmission of a permanent U.S. technology shock to Canadian output and hours worked. By contrast, a model without these three key features can only account for about 10% of the observed transmission.

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[1] In this literature, cross-country comovements are explained fundamentally through the correlation of shocks. However, once that channel is shut down, there is little comovement, implying that there is no substantial endogenous transmission.

The reason for why models without our three key features fail to generate substantial endogenous transmission is because they cannot explain the response of domestic hours to foreign shocks. The response of domestic hours plays a central role for the transmission of the foreign shock because in the absence of a change in the level of domestic technology, increases in output require an increase in hours. When there is a positive permanent technology shock in the foreign country, the supply of foreign goods increases, causing the domestic terms of trade to appreciate. This appreciation of the domestic terms of trade affects both labor supply and labor demand in the domestic economy. In the standard model, on the labor supply side, domestic households become richer, and decrease their labor supply as in Panel (a) of Figure 1. On the labor demand side, for a given appreciation in the terms of trade, labor demand can increase. However, the shift in the labor demand curve is not sufficient to increase hours worked to generate strong endogenous transmission under plausible parameterizations of the standard model. [2]

In contrast, the model with our three key features can generate substantial endogenous transmission. With Jaimovich Rebelo preferences, which allow for a low wealth elasticity of labor supply, the domestic labor supply curve does not shift substantially as in Panel (b) of Figure 1. On the labor demand side, for a given appreciation in the terms of trade, the increase in labor demand can be substantially larger when there are both imported intermediate inputs and variable capacity utilization. These two features increase the marginal product of labor. More specifically, domestic firms increase the amount of imported intermediate inputs from the foreign country given the cheaper price of imports, leading to an increase in labor demand. Additionally, variable capital utilization can shift the labor demand curve further to the right as it amplifies the change in other inputs in the production function. Therefore, in equilibrium, with our three key features, hours can increase significantly in the domestic economy as demonstrated in Panel (b) of Figure 1.

To test the ability of the model to generate endogenous transmission that is consistent with the data, we build an empirical benchmark that characterizes the transmission of shocks across countries. To that end, we document the effects of permanent U.S. technology shocks on the Canadian economy such as output, consumption, investment, hours, net export, and the terms of trade. We identify permanent U.S. technology shocks using the long run identification, which imposes that only permanent U.S. technology shocks can affect U.S. labor productivity in the long run. We find that

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[2]Our key insight is that this relationship between domestic hours and the terms of trade does not depend on the elasticity of substitution between domestic and foreign goods, or the completeness of financial markets, both of which are often emphasized in the literature for transmission of technology shocks.

this identified U.S. technology shock leads to a significant boom in Canada, where output in Canada increases as much as 60% of the increase in U.S. output. Also, hours worked in Canada increases with a similar magnitude as Canadian output, and Canadian terms of trade appreciate.

Given our empirical evidence, we analyze the endogenous transmission in our proposed model, and show that our model generates substantial endogenous transmission by estimating the model. More specifically, we demonstrate our intuition for how models with and without our three key features generate endogenous transmission using a simple calibration exercise. Then, we estimate the model using quasi-Bayesian methods by matching the theoretical impulse responses to a permanent U.S. technology shock with the corresponding empirical responses. This exercise demonstrates that our model can generate substantial endogenous transmission and match the observed transmission without exogenous correlation of technology shocks between the U.S. and Canada. Even when we allow for exogenous correlation of technology shocks, the data still prefer endogenous transmission, which is consistent with our empirical evidence. Furthermore, our estimation suggests that all three key features are necessary for the model's success.

Our insights about the transmission mechanism of technology shocks across countries are different from those proposed in the literature. For example, in Corsetti et al. (2008), the authors propose that the large wealth effect under incomplete markets is important to explain the transmission of technology shocks across countries. In another paper, Burstein et al. (2008) suggest that production sharing by using a low substitutability of domestic and foreign goods can increase the comovement of outputs across countries. However, these features are not able to explain the types of evidence that we have. We do not observe the movements of the terms of trade predicted in those theories. In Corsetti et al. (2008), endogenous transmission arises with the wealth effect channel only when the terms of trade in Canada depreciate. In Burstein et al. (2008), a low elasticity of substitution helps only when the terms of trade in Canada appreciate a few times larger than the movements of hours. In the data, the Canadian terms of trade appreciates with a magnitude slightly larger than hours. Therefore, neither of the features proposed in these papers can create substantial endogenous transmission. Instead, we need our three key features to deliver the results consistent with our empirical findings.

Our insights above carry over to models with nominal rigidities, i.e. our three key features also help to generate substantial endogenous transmission with plausible parameterizations of nominal rigidities. To demonstrate that, we estimate a version of our model augmented with nominal rigidities

by matching additionally the responses of Canadian inflation and nominal interest rate to a permanent U.S. technology shock. We find that when the model has our three key features, it can match the responses of aggregate variables in Canada under moderate nominal rigidities. Without these features, the estimated degree of price stickiness is close to one, meaning prices are fixed. The intuition for this result is as follows. In theory, price stickiness a la Calvo can generate time varying markups, which can shift the labor demand curve. If the markups in Canada decline in response to a positive U.S. technology shock, the demand for hours in Canada can increase and also inflation in Canada increases. In the data, a positive permanent U.S. technology shock has a negligible effect on inflation in Canada. Therefore, only when prices are almost fixed can markups vary sufficiently to help the model match hours without causing substantial inflation in Canada. In contrast, the three key features we propose can help the model to generate endogenous transmission without relying heavily on the time varying markups, which is why the degree of price stickiness does not have to be so high in our case.

Our paper focuses on the transmission of technology shocks from the U.S. to Canada for the following reasons. First, we can address the large literature studying the transmission of technology shocks. Also, uncovering the endogenous transmission mechanism of technology shocks can give insights about that of other types of shocks. Another reason is that we can identify technology shocks using structural VAR without relying on specific structural models, and then use this empirical evidence to test the ability of the model to generate endogenous transmission. Moreover, by focusing on the U.S. and Canada pair, we can treat the U.S. as the rest of the world to Canada since the U.S. accounts for over 70% of Canadian international trade. Lastly, previous papers fail to explain the relationship between these two countries, making it an interesting case to study.

To isolate the effects of shocks on Canadian variables without relying on specific structural model assumptions, we choose a limited information approach where we identify one type of shocks, i.e. permanent technology shocks, to characterize its transmission on Canada instead of using non-structural shocks or full information approach. The reason is as follows. Cross-country comovements can be driven by a number of shocks, each of which can have an opposite effect on the international relative prices. For example, in theory, positive government spending shocks in the U.S. can depreciate Canadian terms of trade while positive U.S. technology shocks can appreciate Canadian terms of trade. Therefore, a non-structural U.S. shock that increases output in the U.S., which is a combination of these two types of shocks, can have ambiguous effects on Canadian terms of trade, leading to a wrong conclusion about endogenous transmission in the model. Furthermore, although full information ap-

proach can also identify structural shocks, identification relies on all aspects of assumptions in the model. In contrast, our empirical approach can help us test a wide range of models since we do not identify technology shocks using specific structural model assumptions. This is appealing for us since we can focus exclusively on the model's ability to generate endogenous transmission with a single benchmark.

The remainder of the paper is organized as follows. In Section 2, we document the effects of permanent U.S. technology shocks on Canada in the structural VAR. We present our baseline model in Section 3. We explain our estimation method for the model in Section 4. Section 5 explains the intuition of the model in details. We estimate our model and present the results in Section 6. We also analyze the crucial features of our model that can generate this result quantitatively in Section 7. Finally, in Section 8, we present a variety of the robustness check, where we add nominal rigidities into the model and compare with the state of the art model in the New Open Economy Model literature. We conclude and suggest possible future work in Section 9.

2   Empirical Evidence

In this section, we document the effects of U.S. permanent technology shocks on Canadian economy using quarterly data for the U.S. and Canada post-Bretton Woods period between 1973Q1 and 2012Q3[3]. Our analysis focuses on the U.S. and Canada relationship because of their tight trade linkages. The U.S. is Canada's single most important trading partner. For the last 30 years, the share of exports to the U.S. in total Canadian exports is, on average, over 75%, and that of imports is 68%. Therefore, U.S. shocks should propagate to Canada through international trade directly, not through a third country, rationalizing the choice of two countries framework. Additionally, the U.S. is ten times larger than Canada and therefore we assume in the VAR that Canada has no effect on the U.S..

2.1   The VAR Model

We estimate a VAR model and identify the technology shocks using long run restrictions. The VAR includes the following variables: the growth rate of the labor productivity $\left(\Delta \ln \frac{y_t^{U.S.}}{h_t^{U.S.}} \right)$, the natural logarithm of hours, the growth rates of consumption and investment for the U.S. block (y_{1t}), and the

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[3]The data are from Statistics Canada, OECD National Accounts and Bureau of Labor Statistics.

growth rates of output, consumption, and investment, the natural logarithm of hours, net exports and the growth rate of the terms of trade in the Canada block (y_{2t}). Throughout the paper, the terms of trade is defined as the ratio of price of imports to price of exports.

Our unit root and stationarity tests[4] suggest that productivity, consumption, output, investment, and the terms of trade to be in difference. Hours in the U.S. and Canada are kept in level as there is no strong evidence of nonstationarity and in the model, hours are stationary. Over-differencing, as suggested by Christiano, Eichenbaum and Vigfusson (2003)[5], can cause model misspecification. The results are similar if we use the ratio of consumption to output and investment to output instead.

Our identification strategy hinges on the assumption that Canada is relatively small compared to the U.S., having no effects on the U.S. block. More specifically, we impose a block exogeneity of the following form:

$$
\begin{bmatrix} A_{11}(L) & A_{12}(L) \\ A_{21}(L) & A_{22}(L) \end{bmatrix} \begin{bmatrix} y_{1t} \\ y_{2t} \end{bmatrix} = \begin{bmatrix} e_{1t} \\ e_{2t} \end{bmatrix}
$$

where the block exogeneity implies that

$$
A_{12}(L) = 0 \text{ for } \forall L.
$$

This assumption has also been placed in earlier works, for example, Schmitt-Grohé (1998) and Justiniano and Preston (2010) although they do not identify any particular shocks.

We then identify U.S. permanent productivity shock from the U.S. block using long run restriction that only permanent technology shocks can affect U.S. labor productivity in the long run. This identification leads to the restriction that in this equation:

$$
y_{1t} = \begin{bmatrix} \Delta \ln \frac{y_t^{US}}{h_t^{US}} \\ \left(\begin{array}{c} \ln h_t^{US} \\ \Delta \ln c_t^{US} \\ \Delta \ln I_t^{US} \end{array} \right) \end{bmatrix} = \begin{bmatrix} C_{11}(L) & C_{12}(L) \\ C_{21}(L) & C_{22}(L) \end{bmatrix} \begin{bmatrix} \varepsilon_{1t}^{US} \\ \varepsilon_{2t}^{US} \end{bmatrix},
$$

$$
C_{12}(1) = 0.
$$

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[4]We perform Augmented Dickey-Fuller and KPSS tests on all U.S. and Canadian variables. For ADF tests, we cannot reject that U.S. output, consumption, investment, Canadian output, consumption, investment, and terms of trade have a unit root with a 10% significance level. For KPSS tests, we can reject trend stationarity for the same variables.

[5]Fisher (2006) also specifies hours in level in his empirical exercise.

We include 4 lags of each of the variables and a constant in the VAR model.

2.2 VAR Result

Using the estimates of the VAR model above, we compute the impulse responses of the variables in Canadian block, y_{2t}, following a one-standard deviation shock in ε_{1t}^{US}. The dynamic responses are invariant to the ordering of the variables within y_{2t}.

The impulse response functions of all the variables in the US are displayed in Figure 2 and in Canada in Figure 3 and 4. Lines marked with a plus sign correspond to the point estimate of the impulse responses, and the shaded areas are the 95% confidence band calculated from bootstrapping 1,000 times[6].

Our result suggests that after a positive US permanent technology shock occurs in period 1,

(1) U.S. output, consumption, investment and hours increase[7].

(2) All of the Canadian aggregate quantities go up and the terms of trade appreciates (falls).

(3) In terms of the magnitude, output in Canada increases as much as 60% of the increase in the U.S.. Investment increases on impact, reaching the highest response of about twice as much as output. Consumption also increases but less than output. Canadian terms of trade appreciate slightly more than Canadian output. Net exports to output ratio in Canada increases significantly. The maximum response of net exports is about half of Canadian output.

(4) Labor productivity increases slightly, about a fourth of Canadian output, but not significant at 95% confidence level.

Our results are different from Schmitt-Grohé (1998) who finds that the terms of trade does not move at all in response to an innovation to U.S. output. One potential explanation for this difference is that the innovation in U.S. output may includes other types of shocks that have opposite effects on the terms of trade. For example, a calibrated model in Backus et al. (1994) suggests that while technology shock in the U.S. causes Canadian terms of trade to appreciate, government spending shock in the U.S. can cause Canadian terms of trade to depreciate. Therefore, after an innovation to the U.S. output, the terms of trade may not change significantly. Focusing on only permanent technology shocks helps us to avoid this problem.

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[6]The bootstrap procedure is as follows: from the centered residuals of the estimation, bootstrap residuals are generated by randomly drawing with replacement. These quantities are used to compute bootstrap time series, which is then re-estimated. The percentile interval is determined as $\left[\widehat{IR} - t_{0.025}^*, \widehat{IR} - t_{0.975}^* \right]$ where $t_{0.975}^*, t_{0.025}^*$ are the 0.975 and 0.025 quantiles, respectively, of the distribution of the centered bootstrap IR (Hall's percentile confidence interval).

[7]On impact, response of hours is close to zero and insignificant.

To gauge the importance of U.S. technology shocks to Canada, we perform a forecast error variance decomposition of this shock on Canadian variables. As summarized in Table 1, U.S. technology shocks explains a nontrivial portion of all real variables, up to 39% of the Canadian output and 24% of hours in 8 quarter horizon. The contribution to consumption in Canada is smaller, about 26% at 8 quarter horizon and 35% at 20 quarter horizon. Only about 14% of investment and 19% the terms of trade variation are explained by this U.S. permanent technology shock at horizon 20, suggesting that the high volatility of these variables is caused by some other factors.

We obtain similar results if we use manufacturing sectors data on productivity and hours in the U.S. to identify U.S. permanent technology shocks as Corsetti et al. (2008). We also use non-fuel terms of trade in the VAR and find that this measure of terms of trade also decreases significantly after a positive U.S. permanent technology shocks. Besides, real exports and imports of machineries, automotive and industrial goods in Canada are most affected by this U.S. shock compared to energy products. This result justifies our choice not to model explicitly oil production in Canada, which can be important to explain unconditional movements in Canadian terms of trade as in Backus and Crucini (2000).

2.3 The U.S. and Canadian Technology Processes

Are the effects of U.S. permanent technology shocks on Canada documented above a product of technology spillover? We next examine how empirically the U.S. and Canadian technology are related. One way to diagnose if the shocks are mostly common is to compute the correlation between U.S. and Canadian permanent technology shocks. We apply the same long run identification to Canadian labor productivity growth, hours, consumption and investment growth rates to extract Canadian permanent technology shock. The correlation turns out to be negative and insignificant contemporaneously (-0.07) and only significant and positive at lag six and negative for lag nine[8].

Technology can also be spillover directly if there is some cointegrating relationship between the U.S. and Canada. To check this possibility, we run cointegration tests for outputs in both countries. Table 2 report the results from the unrestricted cointegration rank test using the trace and maximum eigenvalue methods as Johansen (1991) with four lags and a constant in the cointegrating vector. The trace statistics are less than the 5% critical values (15.41 and 3.76, respectively) for both zero and one cointegrating vector, and similarly, max eigenvalue statistics are less than the 5% critical value.

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[8]The five quarters centered moving average of the U.S. and Canadian shocks are positively but insignificantly correlated contemporaneously and up to 5 lags (0.10).

It is not decisive if there is cointegration between the U.S. and Canada outputs.

These results, together with the small increase in labor productivity in Canada after a U.S. technology shock, suggest that the effects of U.S. technology shocks on Canada should, at least to some extent, come from international goods and financial trades rather than only correlated shocks. Nevertheless, to get a conclusive evidence about the role of spillover, we model below a cointegrating relationship in the technology process and let the data decide how large the role of this propagation of technology between the U.S. and Canada is.

3   The Model

This section details our baseline model, which builds on Backus, Kehoe and Kydland (1992,1995) model. We model Canada as a small open economy and the U.S. as a closed economy. Canada plays no role in the U.S. aggregate variables. The model assumes incomplete financial market where agents can only trade one-period non-contingent bonds. The model also includes two other frictions often used in the literature: investment adjustment cost and debt elastic interest rate.

To generate sufficiently strong endogenous transmission of technology shocks across countries, we include three key features in the model that depart from a plain vanilla international real business cycle model. These three key features are Jaimovich-Rebelo utility function, variable capital utilization, and imported intermediate inputs. The intuition is as follows: For the labor supply side, Jaimovich-Rebelo preference includes a parameter governing wealth effect on labor supply. When wealth effect is strong, household may decrease their labor supply in response to an appreciation in the terms of trade, causing output to decline. This preference adds flexibility into the model to be able to replicate a positive response of hours in the data. Multiple channels work from the labor demand side. First, variable capacity utilization amplifies the effects of the terms of trade and interest rate on hours worked. Additionally, imported intermediate goods also cause hours to increase for a given movement in the terms of trade. The intuition is that firms hire more workers when the marginal product of labor goes up as the price of imported intermediate inputs goes down.

We describe below the structure of the Canadian economy.

3.1 Households

Each household maximizes the expected lifetime utility:

$$\max E_0 \sum_{t=0}^{\infty} \beta^t \frac{\left[C_{1t} - \phi_1^H \frac{1}{1+\frac{1}{v}} X_{1t} H_{1t}^{1+\frac{1}{v}}\right]^{1-\sigma} - 1}{1-\sigma}$$

where C_{1t} is consumption , H_{1t} is hours worked. The subscript 1 denotes country 1, σ is intertemporal elasticity of substitution. $v > 0$ is related with Frish elasticity of labor supply. X_{1t} satisfies the following equation:

$$X_{1t} = (C_{1t})^{\kappa_1} X_{1t-1}^{1-\kappa_1}. \tag{1}$$

This preference specification is due to Jaimovich-Rebelo (2009), featuring parameter κ_1 that governs the wealth elasticity of labor supply. This parameter is estimated to understand the transmission mechanism. We modify the preference specification to include internal habit formation. When $\kappa_1 = 1$, we have the common CRRA utility function characterized by King, Plosser, and Rebelo (1988, KPR henceforth). As $\kappa_1 \to 0$, the utility function becomes linear in consumption and hours worked, which is the Greenwood, Hercowitz, and Huffman (1988, GHH henceforth) preference. In that case, there is no wealth effect on labor supply decision.

We assume that households can only borrow with one period non-contingent bonds denominated in foreign consumption, B_{1t+1}^F, paid with interest rate R_{1t}^F. To ensure a well-defined steady state and stationarity in the model, we assume debt elastic interest rate of the form,

$$R_{1t}^F = R_{2t}^F A \left(q_t B_{t+1}^F \frac{1}{Z_{1t}}\right)$$

where R_{1t}^F is interest rate which country 1 needs to pay and R_2^F is interest rate in country 2. $q_t B_{1t+1}^F \frac{1}{Z_{1t}}$ is a real foreign asset position where q_t is the real exchange rate, which is the relative price of foreign consumption goods in terms of home consumption goods and the term Z_{1t} is technology level in country 1. Following Schmitt-Grohé and Uribe (2003) and Adolfson et al. (2007), we assume that A is given by:

$$A\left(q_t B_{t+1}^F \frac{1}{Z_{1t}}\right) = \exp\left[-\phi_1^B \left(\frac{q_t \frac{B_{t+1}^F}{Z_{1t}}}{\left(\frac{q_t B_{t+1}^F}{Z_{1t}}\right)_{ss}} - 1\right)\right]$$

where $\left(\frac{q_t B_{t+1}^F}{Z_{1t}}\right)_{ss}$ is steady state value of real foreign asset position.

Household is assumed to own capital K_{1t}, which evolves over time under the following law of motion:

$$K_{1t+1} = (1 - \delta) K_{1t} + I_{1t} \left(1 - S \left(\frac{I_{1t}}{I_{1t-1}} \right) \right) \tag{2}$$

where δ is the depreciation rate of capital and I_t is gross investment. Following Christiano et al. (2005), we assume that it is costly to adjust the level of investment for capital, i.e. $S(.)$ is the adjustment cost satisfying $S(\mu_1) = 0$, $S'(\mu_1) = 0$, $S''(\mu_1) = s_1$, where μ_1 is the steady state growth rate of output. We use the quadratic specification of S:

$$S \left(\frac{I_{1t}}{I_{1t-1}} \right) = \frac{s_1}{2} \left(\frac{I_{1t}}{I_{1t-1}} - \mu_1 \right)^2.$$

In addition, household has to pay a utilization cost $a(u_{1t})$ for the intensive use of capital K_{1t} in terms of consumption unit. The capital utilization, u_{1t}, has an increasing and convex cost $a(u_{1t})$ per unit of capital. We adopt a quadratic form of function a:

$$a(u_{1t}) = a_{11} (u_{1t} - 1) + \frac{a_{21}}{2} (u_{1t} - 1)^2$$

with $a_{11}, a_{21} > 0$. The parameter a_{21} is the sensitivity of the utilization cost to variation in the rental rate of capital. The parameter a_{11} governs the steady state level of u_{1t}.

The household budget constraint is then:

$$
\begin{aligned}
& C_{1t} + p_{1t}^I I_{1t} + B_{1t+1}^D \frac{1}{R_t^D} + q_t B_{1t+1}^F \frac{1}{R_{1t}^F} \\
\leq \ & W_{1t} H_{1t} + R_{1t}^k (u_{1t} K_{1t}) + B_{1t}^D + q_t B_{1t}^F - a(u_{1t}) K_{1t}
\end{aligned} \tag{3}
$$

where p_t^I is relative price of investment goods in terms of consumption goods. B_{1t+1}^D is the domestic bond with interest rate R_t^D, W_{1t} is the real wage, and R_{1t}^k is the real return to capital in terms of home consumption goods unit.

3.1.1 Intermediate Good Producer

The intermediate good producer in country 1 specializes in the production of home goods Y_t^D by combining capital service, $u_{1t} K_{1t}$, labor, H_{1t}, and imported and domestic intermediate inputs, M_{21t}

and M_{11t}, respectively, using the production function

$$Y_t^D = \left((u_{1t}K_{1t})^\alpha (Z_{1t}H_{1t})^{1-\alpha} \right)^{1-\alpha_{11}-\alpha_{21}} M\left(M_{11t}, M_{21t} \right), \tag{4}$$

where $\alpha_{11} > 0$ and $\alpha_{21} > 0$ are the shares of domestic and imported intermediate inputs in gross output, $\alpha\left(1 - \alpha_{11} - \alpha_{21}\right) > 0$ is the capital share and $M\left(M_{11t}, M_{21t}\right)$ is the composite of home and imported intermediate good as we assume that the firm uses both its output for intermediate input (M_{11t}) and imported intermediate input (M_{21t}). Roundabout production is introduced to capture the role of intermediate inputs in production and cross border trade. The functional form of $M(.)$ is given as follows:

$$M_t = \left((\alpha_{11})^{\frac{1}{\gamma_1^m}} (M_{11t})^{\frac{\gamma_1^m - 1}{\gamma_1^m}} + (\alpha_{21})^{\frac{1}{\gamma_1^m}} (M_{21t})^{\frac{\gamma_1^m - 1}{\gamma_1^m}} \right)^{\frac{\gamma_1^m}{\gamma_1^m - 1}}. \tag{5}$$

The goods produced domestically, Y_t^D, can be sold to domestic final good producer to make domestic consumption goods, D_{1t}^C, domestic investment goods, D_{1t}^I, or be used for domestic good production, M_{11t}, or sold to foreign producers to make foreign consumption goods, D_{2t}^C, foreign investment goods, D_{2t}^I, or be used in their production, M_{12t}.

Finally, the intermediate good producer's problem is choosing labor, capital service, domestic and foreign inputs to maximize profit measured in consumption goods unit Π_{1t}:

$$\Pi_{1t} = p_{1t}^D Y_{1t}^D - \left[\left(W_{1t}H_{1t} + R_{1t}^k \left(u_{1t}K_{1t} \right) \right) + \underbrace{\left(p_{1t}^D M_{11t} + p_{1t}^F M_{21t} \right)}_{\text{Interemediate goods payment}} \right] \tag{6}$$

subject to the above production function, where p_{1t}^D and p_{1t}^F are prices of domestic and foreign intermediate goods in the domestic market relative to final consumption good price P_{1t} defined below.

3.1.2 Final Good Producer

Final good producer in the small open economy imports foreign consumption F_{1t}^C and investment F_{1t}^I goods from foreign producer at price P_{1t}^F. Final good producer also buys domestic consumption D_{1t}^C and investment D_{1t}^I input from the intermediate good producer at price P_{1t}^D. We assume that the law of one price holds.

Final good producer combines the domestic inputs, D_{1t}^C, and foreign inputs, F_{1t}^C to produce final

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consumption using the following aggregator:

$$C_{1t} = \left(\left(\omega_1^C\right)^{\frac{1}{\gamma_1^C}} \left(D_{1t}^C\right)^{\frac{\gamma_1^C-1}{\gamma_1^C}} + \left(1-\omega_1^C\right)^{\frac{1}{\gamma_1^C}} \left(F_{1t}^C\right)^{\frac{\gamma_1^C-1}{\gamma_1^C}} \right)^{\frac{\gamma_1^C}{\gamma_1^C-1}} \tag{7}$$

where $\omega_1^C > 0$ is the home bias parameter for consumption goods, and γ_1^C is the elasticity of substitution between home and foreign consumption goods. Final consumption good price is then defined as

$$P_{1t} = \left(\omega_1^C \left(P_{1t}^D\right)^{1-\gamma_1^C} + \left(1-\omega_1^C\right) \left(P_{1t}^F\right)^{1-\gamma_1^C} \right)^{\frac{1}{1-\gamma_1^C}}.$$

Final good producer also produce investment goods in the same way as consumption goods:

$$I_{1t} = \left(\left(\omega_1^I\right)^{\frac{1}{\gamma_1^I}} \left(D_{1t}^I\right)^{\frac{\gamma_1^I-1}{\gamma_1^I}} + \left(1-\omega_1^I\right)^{\frac{1}{\gamma_1^I}} \left(F_{1t}^I\right)^{\frac{\gamma_1^I-1}{\gamma_1^I}} \right)^{\frac{\gamma_1^I}{\gamma_1^I-1}}$$

where $\omega_1^I > 0$ is the home bias parameter for investment goods and γ_1^I is the elasticity of substitution between home and foreign investment goods. Similar to price of consumption goods, investment good price is

$$P_{1t}^I = \left(\omega_1^I \left(P_{1t}^D\right)^{1-\gamma_1^I} + \left(1-\omega_1^I\right) \left(P_{1t}^F\right)^{1-\gamma_1^I} \right)^{\frac{1}{1-\gamma_1^I}}$$

Final good producer then sells consumption C_{1t} and investment I_{1t} to household. Final good producer's problem is to choose domestic and foreign inputs to maximize their profits. This yields the following set of demands for each domestic and foreign consumption and investment goods:

$$D_{1t}^C = \omega_1^C \left(p_{1t}^D\right)^{-\gamma_1^C} C_{1t}, \qquad D_{1t}^I = \omega_1^I \left(\frac{p_{1t}^D}{p_{1t}^I}\right)^{-\gamma_1^I} I_{1t},$$

$$F_{1t}^C = \left(1-\omega_1^C\right) \left(p_{1t}^F\right)^{-\gamma_1^C} C_{1t}, \quad F_{1t}^I = \left(1-\omega_1^I\right) \left(\frac{p_{1t}^F}{p_{1t}^I}\right)^{-\gamma_1^I} I_{1t}.$$

3.2 Technology Process

Given our empirical evidence above, we follow Rabanal et al. (2011) and assume that there is a cointegrating relationship between Canada and the U.S. technology. However, the difference is that we allow contemporaneous effect through correlation of shocks. We also eliminate feedback from Canada to the U.S.. The technology process for Canada is described by:

$$\Delta \ln Z_{1t} = \mu_1 + \zeta \left[\ln Z_{2t-1} - \ln Z_{1t-1}\right] + e_{1t}. \tag{8}$$

When technology differential $\frac{Z_{2t-1}}{Z_{1t-1}}$ is smaller than the long run value, $\zeta > 0$ ensures that $\Delta \ln Z_{1t}$ will increase eventually and we can have balanced growth. This representation implies that $\Delta \ln Z_{1t}$ and $\frac{Z_{2t}}{Z_{1t}}$ are stationary processes and ζ governs the speed at which technology ratio $\frac{Z_{2t}}{Z_{1t}}$ goes back to long run value.

For the U.S., we assume their technology growth rate follows an AR(1) process as follows:

$$\Delta \ln Z_{2t} = \mu_2 + \rho_2 \Delta \ln Z_{2t-1} + e_{2t}. \tag{9}$$

The innovations of technology for the U.S. and Canada, e_{1t} and e_{2t}, respectively, have the following relationship:

$$\begin{pmatrix} e_{1t} \\ e_{2t} \end{pmatrix} = A \begin{pmatrix} v_{1t} \\ v_{2t} \end{pmatrix}, v_t \sim N(0, I)$$

where $A = \begin{pmatrix} \bullet & \tau\sigma_2 \\ \bullet & \sigma_2 \end{pmatrix}$, and τ measures the magnitude of impact of shock in the U.S. on Canada. As the purpose of the paper is to understand U.S. shocks affecting Canada, we ignore the first column of matrix A.

3.3 Prices and Equilibrium

Optimal conditions for domestic and foreign bond holdings imply an uncovered interest rate parity condition placing a restriction on the movements of the domestic interest rate. the terms of trade is defined as

$$TOT_t = \frac{p_{1t}^F}{p_{1t}^D}. \tag{10}$$

We normalize $P_{2t} = P_{2t}^F = 1$. Then the law of one price dictates that $p_{1t}^F = q_t$.

With intermediate goods in gross output, we define GDP as gross output subtracting intermediate inputs at steady state prices:

$$GDP_{1t} = Y_t^D - M_{11t} - M_{21t}.$$

Country 2 produces gross output Y_t^F so their GDP is defined analogously:

$$GDP_{2t} = Y_t^F - M_{22t}$$

The model is closed with the demands of home consumption D_{2t}^C, investment D_{2t}^I and intermediate

14

M_{12t} goods from foreign country given exogenously to Canada by:

$$D_{2t}^C = \left(1 - \omega_2^C\right) \left(\frac{p_{1t}^D}{q_t}\right)^{-\gamma_2^C} C_{2t} \tag{11}$$

$$D_{2t}^I = \left(1 - \omega_2^I\right) \left(\frac{p_{1t}^D}{q_t}\right)^{-\gamma_2^I} I_{2t} \tag{12}$$

$$M_{12t} = \frac{\alpha_{12}}{\alpha_{22}} \left(\frac{p_{1t}^D}{q_t}\right)^{-\gamma_2^m} M_{22t} \tag{13}$$

where ω_2^C and ω_2^I are the home bias of consumption and investment goods in the U.S., γ_2^C, γ_2^I and $\gamma_2^m > 0$ are the elasticities of substitution between home and foreign country consumption, investment and intermediate goods in the U.S., respectively, and C_{2t}, I_{2t}, M_{22t} are consumption, investment and domestic intermediate inputs in country 2.

Finally, the general equilibrium requires all markets clear:

$$D_{1t}^C + D_{1t}^I + D_{2t}^C + D_{2t}^I + M_{12t} + M_{11t} = Y_t^D \tag{14}$$

$$C_{2t} + I_{2t} + M_{22t} = Y_t^F \tag{15}$$

4   Estimation Method

This section discusses our estimation method. We start with the calibrated parameters. We then explain the quasi-Bayesian methods to match the theoretical impulse responses with the empirical counterparts to estimate the rest of the parameters.

4.1   Calibration

We calibrate parameters related to the steady state and commonly used in the literature. The rest of the parameters are estimated using impulse response matching method.

Table 1 displays the calibrated parameters taken from previous studies. We set the relative risk aversion parameter, σ, to be 2, which is standard in the business cycle literature such as Backus et al. (1994), Heathcote and Perri (2000) and Garcia-cicco et al. (2010). The capital share is set to be 0.36, and the depreciation rate, δ_0, to be 0.025. The debt elastic interest parameter is set to a small number 0.001 to induce stationarity as in Schmitt-Grohe and Uribe (2003). Following Garcia-Cicco et al. (2010), we set v to 1.6 which is the Frisch elasticity in a GHH preference, $(\kappa = 0)$.

We calibrate the rest of the parameters that affect the model's steady states using the actual U.S. and Canada data. We set the steady state growth rates of output, μ_1 and μ_2, for both the U.S. and Canada to be 0.34% per quarter using average output growth rates of the two countries between 1973Q1 and 2012Q3. In the production side, using the 2011 I-O table of the U.S., we set α_{22} to be equal to the share of the intermediate input in gross output which is 0.42. The rest of the parameters for the U.S. governing home bias for consumption and investment, ω_2^C, ω_2^I, and imported intermediate, α_{12}, are set to target the following: the export share in total GDP in Canada, which is averaged to be 0.31 during the 1973Q1-2012Q3 period, consumption goods share in total export, investment goods share in total export and intermediate goods share in total export to be $0.21, 0.12$, and 0.67, respectively. These shares are calculated using the annual Canadian trade data between 1980 and 2011, and assuming the primary good is used as intermediate goods. Similarly, we set the parameters for Canada governing home bias for consumption and investment goods, ω_1^C, ω_1^I, and imported intermediate share in the production function, α_{21}, to target the followings: the average import share in total Canadian GDP to be 0.29, the consumption goods, investment goods and intermediate goods share in total import to be $0.25, 0.19$, and 0.56, respectively. In the end, the imported intermediate share in Canadian production function, α_{21}, is 0.076.

Finally, to examine the strength of the endogenous transmission within our model, we set $\tau = 0$ and $\zeta = 0.001$, which means that there is no exogenous correlation of technology shocks between the U.S. and Canada.

4.2   Quasi-Bayesian Estimation Method

In the estimation below, we assume $\gamma_1^C = \gamma_2^C = \gamma_1^I = \gamma_2^I = \gamma_1^m = \gamma_2^m$. Therefore, the remaining parameters including elasticities of substitution between home and foreign goods in both countries, investment adjustment cost, cost of utilization, wealth elasticity of labor supply and the parameters of U.S. shocks process, $\left(\gamma, s_i, \left(\frac{a_2}{a_1}\right)_i, \kappa_i, \rho_{22}, \sigma_2, \phi^D\right)$ for $i = \{1,2\}$, are estimated by minimizing a measure of the distance between the model and empirical impulse responses. Let $IR(\Theta)$ denote theoretical impulse response given estimated parameters Θ and calibrated parameters Θ_{-1}, and $\widehat{IR}$ is the corresponding empirical estimates. We include the first 30 periods of each response function because technology process is fairly persistent and including long periods helps to identify parameters. To identify the U.S. block of parameters including technology process and demand for Canadian goods, we use the impulse response functions of U.S. output, consumption, investment and hours. For the

Canadian block, we include the responses of Canadian output, consumption, investment, hours, net export to output ratio and the terms of trade. The results reported below do not change if we include real imports and real exports in $\widehat{IR}$. We find Θ to:

$$\min_{\Theta} \left[\widehat{IR} - IR\left(\Theta|\Theta_{-1}\right) \right]' V^{-1} \left[\widehat{IR} - IR\left(\Theta|\Theta_{-1}\right) \right] \tag{16}$$

Here, V is a diagonal matrix with the inverse of sample variance of $\widehat{IR}$'s along the diagonal. With this choice of V, Θ is chosen so that $IR\left(\Theta|\Theta_{-1}\right)$ lies as much as possible within confidence interval plotted in Figure 1 and 2. For practical implementation, we use quasi-Bayesian estimator proposed in Chernozhukov and Hong (2003) to estimate and construct confidence intervals for the parameters. This procedure treats the objective function above as quasi-likelihood and use Markov Chain Monte Carlo method to compute estimator. One of advantages of this approach is that we can avoid the curse of dimensionality inherent in the computation of the classical minimization problem. The estimates are as efficient as the extremum estimates. Also, the inference procedures based on the quantile of the quasi-posterior distribution yield valid confidence intervals.

5 Understanding the Transmission Mechanism

Before estimating the model, we explain in this section the transmission mechanism in the model. We first look at the failure of standard models without our three key features, then we discuss how our three key features help to reconcile the model with the data.

5.1 The Failure of Standard Models

We explain why standard models such as Backus et al. (1994) with incomplete market, Corsetti et al. (2008), Burstein et al. (2008) without our three key features fail in explaining the substantial endogenous transmission in the data. These models either get the sign incorrectly, or quantitatively not able to generate enough movements in Canadian economy as we observe. To that end, we shut down the three key features in the model: household's preferences are standard King-Plosser-Rebelo preferences, there is no variable capacity utilization, and there is no imported intermediate inputs.

The response of domestic hours plays a central role for the transmission of the foreign shock because in the absence of a change in the level of domestic technology, increases in output require an

increase in hours. Therefore, we first look at the labor demand and labor supply conditions:

$$-\frac{\frac{\partial U_t}{\partial H_{1t}}}{\frac{\partial U_t}{\partial C_{1t}}} = W_{1t} \tag{17}$$

$$p_{1t}^D \frac{\partial F}{\partial H_{1t}} = W_{1t} \tag{18}$$

Also, from the final good aggregators, the domestic price level is related to the terms of trade as follows:

$$\left(p_{1t}^D\right)^{\gamma_1^C} = \left[\omega_1^C + \left(1 - \omega_1^C\right)(TOT_t)^{\gamma_1^C}\right]^{-\frac{1}{\gamma_1^C}} \tag{19}$$

To investigate the quantitative aspects of the model, we log-linearize and combine the equilibrium conditions above to eliminate wage and domestic goods price. Then, we can express the log deviation of hours as a function of the change in the terms of trade, consumption, technology and capital[9]:

$$\widehat{H_{1t}} = \frac{1}{\alpha + \frac{1}{v}}\left[-\widehat{C}_{1t} - \left(1 - \omega_1^C\right)\widehat{TOT}_t + (1-\alpha)\widehat{Z}_{1t} + \alpha\widehat{K}_{1t}\right] \tag{20}$$

This equation allows us to decompose the movement of hours in the domestic economy into four components: the wealth effect from the change in consumption, the terms of trade effect, the technology effect and the capital accumulation effect[10]. To further simplify our analysis, we ignore the effect of capital accumulation since it is not quantitatively important in the short run[11]. Then, under these assumptions, when there is no exogenous correlation of technology shocks, i.e. $Z_{1t} = 0$, if the

---

[9]We assume a standard King-Plosser-Rebelo preference, $U\left(C_t, H_t\right) = \frac{C_t^{1-\sigma}}{1-\sigma}V(H)$ where $V(H) = \exp\left(1 - \phi_H \frac{1}{1+\frac{1}{v}}H_t^{1+\frac{1}{v}}\right)^{1-\sigma}$.

[10]If we assume utility function as in Backus et al. (1995), then $U = \frac{\left(C^\mu(1-H)^{1-\mu}\right)^{1-\sigma}}{1-\sigma}$, we get

$$\widehat{H_{1t}} = \frac{1}{\alpha + \frac{H}{1-H}}\left[-\widehat{C}_{1t} - \left(1 - \omega_1^C\right)\widehat{TOT}_t + (1-\alpha)\widehat{Z}_{1t} + \alpha\widehat{K}_{1t}\right]$$

With separable utility function $U = \frac{C^{1-\sigma}}{1-\sigma} - \phi_H \frac{H^{1+\frac{1}{v}}}{1+\frac{1}{v}}$, we get

$$\widehat{H_{1t}} = \frac{1}{\alpha + \frac{1}{v}}\left[-\sigma\widehat{C}_{1t} - \left(1 - \omega_1^C\right)\widehat{TOT}_t + (1-\alpha)\widehat{Z}_{1t} + \alpha\widehat{K}_{1t}\right]$$

[11]If we log linearize capital accumulation equation, we get

$$\widehat{K}_{t+j} = (1-\delta)^j \underset{(=0)}{\widehat{K}_t} + \delta\left[\widehat{I}_{t+j-1} + ... + (1-\delta)^{j-1}\widehat{I}_t\right]$$

If we assume 1% permanent increase in investment until period j, we have

$$\widehat{K}_{t+j} = 0.01\left[1 - (1-\delta)^j\right]$$

It takes approximately 30 periods for capital to increase by 0.5%.

model were to match the empirical consumption increase in a domestic economy, hours in a domestic economy can increase on impact only if

$$\widehat{C_{1t}} < -\left(1 - \omega_1^C\right) \widehat{TOT_t}$$

To match a 0.5% increase in consumption and a 1% appreciation of the terms of trade found in VAR, i.e. the terms of trade go down with the magnitude above, $\omega_1^C < 0.5$ to get a positive response of hours. In general, ω_1^C is interpreted as a home bias parameter, which means $\omega_1^C > 0.5$. For example, we calibrate $\omega_1^C = 0.9$ to match the export shares in Canada. Therefore, in a plain vanilla model without our three key features, hours cannot increase in Canada. To see this point in a different way, when we calibrate $\omega_1^C = 0.9$ for Canada, the above condition means hours in Canada can increase only if $\widehat{C_{1t}} < -0.1\widehat{TOT_t}$. From our VAR, the increase in consumption is more than 10% of the appreciation of the terms of trade, which implies that hours can decrease.

An important insight of our analysis above is that this result does not depend on v, the labor supply elasticity parameter with respect to real wage under the assumed utility function. Furthermore, unlike Corsetti et al. (2008) and Enders and Muller (2009) who emphasize on the incompleteness of the financial markets as an important transmission mechanism, we find that the relationship of hours and the terms of trade does not depend on such assumption. Also, the relationship is not dependent on the elasticity of substitution, γ_1, given the movement of the terms of trade. In Corsetti et al. (2008), incomplete markets together with a large elasticity of substitution can generate endogenous transmission because there is a depreciation in the terms of trade for Canada and a decrease in consumption. However, empirically, we observe an increase in consumption for Canada, which suggests that this mechanism also does not work.

Another possible remedy proposed in the literature is to assume low elasticity of substitution, which can be interpreted as production sharing (Burstein et al. (2008)). However, as explained above, the relationship between hours and the terms of trade does not depend on the elasticity of substitution parameter. Another explanation is that by lowering the elasticity of substitution, the model can increase hours worked but at the cost of appreciating the terms of trade several times larger than what is observed empirically. Therefore, if we try to match the joint movement of consumption, hours and the terms of trade, changing the elasticity of substitution does not work, which is clear from the above equation that does not have the parameter of elasticity of substitution.

Overall, our analysis suggests that standard models with fixes in terms of the completeness of

the financial markets or substitutions across domestic and foreign goods do not matter to generate strong endogenous transmission. We could also explain the intuition behind the problem in terms of both the labor demand side and the labor supply side. In the labor supply side, the appreciation of terms of trade causes an increase in consumption, leading to a decline in labor supply. In the labor demand side, the appreciation can shift the labor demand curve to the extent households import consumption goods. However, this shift in labor demand curve is quantitatively small because the share of imported consumption goods is about 10% of total consumption in Canada.

5.2 The Three key features

To fix the problem pointed above, we introduce three key features that change both labor demand and labor supply conditions. As explained in the model above, the three key features are: Jaimovich-Rebelo preferences, variable capital utilization and imported intermediate inputs. We present here the analysis of these three key features on hours given the movements of international relative prices.

5.2.1 Wealth Effect

One reason for the failure of the standard models is the strong wealth effect that reduces labor supply. As we show above, since Canadian households become wealthier after a U.S. permanent technology shock, they increase consumption. This increase in consumption causes hours in Canada to decrease, resulting in a negative comovement of hours between the two countries. Therefore, similar to Jaimovich and Rebelo (2009), unless labor demand curve shifts sufficiently, we need to have a small wealth effect on labor supply so that hours can increase in equilibrium. In a specific case of Jaimovich-Rebelo preference, the wealth effect is zero on the labor supply, which is similar to the GHH utility function that reflects home production in a reduced form. Therefore, our analysis below assumes GHH utility function to simplify our exposition[12].

We can write the relationship between the terms of trade and hours as follows:

$$\widehat{H}_{1t} = \frac{1}{\alpha + \frac{1}{v}} \left[- \left(1 - \omega_1^C\right) \widehat{TOT}_t + (1 - \alpha) \widehat{Z}_{1t} + \alpha \widehat{K}_{1t} \right].$$

Since consumption does not appear in the equation, Canadian hours can go up without any change in technology and capital as long as the terms of trade appreciate. In other words, shutting down

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[12]In the estimation, we use Jaimovich-Rebelo preferences instead of GHH preferences to allow the possibility that wealth effect on the labor supply is not zero because there is no strong evidence for it.

wealth effect can help increase endogenous transmission within the model.

However, the fact that hours increase does not translate to substantial endogenous transmission. We can see how large having no wealth effect can replicate the magnitude of response of hours. Using the calibrated parameters above, we find that hours can go up about 0.1% when the terms of trade appreciates by 1% as

$$
\begin{aligned}
\widehat{H}_{1t} &= -\frac{1}{\alpha + \frac{1}{v}} \left(1 - \omega_1^C\right) \widehat{TOT}_t \\
&\simeq -0.1 \widehat{TOT}_t
\end{aligned}
$$

Empirically, the response of hours is slightly smaller than the response of the terms of trade. Therefore, quantitatively this preference only *cannot* solve the problem of weak endogenous transmission. Intuitively, the modification of the household preference prevents hours from declining but does not push hours to increase as it only fixes the movement of labor supply curve. lAs discussed above, the reason why hours go up is because households import consumption goods with cheaper price and reduces real wage measured in consumption goods. However, this effect is quantitatively small, so it is not sufficient to generate substantial endogenous transmission. To have a sufficiently large increase in hours, we need also a sufficient increase in labor demand and we next look at labor demand side.

5.2.2 Variable Capacity Utilization

We now show how adding the second feature to Jaimovich-Rebelo preference can help to increase endogenous transmission in the model. To simplify the analysis, we again assume GHH utility function. From labor supply and demand condition, we have the following relationship between hours and utilization and domestic goods price:

$$
\phi_H H_t^{\frac{1}{v}} = p_t^D \left(1 - \alpha\right) \left(u_t K_t\right)^\alpha \left(Z_t H_t\right)^{-\alpha}.
$$

This equation implies that an increase in utilization shifts labor demand curve and increases hours.

To investigate the response of utilization, we can use the first order condition for utilization and combine with the labor market conditions, we can get:

$$
\frac{\phi_H H_t^{\frac{1}{v}}}{a'\left(u_t\right)} = \frac{1 - \alpha}{\alpha} \frac{u_t K_t}{Z_t H_t},
$$

implying that utilization is increasing in hours given the level of capital and technology. Therefore, utilization moves in the same direction as hours and amplifies the effect of other factors to increase hours[13].

To gauge how large the amplification of variable capital utilization has on hours in Canada, we assume that $\left(\frac{a_1}{a_2}\right)_1 = 0.08$, i.e. there is a high elasticity of utilization with respect to return. Then, from the equilibrium conditions, we can express hours in terms of the terms of trade and cost of utilization as follows:

$$\left(\alpha \frac{\left(\frac{a_1}{a_2}\right)_1}{1 + \left(\frac{a_1}{a_2}\right)_1} + \frac{1}{v}\left(1 - \frac{\alpha}{1 + \left(\frac{a_1}{a_2}\right)_1}\right)\right)\widehat{H}_{1t} = -\left(1 - \omega_1^C\right)\widehat{TOT}_t + ...,$$

where "..." stands for the terms for technology and capital accumulation. Substituting the estimated value of utilization parameter, we get $\widehat{H}_{1t} \simeq -0.23\widehat{TOT}_t + ...$ which means utilization can double the response of hours to the movements of the terms of trade.

5.2.3 Imported Intermediate Inputs

The third key feature of our model is imported intermediate inputs, which makes labor demand to respond more strongly to the movement of relative price of domestic goods. The first order condition for imported intermediate goods is given by:

$$\frac{\partial F}{\partial M_{21t}} = \frac{p_t^F}{p_t^D} = TOT_t.$$

Therefore, intermediate goods import increases when relative price becomes cheaper. Since marginal product of labor is increasing in imported intermediate goods, change in relative price shifts labor demand curve. We can see this by combining firms' log-linearized optimality conditions as follows:

$$\widehat{H}_{1t} = \frac{1}{\alpha + \frac{1}{v}}\left(-\left[\left(1 - \omega_1^C\right) + \frac{\alpha_{21}}{1 - \alpha_{11} - \alpha_{21}}\right]\widehat{TOT}_t + + (1 - \alpha)\,\widehat{Z}_{1t} + \alpha\widehat{K}_{1t}\right),$$

where we assumed again GHH utility function. We have additional term $-\frac{1}{\alpha+\frac{1}{v}}\frac{\alpha_{21}}{1-\alpha_{11}-\alpha_{21}}$ for the terms of trade. This term reflects the effect of imported intermediate goods on labor demand. Quantitatively, this effect is important as it can increase hours more than just the usual terms of trade

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[13]With a different utilization cost specification such as $K_{t+1} = (1 - \delta(u_t))\,K_t + I_t$, the amplification can be weaker because the value of capital can increase, which increases the cost of utilization and reduces the response of utilization.

channel through consumption goods trade $-\frac{1}{\alpha+\frac{1}{v}}\left(1-\omega_1^C\right) \simeq 0.1$ because $-\frac{1}{\alpha+\frac{1}{v}}\frac{\alpha_{21}}{1-\alpha_{11}-\alpha_{21}} \simeq 0.16$ in our calibration. Therefore, imported intermediate goods can also more than doubles the response of hours to the terms of trade. In other words, imported intermediate inputs can be an important channel to generate substantial endogenous transmission.

The main insight from our simple analysis above is that for the model to generate strong endogenous transmission, we need three key features that alter the movements of Canadian hours in response to an independent U.S. permanent technology shocks. We next quantitatively evaluate the model to show that this insight holds true, and that having one or another feature is not sufficient to generate substantial comovement in Canada.

6   Estimation Results

This section presents the main results of the paper. We show that our model matches over 90% of the empirical evidence. The reason is that the model generates substantial endogenous transmission of U.S. technology shocks to Canada through international trade. As a result, even when we allow for exogenous correlation of technology shocks, the estimation assigns no role for exogenous correlation of technology shocks, consistent with our empirical finding. In contrast, without our three key features, the model can match less than 10% of the movements in Canadian variables, and has to rely on exogenous correlated shocks to match the movements of output.

6.1   The Baseline Model

We first discuss our baseline model results in terms of the estimated parameters and matching the empirical impulse responses. The first column in Table 4 presents the estimates of our baseline model, which includes our three key features without exogenous technology shock correlation. The elasticity of substitution is tightly estimated to be around 0.4, suggesting a strong complementarity between U.S. and Canadian goods. The low value of the elasticity of substitution has been found in previous papers such as Corsetti et al. (2008) and Enders and Mullers (2009) when they focus on the effects of U.S. productivity shocks on U.S. real exchange rate. Justiniano and Preston (2010) also estimate this parameter to be smaller than one in Canada. Additionally, the elasticity of utilization adjustment is small, 0.07, suggesting that the cost of changing utilization is low. We show that this result is consistent with how utilization data in Canada changes in response to a U.S. technology

shock below. An important parameter in our three key features is the Jaimovich-Rebelo preference parameter which governs the wealth elasticity of labor supply. We estimate that κ_1 is tightly around 0.03, meaning there is low wealth elasticity of labor supply, consistent with our analysis above. With our estimation, we provide an evidence for weak wealth effects in labor supply that previous papers in the open economy models assume such as Schmitt-Grohé (1998), Garcia-Cicco et al. (2010) among others.

Three other parameters that we estimate are investment adjustment cost, and debt elastic interest rate parameter. The investment adjustment cost is estimated to be about 5, which may seem large. We explore in the robustness section how much our results are driven by this adjustment cost. Another parameter we estimate is the debt elastic parameter affecting the interest rate that Canadian households face. This parameter is quite large, 0.73, meaning 1% change in net asset positions leads to 0.73% increase in interest rate. This estimate of the debt elastic interest rate implies that households face some financial frictions as suggested in Garcia-Cicco et al. (2010), which explains why, as we show below, this parameter matters only for the large response of net exports in Canada.

Given these parameters, we find that our model can match over 90% of the empirical responses of Canadian economy observed in the data. We plot in Figure 5 the theoretical responses of Canadian variables in response to a positive U.S. permanent technology shock occurred in period one calculated at the mean of the posterior draws, together with the empirical responses from the VAR. Consistent with the data, in response to a positive U.S. permanent technology shocks, Canadian output, consumption, investment and hours all increase significantly. The response of the terms of trade in the model is also similar to the data. As τ is set to be zero and ζ is close to zero, implying a slow cointegrating process, the behaviors of the model reflect the strong endogenous transmission mechanism within the model. When there is a positive U.S. permanent technology shock, U.S. goods are more abundant, causing Canadian terms of trade to appreciate. As a result, although technology in Canada does not increase, the strong demand from the firm side leads to an increase in hours. Given this increase in hours, output in Canada can increase. Investment also increases because of the complementarity between hours and capital. In the end, the model can account for over 90% of the movements of macroeconomic activities in Canada, which is in contrast with the inability of the models in previous studies to explain the transmission of shocks across countries. Our result suggests that the international real business cycle model with small changes in the production side and household preference as suggested in closed economy literature can match the empirical evidence.

To gauge how reasonable our model captures the reality, we plot in Figure 6 the dynamic responses of real exports, real imports, capacity utilization, and real wages to U.S. permanent technology shocks implied by the model alongside with their empirical counterparts. First, the model correctly predicts both real exports and real imports increase after a U.S. permanent technology shock. The magnitudes of both real exports and real imports are lower than the empirical counterpart, although the discrepancy between the empirical response and model response of imports is not large. A possible reason for the lower real exports is that our model abstracts from vertical production sharing. As we explain above, vertical production sharing differs from imported intermediate input in the sense that some Canadian exports which include imports from the U.S. are only consumed in the U.S.. When a good U.S. shock happens, the volume of trade are magnified with the vertical production sharing, so the responses of gross real exports can be larger than our baseline model.

Second, both the model responses and the empirical responses of capacity utilization in Canada increase after a shock in the U.S.. Since there is no perfect measure of capacity utilization, we use capital utilization data of the Canadian Statistics and Bank of Canada between 1973Q1 and 2012Q3 to construct the empirical responses of utilization to a U.S. permanent technology shock. Even though the model implies a smaller responses of capacity utilization, the consistency in direction between the model and the data is promising. The reason is as we explain below, the responses of utilization to a U.S. permanent technology shock is important for the model to match the aggregate responses of output and hours. Therefore, if anything, this result indicates that the model understates the importance of variable capacity utilization.

Last, we compare how real wage in the model behaves relative to the data. We measure real wages as total wage and compensation deflated by CPI between 1981Q1 and 2012Q3. Real wage is informative about the relative role of labor supply and demand. For example, if there is a large negative wealth effect on labor supply and labor demand shifts sufficiently to increase hours in equilibrium, we should observe large increase in real wage. On the other hand, if the labor supply curve is flat and wealth effect is small, and demand curve shifts to increase hours, we should observe small increase in real wage. Empirically, real wage does not move much in the short run and increases significantly in the long run. This is consistent with our model because in the short run demand shifts dominate in our estimated model and real wage does not increase. In terms of magnitude, the real wage movements in our model are smaller than the large increase in real wage after five quarters. However, this evidence suggests that the mechanism of the model is consistent with the data.

We also examine the movement of real interest rate in Canada. Our estimate model generates endogenous transmission through terms of trade but potentially interest rate can also generate endogenous transmission. However, between two countries and conditional on permanent technology shocks, the movement of real interest rate is very small, casting doubt on strong endogenous transmission through interest rate[14].

These additional evidence suggests that our mechanism in generating substantial endogenous transmission is consistent with the observed behaviors of the data in Canada.

6.2   Model without our three key features

Consistent with our analysis in the previous section, we now show quantitatively that models without our three key features cannot generate substantial endogenous transmission, causing model to fail to account for the responses of Canadian economy observed in the data.

To that end, we shut down the three key features in the model: household preference is the standard King-Plosser-Rebelo preference, which means $\kappa_1 = 1$, there is no variable capacity utilization, and there is no imported intermediate inputs. We re-estimate this model using the same method as in the baseline estimation. The number of parameters estimated in this case is two parameters fewer than the baseline model: Jaimovich-Rebelo parameter κ_1 and utilization cost $\left(\frac{a_2}{a_1}\right)_1$.

The estimated parameters along with its confidence intervals are displayed in Column 3 of Table 4. Compared to the baseline model, the elasticity of substitution is larger, 0.79, but is still smaller than one, suggesting that U.S. and Canadian goods are complements. The other parameters, investment adjustment cost and debt elastic parameter, are much different from those estimated in the baseline model, although we show later that these features do not affect our results.

With these estimated parameters, we find that around 10% of the Canadian responses observed in the data can be accounted for by the model without our three key features, suggesting that this model cannot generate substantial endogenous transmission. We plot in Figure 7 the impulse responses in the model without our three key features with the empirical responses of the macroeconomic variables in Canada. Clearly, the model without our three key features is unable to capture the dynamic responses of output and hours as well as other aspects of the data such as consumption and investment. We can explain the failure of this model without our three key features using our analysis above. As the estimation tries to match the terms of trade and the relationship between hours and the terms of trade

[14]In fact, when we add working capital requirement for wage payment as in Neumeyer and Perri (2005), endogenous transmission generated by working capital is negligible and performance of the model is quantitatively very similar.

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are determined by the strength of the wealth effects, the terms of trade and capital accumulation, hours cannot increase significantly in Canada, and even decrease on impact, consistent with our analysis above. Without much change in hours, output in Canada cannot increase. In other words, without our three key features, the model cannot generate substantial endogenous transmission.

7   Understanding the Features of the Model Quantitatively

This section analyzes quantitatively the critical features of the baseline model which can help the model to generate substantial endogenous transmission. More specifically, we show that we need *all* of the three key features in the model for the model's success.

First, the model with only one of the three key features cannot quantitatively generate sufficient endogenous transmission. We reestimate the baseline model with the maintained assumption that there is no exogenous correlation of technology shock and without two of the three key features. In other words, there are three cases plotted in Figure 10: (i) the baseline model without variable capital utilization and imported intermediate inputs, "JR", (ii) the baseline model without variable capital utilization and Jaimovich-Rebelo preference, "intermediate", (iii) the baseline model without Jaimovich-Rebelo preference and imported intermediate inputs, "utilization". To see how keeping one feature helps to generate endogenous transmission compared to standard models , we also plot in Figure 10 the case when there is none of the three frictions, "w/o all three". Consistent with the examination of each feature above, one feature is not enough to explain the movement of hours and output. In all cases, the model explains less than half of the movements of output and hours. We can explain this result as follows. The estimation tries to fit not only hours and output, but also the terms of trade and consumption. The model can match the movements of output and hours if the terms of trade appreciate more. Therefore, the terms of trade are predicted to appreciate more than in the data in all cases. Nevertheless, since the estimation procedure also tries to fit the terms of trade, this appreciation cannot be large enough to fit output and hours. Also, when there is no Jaimovich-Rebelo preference, the estimation faces a trade off between an increase of consumption and hours. If the model fits an increase of consumption, it implies a large negative wealth effect on labor supply, leading to a smaller increase in hours. Therefore, the estimation tends to underpredict the increase of consumption to increase hours. On top of these problems, investment is underpredicted in the case "utilization", i.e. the standard model with only variable capital utilization. One reason is that the return to investment, which is related with the expected marginal product of capital,

does not increase sufficiently in the model since hours do not increase sufficiently. If hours increase more, marginal product of capital can increase and so can investment. In other words, the match of investment is related with the match of hours. Additionally, in all cases, the model cannot account for the large increase in Canadian net export over output ratio. The intuition for this result is the fact that output does not increase much to give an incentive for households to save more. Therefore, this problem is also related with the problem of hours.

Second, we show that the baseline model with only one of three key features is also not able to generate substantial endogenous transmission. We plot in Figure 11 the three cases when the feature listed on the y-axis is shut down from the estimated baseline model. When we shut down JR preference, the model predicts much smaller responses of the output and hours. As explained above, this is because of the strong wealth effect associated with KPR preference. When there is no variable capital utilization, the model actually predict larger movements of output and hours than the data. However, this is because the model also generates too large an appreciation of the terms of trade. Lastly, when there is no intermediate goods trade, the model also cannot match the large movements of output and hours, consistent with the role of imported intermediate goods discussed above.

These exercises demonstrate that all of three key features are important for the model to generate substantial endogenous transmission, which comes from the movements of hours. More generally, we argue that we need to consider features that affect the labor demand and supply conditions to be able to generate strong endogenous transmission. For the labor supply side, we need features that prevent labor supply to decrease sharply. It can be other features such as real wage rigidity, in which households need to supply labor given a fixed real wage. For the labor demand side, we need frictions which increase demand sufficiently. It can also be time varying countercyclical markup such as deep habit mechanism. Judging the relative importance of those frictions requires additional data and is beyond the scope of this paper. We argue that between Canada and the U.S. our features are sufficient to explain the observed transmission of U.S. permanent technology shocks, and are based on both empirical and theoretical grounds.

8   Robustness

This section discusses the robustness of our results. First, we show that even when there is exogenous correlation of technology shocks between the U.S. and Canada, the estimation favors endogenous transmission to explain the effects of U.S. technology shocks on Canada, consistent with the empirical

results. Furthermore, we analyze the sensitivity of our results with respect to investment adjustment cost and the debt elastic interest rate. Additionally, we discuss how our three key features still help to generate substantial endogenous transmission when the model includes nominal rigidities.

8.1 Exogenous correlation of technology shocks

To address the possibility that technology shocks between the U.S. and Canada are correlated, we allow shocks to be correlated and re-estimate our baseline model which includes the three key features. The estimated parameters of this version of the baseline model are presented in the second column in Table 4. One noticeable feature of the estimated parameters is that they are similar to the estimated parameters of the baseline model without any exogenous correlation of technology shocks. In fact, the estimated direct technology correlation τ is 0.10, but its 90% confidence interval includes zero, which means that the shocks are not strongly correlated. Moreover, the cointegration parameter, ζ, is estimated to be close to 0.

As the estimated parameters are similar between the baseline model with correlation and the baseline model, the estimated baseline model with exogenous correlation of technology shocks matches the empirical responses similar to the model estimated without exogenous correlation, as plotted in Figure 8. In particular, the baseline model with correlation can match over 90% of the empirical responses. This result suggests that the data assign a negligible role to the exogenous correlation of technology shocks when the model is able to generate strong endogenous transmission, which is consistent with the empirical evidence in the VAR presented above.

Finally, we re-estimate the model without our three key features allowing for exogenous correlated technology shock. As shown in the last column of Table 4, the estimated parameter for the cointegrating process, ζ, is 0.92 and that for the contemporaneous correlation of shock, τ, is 0.75, both of which are large and significant. In other words, the estimation prefers exogenous correlation in order to explain the large responses of output. As shown in Figure 9, due to the strong exogenous correlation of technology shocks, output in Canada increases. However, the movements of hours are still much smaller than those of the empirical responses. This model does not improve in matching the response of hours compared to the model without our three key features with no correlation in technology shocks. Therefore, we conclude that when the model is not able to generate substantial endogenous transmission, the estimation requires a strong presence of the exogenous correlation of technology shocks in order to replicate the data.

8.2 Investment Adjustment Cost

Since investment adjustment cost is estimated to be large in the baseline model, we examine how shutting down this investment adjustment cost affects our results to examine its role in generating substantial endogenous transmission. To that end, we estimate a version of the baseline model where there is no investment adjustment cost, i.e. $s_1 = 0$. The theoretical responses of the estimated model are plotted in Figure 12. We find that investment still increases, so do consumption and output. Other responses also match up to 90% of the empirical impulse responses. In other words, the role of investment adjustment cost is negligible in generating endogenous transmission. Investment adjustment cost reduces the volatility of investment, but does not stop the outflow of investment from Canada to the U.S.. The reason for the right response of investment is the increase in hours. With the three key features in the model, hours can increase, causing marginal product of capital to increase, leading to an increase in investment. In the baseline model, when we set $s_1 = 0$, i.e. there is no investment adjustment cost, investment would increase too large relatively to the data so the estimated adjustment cost s_1 turns out to be large.

8.3 Debt Elastic Interest Rate

Although our baseline model estimates the debt elastic parameter, ϕ_D to be large, this result is not crucial for the model to generate substantial movements of output and hours in Canada. In our model, the debt elastic interest rate reflects the financial friction that households face in international borrowing and lending. Our baseline model estimates that this debt elastic parameter, ϕ_D, is large, implying that there is a high cost of borrowing or lending internationally for Canadian households. Nevertheless, this parameter turns out to be not important in explaining the observed responses of output and hours in Canada. When we re-estimate the model with ϕ_D being set to be small, 0.001, as plotted Figure 12, this version of the baseline model can still match most of the empirical impulse responses of Canada. The exception is the net exports in Canada, which is lower than the empirical response. Therefore, we conclude that ϕ_D is not important to generate endogenous transmission in the model but has a role in explaining the movement of net exports.

Finally, although not shown here, the baseline model without investment adjustment cost, habit or high debt elastic interest rate can match the effects of U.S. permanent technology shocks on Canada. Thus, the success of our model only depends on the three key features which directly affect the responsiveness of the labor market to changes in international relative prices.

8.4 Model with nominal rigidities

We examine the role of nominal rigidities to see if our intuition goes through. We introduce sticky price a la Calvo in the simple form to our baseline model. In the following, we explain the structure of country 1 because country 2 is simply closed economy version of country 1. Final good firms produce final good Y_{1t} combining a continuum of intermediate goods $Y_{1t}(j)$ where $j \in [0,1]$ using the following technology.

$$Y_{1t} = \left[\int_0^1 Y_{1t}(j)^{\frac{1}{\eta_p}} \, dj \right]^{\eta_p}$$

where η_p is price markup in the steady state. Monopolistic intermediate firms use the production function of the following form.

$$Y_{1t}(j) \leq (u_{1t}(j) K_{1t}(j))^\alpha (Z_{1t} H_{1t}(j))^{1-\alpha} - FC_{1t}$$

where FC_{1t} is a fixed cost to have zero profits in a steady state. We assume that intermediate goods firms can change the price with fixed probability θ_{1p} as in Calvo (1983). Lastly, we assume the Taylor-type rule of the form,

$$\ln R_t^D = \rho_R \ln R_{t-1}^D + (1 - \rho_R) \left[\ln R_{ss}^D + s_\pi \ln \left(\frac{\pi_{1t}}{\pi_1^*} \right) + s_{\Delta Y} \ln \left(\frac{\Delta Y_{1t}}{\Delta Y_{1ss}} \right) \right]$$

where R_{ss}^D is a steady state level of nominal interest rate, π_1^* is a steady state level of inflation and ΔY_{1t} is a growth rate of output and ΔY_{1ss} is a steady state level of ΔY_{1t}.

To identify the movements of markup in response to U.S. permanent technology shocks, we augment the baseline VAR with inflation and nominal interest rate in both countries. We then estimate our baseline model with nominal rigidities to match these impulse responses. We find that our model can still match the data reasonably with estimated nominal price stickiness $\theta_p = 0.71$. Shutting down our features, this model would require sticky price parameter to be 0.99, meaning price is fixed. The reason is that in the data, inflation decreases slightly. Therefore, to match the strong movement of hours, the model requires large movement in markup, which can only be attained by strong price rigidities. This result highlights the importance of our features to match the transmission observed in the data.

We additionally add sticky wage into the model. In this case, we also find that our baseline model with both nominal price and wage rigidities can match the data reasonably with estimated price and

wage stickiness to be around 0.68 and 0.38. Once we shut down our three key features, this model would require wage stickiness to be 0.99. Again, this result suggests that our features are important to match the transmission observed in the data.

8.5 Comparison with literature

We can compare our result with Justiniano and Preston (2010), which is closest to our paper. They also use Canada and the U.S. pair and examines the transmission. Although they use Bayesian estimation method and consider overall comovement rather than conditional comovement, our analysis can point out why they find negative result that U.S. shocks cannot explain Canadian business cycles. In their real side of model, they do not have frictions which affects strongly labor supply and demand conditions. Specifically, they have KPR preference instead of JR preference and they do not have capital utilization nor imported intermediate inputs. They have sticky price and wage but ,as we argue above, markup up movement associated with these frictions do not necessarily generate large endogenous transmission when trying to match with the data such as the dynamic of inflation and real wage. Therefore, it is reasonable that their model cannot explain strong comovement between these two countries.

9 Conclusion

This paper examines the transmission mechanism of technology shocks across countries. We show that the nature of such transmission depends fundamentally on the features that determine the responsiveness of labor supply and labor demand to international relative price. We augment a standard real international business cycle model with three key features that can generate substantial endogenous transmission. The three key features are a low wealth elasticity of labor supply, variable capacity utilization and imported intermediate inputs. Estimating this model using the data for Canada and the U.S. between 1973Q1 and 2012Q3, we show that it can explain over 90% of the observed effects of permanent U.S. technology shocks on Canadian output and hours. We find that endogenous transmission explains the majority of the observed comovement conditional on permanent U.S. technology shocks while exogenous correlation of technology shocks is not important. Our estimation further suggests that we need all three key features for the success of the model in replicating the data. We extend the model to include nominal rigidities and show that our insights also carry over to this

setting.

An interesting application of our mechanism is to use the proposed model to resolve the trade-comovement puzzle documented in Kose et al. (2006), as we suggest that our mechanism generates substantial comovement through international trade alone. Another interesting extension of this paper is to investigate if there is any different transmission mechanism of other foreign shocks such as government spending or oil price shocks. Finally, we can examine if the model can quantitatively account for the overall comovements across countries taking into account the movements of international relative prices such as the terms of trade.

References

ADOLFSON, M., S. LASÉEN, J. LINDÉ, AND M. VILLANI (2007): "Bayesian estimation of an open economy DSGE model with incomplete pass-through," *Journal of International Economics*, 72(2), 481–511.

——— (2008): "Evaluating an estimated new Keynesian small open economy model," *Journal of Economic Dynamics and Control*, 32(8), 2690–2721.

ALESSANDRIA, G., J. KABOSKI, AND V. MIDRIGAN (2013): "Trade wedges, inventories, and international business cycles," *Journal of Monetary Economics*, 60(1), 1–20.

AMBLER, S., E. CARDIA, AND C. ZIMMERMANN (2002): "International transmission of the business cycle in a multi-sector model," *European Economic Review*, 46(2), 273–300.

BACKUS, D., P. KEHOE, AND F. KYDLAND (1992): "International real business cycles," *Journal of political Economy*, 100(4), 745–775.

——— (1994): "Dynamics of the trade balance and the terms of trade: The J-curve," *American Economic Review*, 84(1), 84–103.

——— (1995): "International business cycles: theory and evidence," in *Frontiers in Business Cycle Research (T. Cooley, ed)*, Princeton University Press.

BACKUS, D. K., AND M. J. CRUCINI (2000): "Oil prices and the terms of trade," *Journal of International Economics*, 50(1), 185–213.

BAXTER, M., AND D. D. FARR (2005): "Variable capital utilization and international business cycles," *Journal of International Economics*, 65(2), 335–347.

BOILEAU, M. (1999): "Trade in capital goods and the volatility of net exports and the terms of trade," *Journal of International Economics*, 48(2), 347–365.

———— (2002): "Trade in capital goods and investment-specific technical change," *Journal of Economic Dynamics and Control*, 26, 963–984.

BURSTEIN, A., C. KURZ, AND L. TESAR (2008): "Trade, production sharing, and the international transmission of business cycles," *Journal of Monetary Economics*, 55(4), 775–795.

CHRISTIANO, L. J., M. TRABANDT, AND K. WALENTIN (2011): "Introducing financial frictions and unemployment into a small open economy model," *Journal of Economic Dynamics and Control*, 35(12), 1999–2041.

CORSETTI, G., L. DEDOLA, AND S. LEDUC (2008a): "International Risk Sharing and the Transmission of Productivity Shocks," *Review of Economic Studies*, 75(2), 443–473.

CORSETTI, G., L. DEDOLA, AND S. LEDUC (2008b): "Productivity, external balance, and exchange rates: Evidence on the transmission mechanism among G7 countries," *NBER International Seminar on ....*

CORSETTI, G., L. DEDOLA, AND F. VIANI (2011): "Traded and Nontraded Goods Prices, and International Risk Sharing: An Empirical Investigation," *NBER International Seminar on Macroeconomics*, 8(1), 403–466.

EICHENBAUM, M., R. VIGFUSSON, AND L. J. CHRISTIANO (2004): "What Happens After A Technology Shock ? ,".

ENDERS, Z., AND G. J. MÜLLER (2009): "On the international transmission of technology shocks," *Journal of International Economics*, 78(1), 45–59.

ENGEL, C., AND J. WANG (2011): "International trade in durable goods: Understanding volatility, cyclicality, and elasticities," *Journal of International Economics*, 83(1), 37–52.

GARCÍA-CICCO, B. J., R. PANCRAZI, AND M. URIBE (2010): "Real Business Cycles in Emerging Countries ?," *American Economic Review*, 100(December), 2510–2531.

HEATHCOTE, J., AND F. PERRI (2002): "Financial autarky and international business cycles," *Journal of Monetary Economics*, 49(3), 601–627.

HERNANDEZ, K., AND A. LEBLEBICIOGLU (2013): "The Transmission of US Shocks to Emerging Markets," *Working Paper.*

HUANG, K. X., AND Z. LIU (2007): "Business cycles with staggered prices and international trade in intermediate inputs," *Journal of Monetary Economics*, 54(4), 1271–1289.

JAIMOVICH, N., AND S. REBELO (2009): "Can news about the future drive the business cycle?," *American Economic Review*, 99(4), 1097–1118.

JIN, K., AND N. LI (2012): "International transmission through relative price," .

JOHNSON, R. (2012): "Trade in intermediate inputs and business cycle comovement," *Journal of International Economics*, 40(3), 573–595.

JUSTINIANO, A., AND B. PRESTON (2010): "Can structural small open-economy models account for the influence of foreign disturbances?," *Journal of International Economics*, 81(1), 61–74.

KOSE, M. A., C. OTROK, AND C. H. WHITEMAN (2013): "Business Cycles : World , Region , International and Country-Specific Factors," 93(4), 1216–1239.

KOSE, M. A., AND K.-M. YI (2006): "Can the standard international business cycle model explain the relation between trade and comovement?," *Journal of International Economics*, 68(2), 267–295.

LEVCHENKO, A., L. LEWIS, AND L. TESAR (2010): "The Collapse of International Trade During the 2008-2009 Crisis: In Search of the Smoking Gun," *IMF Economic Review*, 58(2), 214–253.

LUBIK, T., AND F. SCHORFHEIDE (2006): "A Bayesian look at the new open economy macroeconomics," *NBER Macroeconomics Annual 2005, Volume 20*, 20(April).

LUBIK, T. A., AND F. SCHORFHEIDE (2007): "Do central banks respond to exchange rate movements? A structural investigation," *Journal of Monetary Economics*, 54(4), 1069–1087.

MAĆKOWIAK, B. (2007): "External shocks, U.S. monetary policy and macroeconomic fluctuations in emerging markets," *Journal of Monetary Economics*, 54(8), 2512–2520.

MENDOZA, E. (1995): "The terms of trade, the real exchange rate, and economic fluctuations," *International Economic Review*, 36(1), 101–137.

MIYAMOTO, W., AND T. L. NGUYEN (2013): "The role of common shocks in small open economies between 1900 and 2006 : a structural estimation," .

NEUMEYER, P., AND F. PERRI (2005): "Business cycles in emerging economies: the role of interest rates," *Journal of Monetary Economics*, 52(2), 345–380.

PETERMAN, W. B. (2013): "Reconciling Micro and Macro Estimates of the Frisch Labor Supply Elasticity," pp. 1–32.

RABANAL, P., J. F. RUBIO-RAMÍREZ, AND V. TUESTA (2011): "Cointegrated TFP processes and international business cycles," *Journal of Monetary Economics*, 58(2), 156–171.

RAFFO, A. (2008): "Net exports, consumption volatility and international business cycle models," *Journal of International Economics*, 75(1), 14–29.

——— (2009): "Technology Shocks : Novel Implications for International Business Cycles," *Working Paper*.

SCHMITT-GROHE, S. (1998): "The international transmission of economic fluctuations:: Effects of US business cycles on the Canadian economy," *Journal of International Economics*, 44, 257–287.

STOCKMAN, A., AND L. TESAR (1995): "Tastes and technology in a two-country model of the business cycle: Explaining international comovements," *American Economic Review*, 85(1), 168–185.

URIBE, M., AND V. Z. YUE (2006): "Country spreads and emerging countries: Who drives whom?," *Journal of International Economics*, 69(1), 6–36.

WALQUE, G. D., F. SMETS, AND R. WOUTERS (2005): "An estimated two-country DSGE model for the Euro area and the US economy," .

ZIMMERMANN, C. (1997): "International real business cycles among heterogeneous countries," *European Economic Review*, 41(2), 319–356.

Appendix A   Non-fuel Terms of trade

Following Baxter and Crucini (2000), we can decompose the terms of trade as followed:

$$\left(\frac{P_t^F}{P_t^D}\right)_{nf} = \frac{P_t^F}{P_t^D}\left(\frac{S^F}{S^D}\right)_{nf}\frac{Q^F}{Q^D}$$

where nf denotes non-fuel, S^i is the share of non-fuel export (import) in total export (import) in current prices, Q^F is the ratio of the quantity of non-fuel imports to the quantity of total trade valued at base year. Assume $Q^F = Q^D$, we calculate the non-fuel terms of trade.

Appendix B   Tables and Figures

	2 quarters ahead	4 quarters ahead	8 quarters ahead	20 quarters ahead
Output	0.12	0.23	0.39	0.52
Consumption	0.08	0.16	0.26	0.35
Investment	0.04	0.07	0.08	0.14
Hours	0.05	0.15	0.24	0.34
Net exports to output	0.04	0.07	0.23	0.4
Terms of trade	0.03	0.08	0.14	0.19
Real exports	0.18	0.27	0.48	0.57
Real imports	0.11	0.23	0.34	0.42

Table 1: Forecast variance decomposition of Canadian variables conditional on the U.S. permanent technology shock

Number of vectors	Eigenvalue	Trace	5% critical value	Max-Eigenvalue	5% critical value
0		5.72	15.41	5.43	14.07
1	0.1	0.28	3.76	0.28	3.76

Table 2: Cointegration statistics: Johansen's test for output

	Parameter	Value	References
β	discount parameter	0.99	
σ	risk aversion	2	Heathcote and Perri (2002)
v	governing Frisch elasticity	1.6	Garcia-Cicco et. al. (2010)
α	capital share	0.36	Backus et. al. (1992)
δ	depreciation rate of capital	0.025	Backus et. al. (1992)
μ_1	steady state output growth in Canada	1.0034	average Canadian data
μ_2	steady state output growth in the U.S.	1.0034	average U.S. data
α_{11}	Canadian intermediate share	0.45	Canadian I-O table 2009
α_{21}	Canadian imported intermediate share	0.076	Canadian I-O table 2009
α_{22}	U.S. intermediate share	0.42	U.S. I-O table 2011
ω_1^C	consumption home bias	0.90	target $\frac{F_1^C}{RIMP} = 0.25$
ω_1^I	investment home bias	0.77	target $\frac{F_1^I}{RIMP} = 0.19$

Table 3: Calibrated parameters

	Parameter	Baseline	Baseline w/ correlation	W/o 3 key features	W/o 3 key features w/ correlation
		Canada block			
γ	Elasticity of substitution	0.40	0.39	0.79	0.65
		(0.36,0.44)	(0.35,0.44)	(0.75,0.83)	(0.62,0.69)
s_1	Investment adjustment cost	5.07	5.08	1.37	8.00
		(1.32,9.08)	(1.24,9.07)	(0.19,4.18)	(5.15,9.79)
κ_1	Jaimovich-Rebelo parameter	0.03	0.04		
		(0.03,0.04)	(0.03,0.05)		
$(a_1/a_2)_1$	Utilization cost elasticity	0.07	0.08		
		(0.02,0.15)	(0.02,0.17)		
ϕ_D	debt elastic	0.73	0.75	0.03	0.00
		(0.41,0.97)	(0.47,0.97)	(0.00,0.10)	(0.00,0.01)
		Shock processes			
ρ_2	Autoregressive for U.S. technology	0.79	0.79	0.77	0.71
		(0.75,0.82)	(0.76,0.83)	(0.73,0.80)	(0.67,0.75)
σ_2	Standard deviation of U.S. shock	0.17	0.16	0.17	0.21
		(0.14,0.20)	(0.14,0.19)	(0.15,0.21)	(0.19,0.24)
τ	Direct technology correlation		0.10		0.75
			(-0.18,0.37)		(0.51,0.94)
ζ	Cointegration parameter		0.00		0.92
			(0.00,0.01)		(0.80,0.99)
		U.S. block			
s_2	Investment adjustment cost	2.24	2.06	8.04	1.34
		(0.84,4.33)	(0.71,3.91)	(5.49,9.77)	(0.11,3.32)
κ_2	Jaimovich-Rebelo parameter	0.03	0.03	0.02	0.02
		(0.02,0.04)	(0.02,0.03)	(0.02,0.03)	(0.02,0.03)
$(a_1/a_2)_2$	Utilization elasticity	0.12	0.11	0.09	0.27
		(0.02,0.27)	(0.02,0.24)	(0.02,0.21)	(0.16,0.40)

Table 4: Estimated parameters for the baseline model with and without correlation of technology shocks, for the simplified model with and without correlation of technology shocks. The numbers in parentheses are the $5-95\%$ confidence intervals calculated from the quasi-Bayesian estimation.
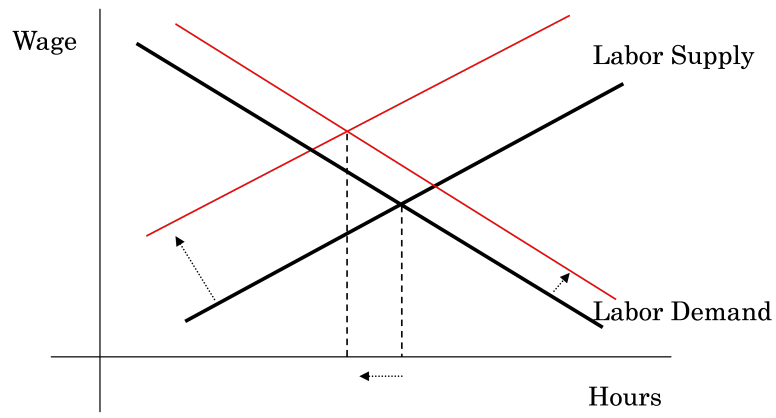
(a) Plain vanilla case
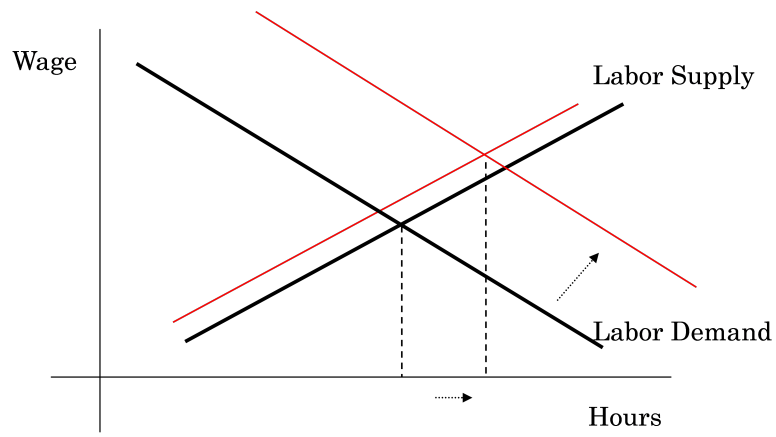
(b) With three key features

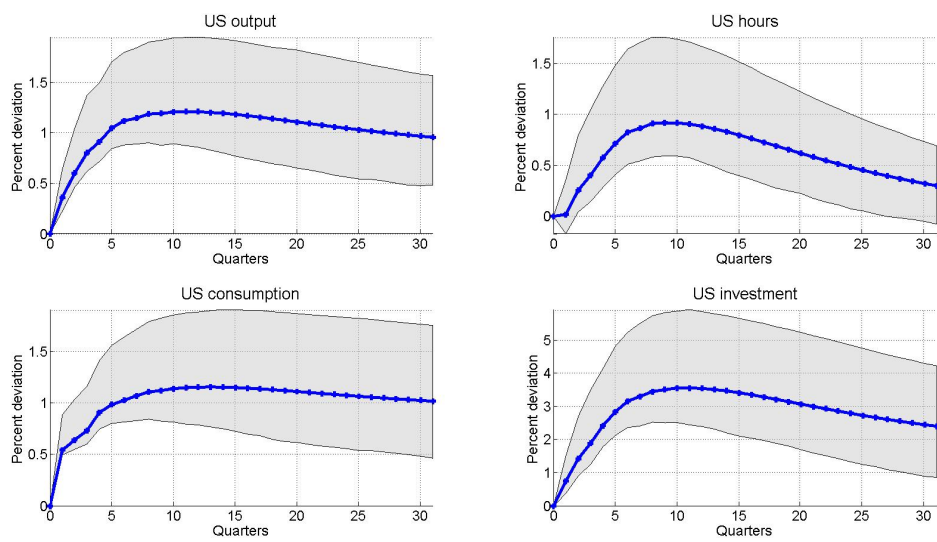Figure 1: Intuition for why model generates endogenous transmission

Figure 2: Responses of the U.S. output, consumption, investment and hours to the U.S. technology shock occurring in period one. Lines with plus sign is the point estimate and the shaded areas are the 95% confidence intervals.
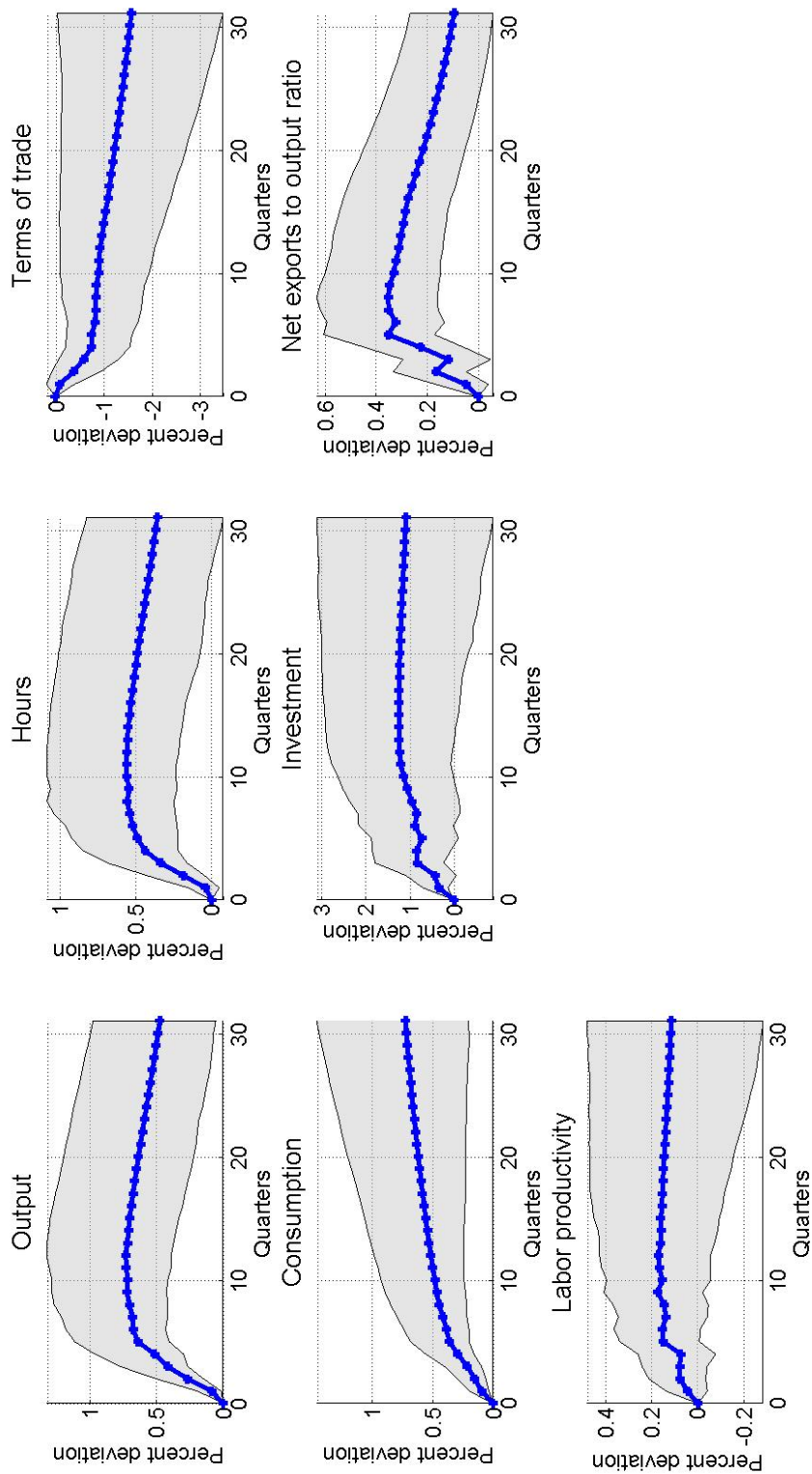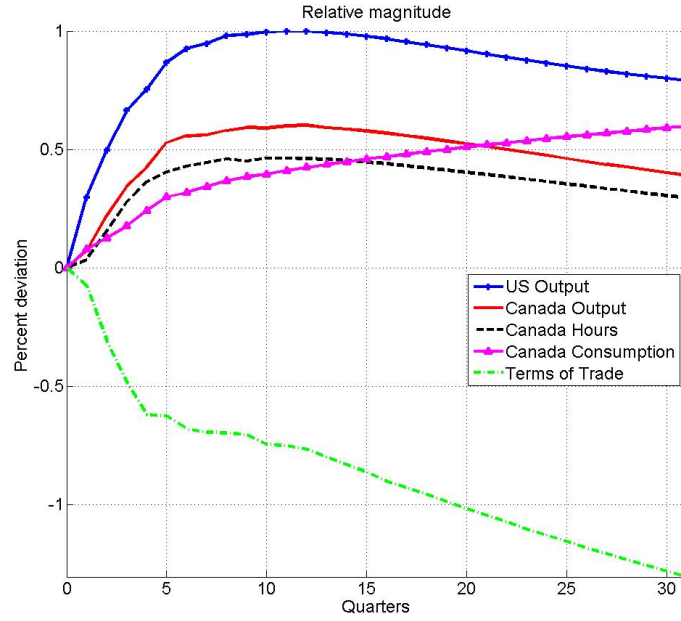
Figure 3: Canadian output, consumption, investment, hours, terms of trade, net export, labor productivity to a positive U.S. technology shock occurring in period one. Lines with plus sign is the point estimate and the shaded areas are the 95% confidence intervals.

Figure 4: Relative magnitude of the responses of Canadian economy to the U.S.
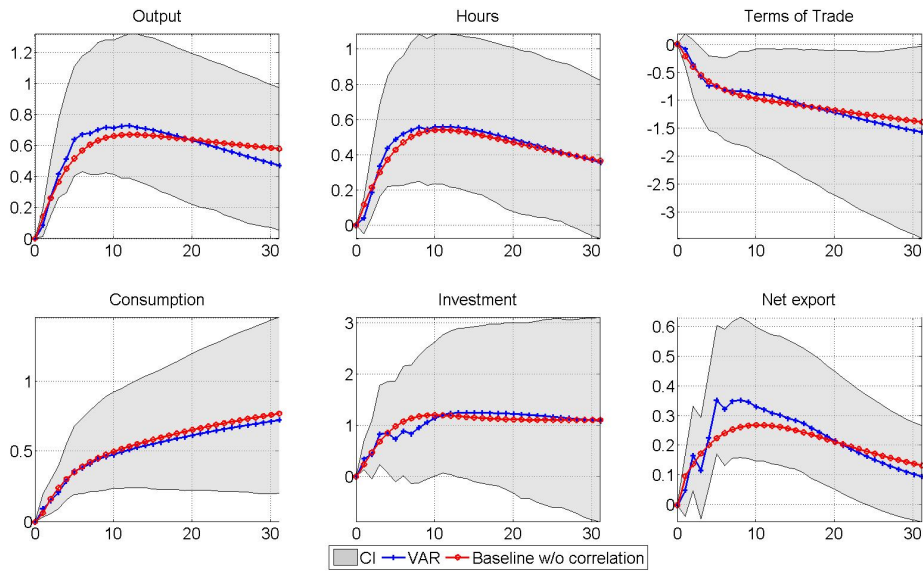
Figure 5: The theoretical impulse responses of Canadian economy to a positive U.S. shock. Lines with plus sign is the point estimate and the shaded areas are the 95% confidence intervals. Lines with square sign is theoretical responses of the baseline model.
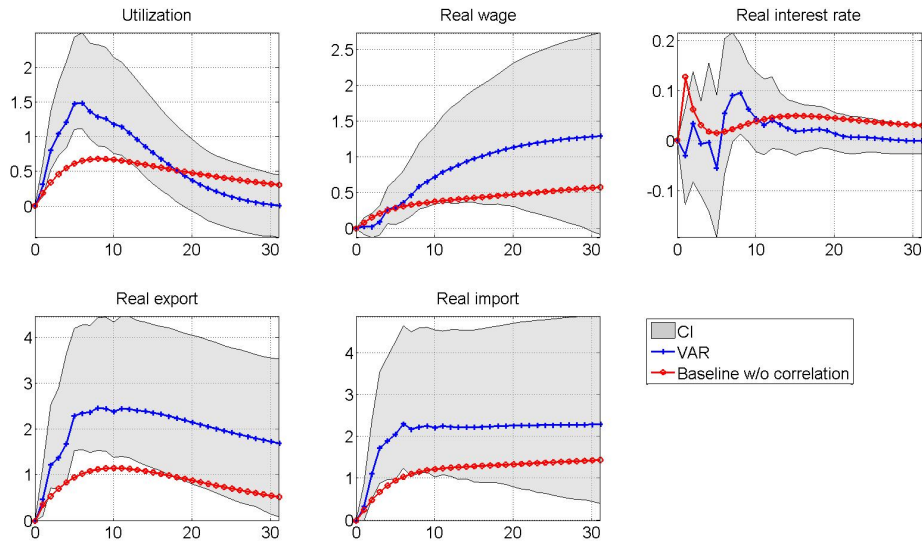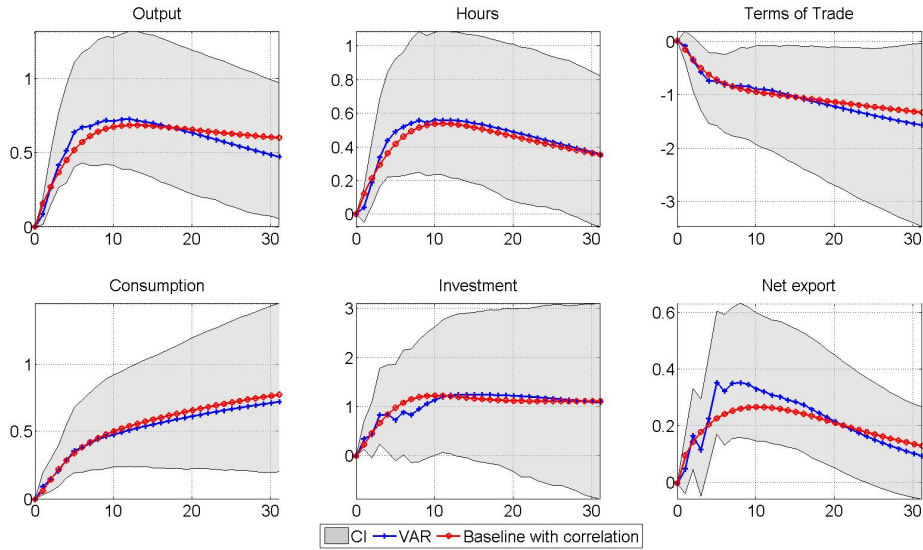
Figure 6: The theoretical impulse responses of additional variables for Canadian economy to a positive U.S. shock. Lines with plus sign is the point estimate and the shaded areas are the 95% confidence intervals. Lines with square sign is theoretical responses of the baseline model.
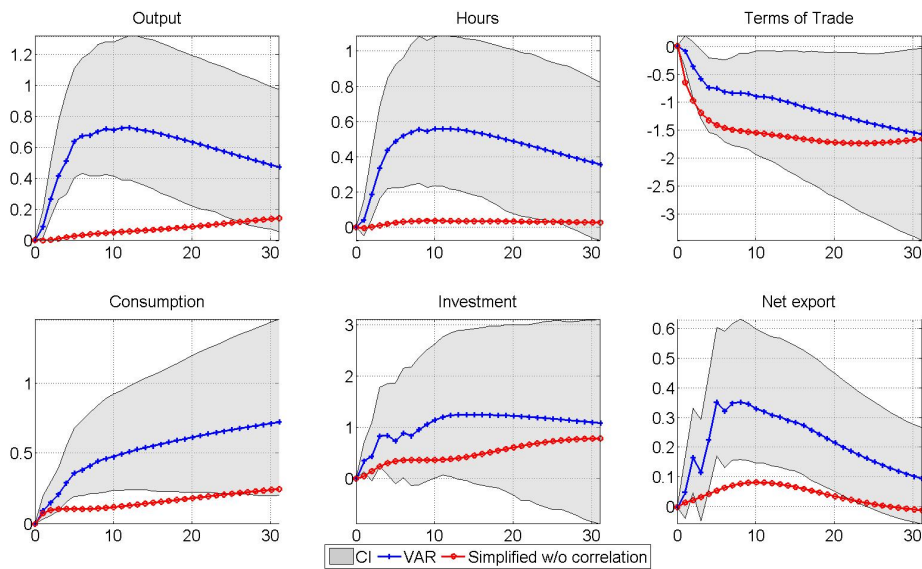
Figure 7: The theoretical impulse responses of Canadian economy to a positive U.S. shock in the baseline model without our three key features. Lines with plus sign is the point estimate and the shaded areas are the 95% confidence intervals. Lines with squared sign is the theoretical responses from the baseline model without our three key features.

Figure 8: The theoretical impulse responses of the baseline model with exogenous correlation of technology shocks to a positive U.S. shocks. Lines with plus sign is the point estimate and the shaded areas are the 95% confidence intervals. Lines with squared sign is theoretical responses from baseline model.
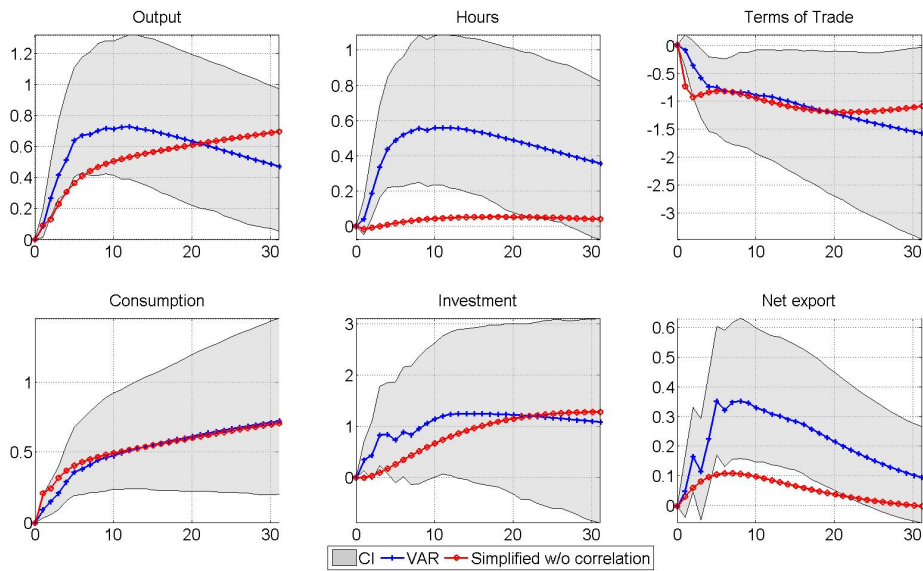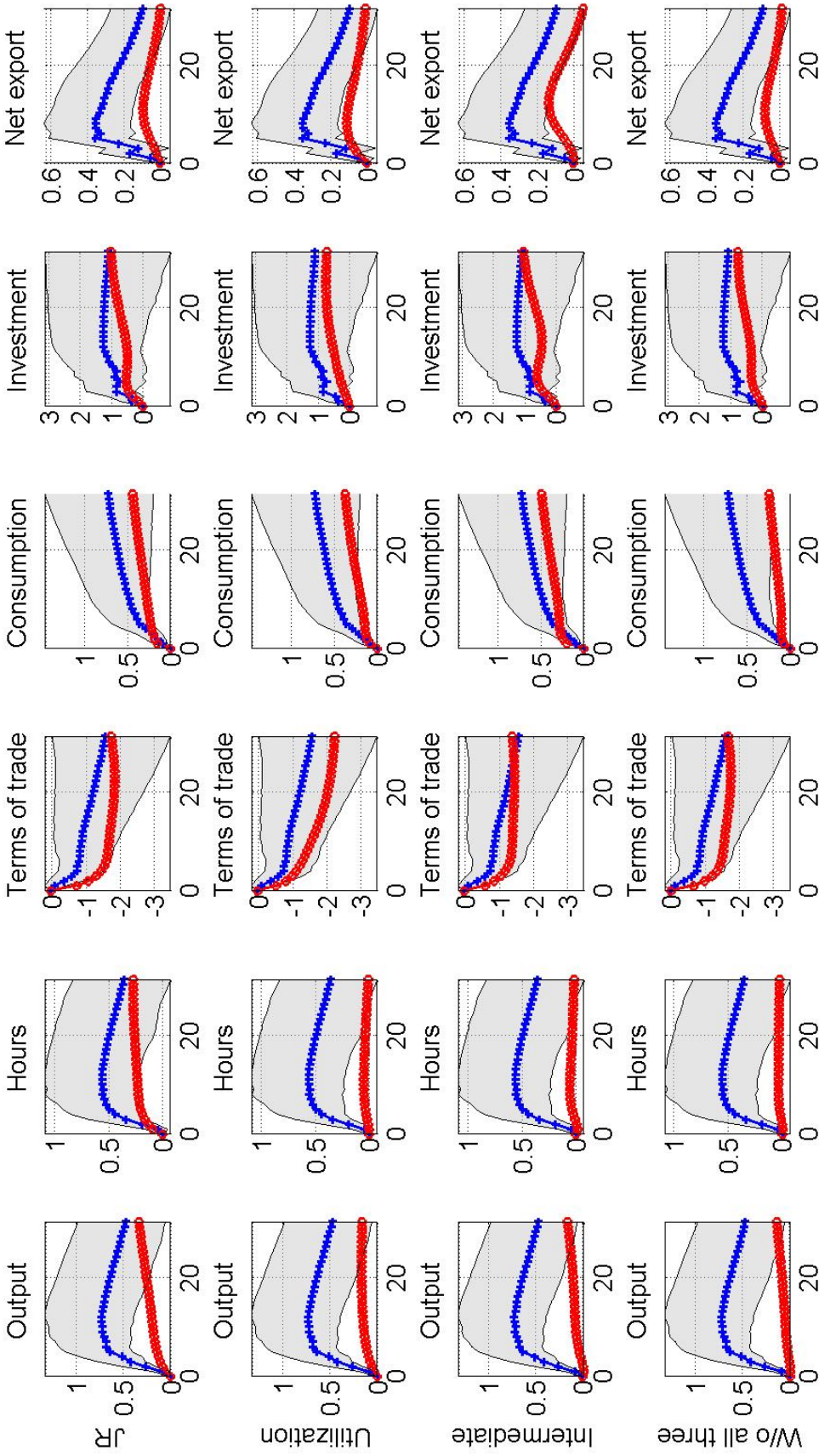

Figure 9: The theoretical impulse responses of the baseline model without our three keyfeatures with exogenous correlation of technology shocks to a positive U.S. shocks. Lines with plus sign is the point estimate and the shaded areas are the 95% confidence intervals. Lines with squared sign is theoretical responses from baseline model.

Figure 10: The importance of our features in generating endogenous transmission: The estimated variants of the baseline model when two of the three key features are shut down. Lines with plus sign is the point estimate and the shaded areas are the 95% confidence intervals. Lines with squared sign is theoretical responses from the model listed on the y-axis, where (i) the baseline model without variable capital utilization and imported intermediate inputs, "JR", (ii) the baseline model without variable capital utilization and Jaimovich-Rebelo preference, "intermediate", (iii) the baseline model without Jaimovich-Rebelo preference and imported intermediate inputs, "utilization", (iv) the baseline model without any of the three frictions, "w/o all three".
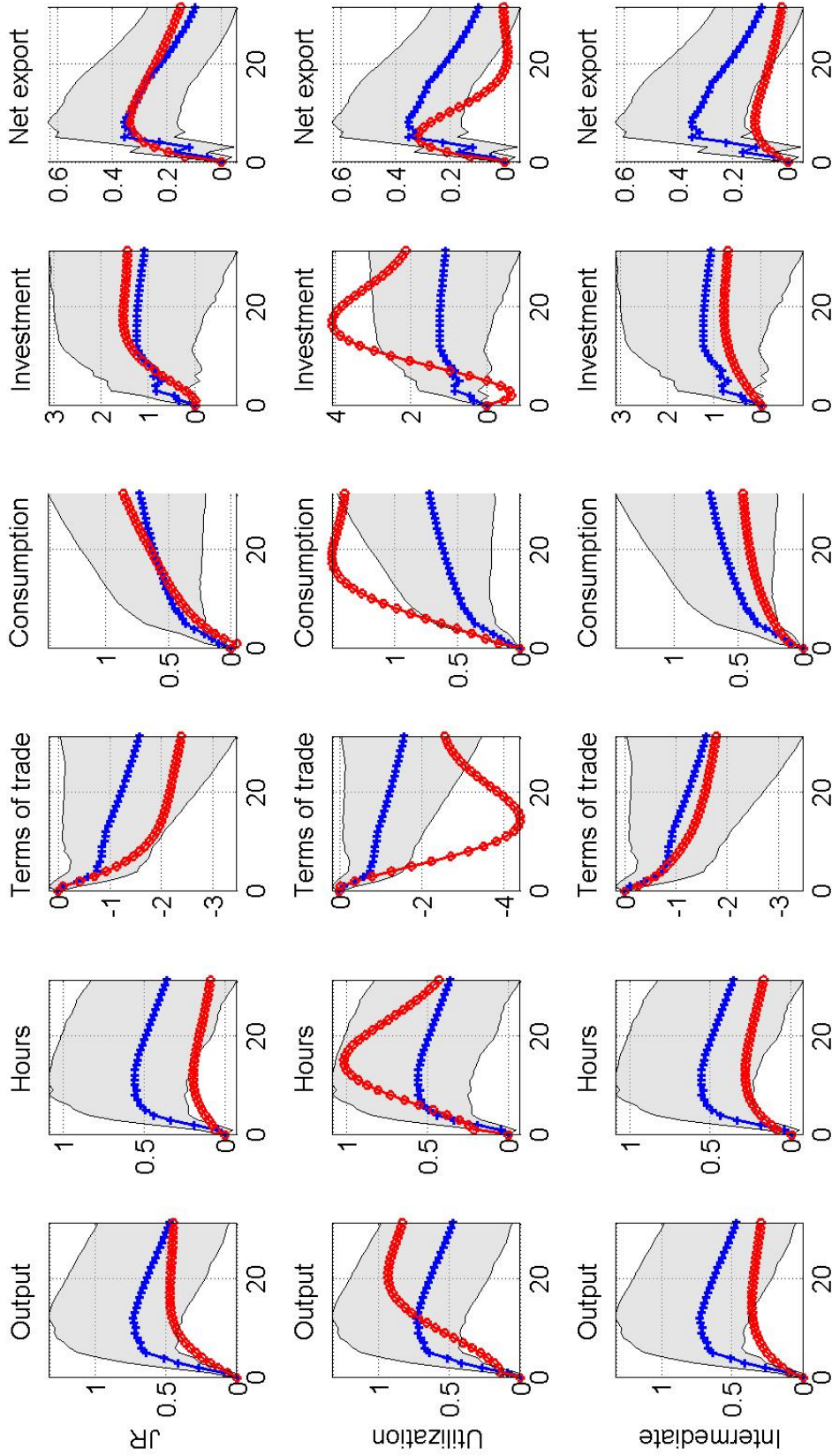
Figure 11: The importance of our features in generating endogenous transmission: Using the baseline estimated parameters, the responses of the model when one feature is shut down. Lines with plus sign is the point estimate and the shaded areas are the 95% confidence intervals. Lines with squared sign is theoretical responses from the model listed on the y-axis.
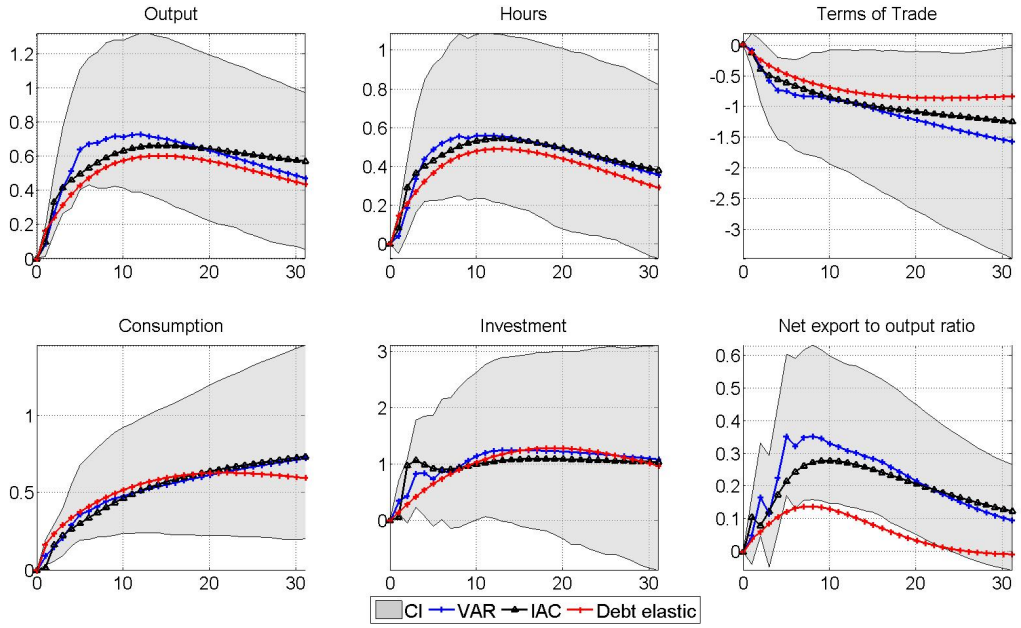
Figure 12: Robustness of the results when the baseline model has no investment adjustment cost, debt elastic interest rate. Lines with plus sign is the point estimate and the shaded areas are the 95% confidence intervals.
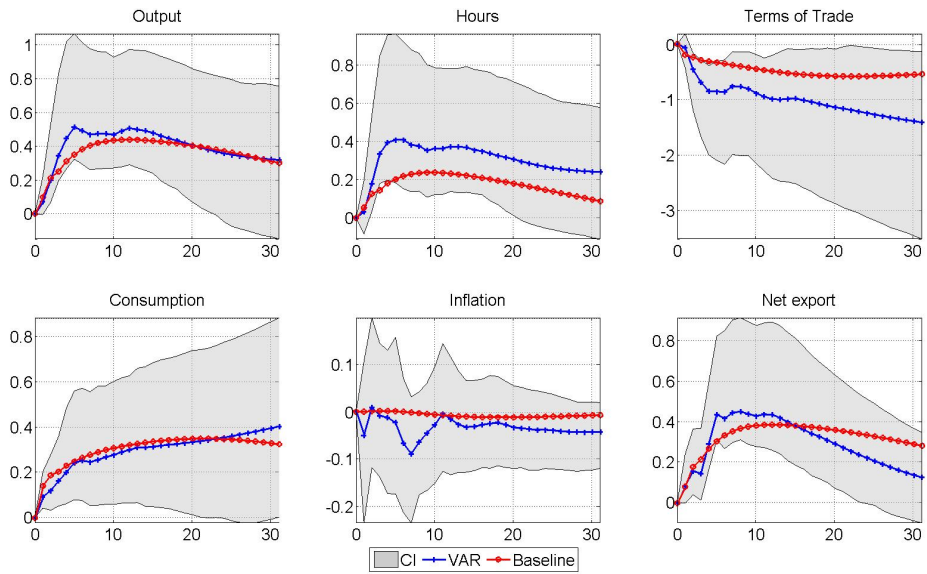

Figure 13: Fit of the baseline model with nominal price and wage stickiness.